Economic and Technological Assessment of Fuels for a Sustainable Transportation Sector in Brazil

Graduate Independent Capstone Research Paper

ENVR E- 599 – Independent Research Capstone

Projects in Sustainability & Environmental Management

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Summer 2018

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Abstract

Brazilian private vehicles are responsible for most of the greenhouse gas emissions associated with its energy sector. When accounting for their life cycle, the environmental impacts of its fuels are not restricted to atmospheric concerns. This study examines five renewable fuel technologies with the purpose of determining which would be best-suited for private transportation in Brazil, considering financial, technological and sustainability factors.

For each parameter investigated among the technologies analyzed, the methodology enabled quantitative comparisons. Accordingly, this research verified the scalability, efficiency, and financial competitiveness of each fuel approach. For technologically and economically competitive approaches, associated environmental impacts were analyzed quantitatively. The results showed that in its current state, bacterial synthetical fuel technology is not yet technically viable for meeting demand. Presently, algae biofuels and high-temperature electrolysis synthetic fuels are not economically viable. Although the batteries of electric vehicles are still expensive, government subsidies are a reality that enables their viability. Biofuels derived from sugarcane monocultures are less polluting than fossil fuels, but have many environmental impacts that are not commonly highlighted or quantified. The technologies were compared, revealing battery-operated electric vehicles to be the most suitable technology with the highest sustainability index and greatest economic viability.

Consequently this technology was concluded to be most likely to ensure the sustainable prosperity of the Brazilian private transport sector. The study concludes with recommendations for public policies for next-phase technological development and progress, aiming for the highest economic, social and environmental benefits to the Brazilian people.

1. Introduction and Background

1.1 Why investigate fuel solutions to the private transportation sector in Brazil?

Currently, one-seventh (14%) of human-derived greenhouse gas (GHG) emissions are due to transportation activities (IPCC, 2014). Some countries lack sufficient rail and marine transportation, instead compensating with increased dependency upon transportation via roadways, with its attendant increased emissions. This is the case with most of Latin America and Brazil. Accordingly, this research poses an important question: what is the best fuel for private transportation in Brazil, considering current financial, technological and sustainability factors?

The transportation sector consumes 32.4% of all energy consumed in Brazil and is responsible for almost half (45.3%) of all emissions associated with energy production (EPE, 2017). In the Brazilian transportation sector, road transport is the main source for GHG emissions. Its emissions produce more than 90% of all carbon dioxide (CO_2), 93% of all nitrogen dioxide (NO_2), and 99% of all methane (CH4) emissions of the entire transportation sector (MTPA & EPL, 2017).

The Brazilian road transportation sector is mainly composed of light vehicles: 84.1% of road transport is attributed to cars and motorcycles (DENATRAN, 2018). Of this portion, there are 51.3 million cars (representing 56.2% of road transport vehicles), fewer utility vehicles (11.7%), and still fewer trucks (3.6%), and buses (1.1%) (MTPA & EPL, 2017). Light vehicles consume most of the gasoline and ethanol produced, totalizing approximately 46% of all consumed fuels (EPE, 2017). Most of the GHG emissions are derived from cars, reaching between 35% to 37% as is noted in Figure 1 (ANTT, 2011).

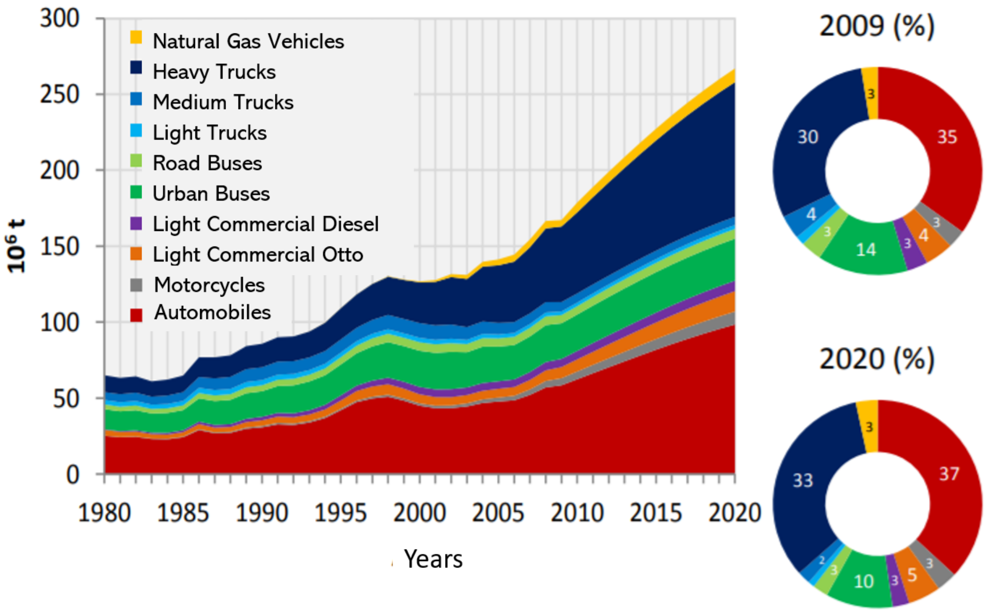


Figure 1. *Emissions of CO_2 by Vehicle Category in Brazil (ANTT, 2011). Translated by the Author.*

Therefore, cars and their suitable fuels are the most relevant actors in the atmospheric environmental impacts of the Brazilian transportation sector.

1.2 Energy and transportation sector storage necessities

Clean, renewable energy is a potential solution to reduce the production of carbon dioxide from dirty fossil fuel consumption. However, the most promising and abundant clean energy forms, solar and wind power generation, are intermittent sources of energy. Therefore, they may produce insufficient energy at times of greatest demand. But such demand could be met if it was possible to store the vast quantity of electricity generated by these sources during their peak periods. Figure 2 demonstrates this problem through highlighting the electricity production from the wind and solar plants (black line) versus demand (red line).

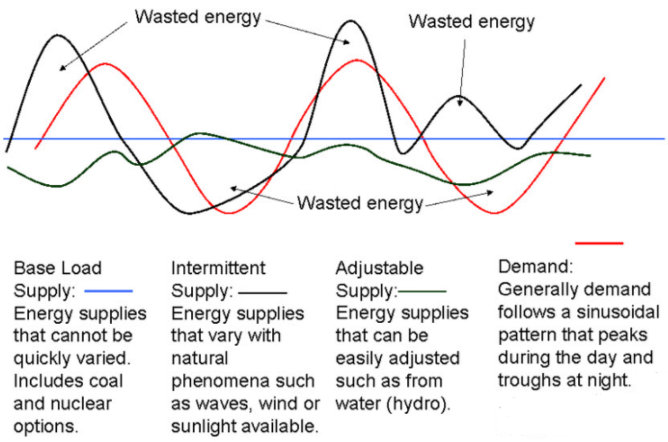


Figure 2. The Interrelation between Electricity Production (by sources types) and demand (Green, n.d.).

The gap in storage technology for solar and wind energies undermines their reliability and further deployment. Therefore, other sources of possibly less sustainable--but still more reliable-- energy, such as hydro, nuclear, and coal power plants, are currently necessary to fulfill the demand for electricity (Nasiri, 2013).

The current stationary methods of electricity storage are comprised of mechanical storage (gravitational potential and flywheels), electrical storage (supercapacitors), electrochemical storage (batteries, flow batteries), and thermal energy storage. These do not meet the economic, social, and environmental requirements which entail being fully-developed, affordable and efficient, while sustainable in the long run (Chen et al., 2009).

Electricity carriers on vehicles could be the answer and seems to be the ultimate sustainable goal for the transport sector, since they emit neither GHG nor pollutants and create the opportunity to apply a vehicle-to-grid transmission scenario, wherein energy from vehicles could be transmitted back to the grid in peak hours, helping the grid stability (Karen, Moodenbaugh, Goldberger, Santhosh, and Woodward, 2006).

But storage of electricity is also one big challenge in using electricity carriers. New forms of energy storage, such as compressed air flywheels and ultracapacitors, are still at a raw stage of development (Chen et al., 2009). Lithium-ion batteries are expensive and energy storage through hydrogen cells would need a complete overhaul of infrastructure to be produced at a large scale both in terms of energy used and vehicle adaptation.

Electric vehicles (EVs) powered by batteries and fuel cells may have a relevant environmental impact when assessed from an LCA perspective. But it is not evident whether using electric-powered vehicles is the best path for the transportation sector in Brazil, even with the latter producing 82% of its electricity from renewable sources (Agência Nacional de Energia Elétrica [ANEEL], 2018a). Nevertheless, the technological challenges related to storage open a window for the inclusion of clean biofuels in hybrid vehicles until a total transition from combustion engines to electric propulsion has taken place, as shown in Figure 3.

For this, liquid hydrocarbons are excellent forms of energy storage because they can storea great deal of energy in a small space (high energy density) and already have a full set of infrastructure. This characteristic makes liquid fuels optimal for renewable power storage (Cook et al.,2010).

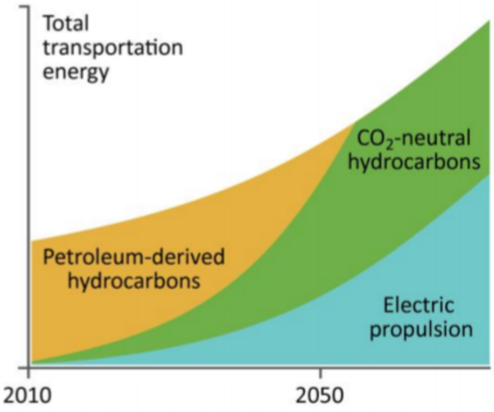


Figure 3. Transportation transition scenario for a sustainable future. Adapted by Daniel Peon from Graves et al. (2011).

Another independent study conducted by Granovskii, Dincer, & Rosen, (2006) studied the economic and environmental effects of electric, hybrid, hydrogen, and conventional vehicles, denoting that the advantage of hybridization was the best economic path for future development of electric vehicles. Based on that, “carbon-neutral” biofuels from biomass seems to be the sustainable answer to electricity storage, but such solution brought and may still bring devastating hitches.

1.3 Are biofuels the solution to the environmental problems of the sector?

Vehicles consume two-thirds of the 15 billion liters of oil consumed globally per day (Energy Information Administration [EIA], 2016a). The biofuel industry emerged as a response to the transportation sector dependency on oil. Today it provides 4% of global transportation needs, largely produced by the USA and Brazil (International Energy Agency [IEA], 2016a).

In the 1970's, the global fossil fuel crisis drove Brazil towards the development of its *Pro-Ethanol* program, which fostered the research and development of biofuels. This enabled Brazil to master the use of sugarcane ethanol for transportation (Szmrecsányi & Moreira, 1991). Currently, 62.7% of existing cars in Brazil are the "flex-fuel" vehicles, which can use either pure gasoline or ethanol or any mixture of those (Sindipeças, 2017).

The reasons why Brazilians are not using only ethanol for their flex cars and motorcycles are mainly financial, and are the consequence of market's commodity price changes (Leite & Leal, 2007). As a default, the price of ethanol is lower than gasoline because its energy density is also lower, approximately 70% of its counterpart (Gable, Christine & Scott, 2017). As the fuel price fluctuates, gas stations in the country show at the level of the pumps, which fuel is financially better for the flex-fuel consumers.

Despite their well-established presence in Brazil (see Figure 4), biofuels derived from monocultures of sugarcane do have significant environmental impacts that are usually not accounted for in cost-benefit analysis studies (Pugliese, Lourencetti, & Ribeiro, 2017).

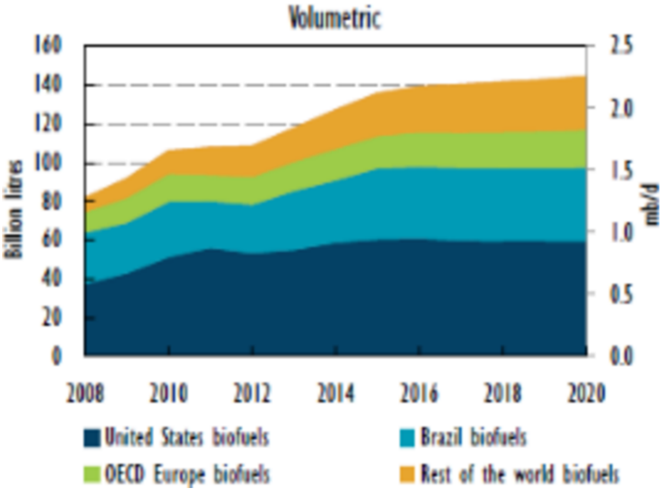


Figure 4. World Volumetric Biofuel Production by Region and Future Predictions (IEA, 2016a).

Biofuels from biomass have the potential to be carbon neutrally produced, but they also can severely harm the environment.

Biofuels are regarded as a green solution to substitute for fossil fuels because they could develop rural economy while securing the fuel supply and reducing CO_2 emissions (Reijnders, 2006; Yan and Lin, 2009). In theory, the CO_2 emissions from combustion would be sequestered by the plants during photosynthesis, closing the loop as shown in Figure 5. However, the sustainability of such an idea depends on how and where biofuels are produced (Fargione, Hill, Tilman, Polasky, & Hawthorne, 2008).

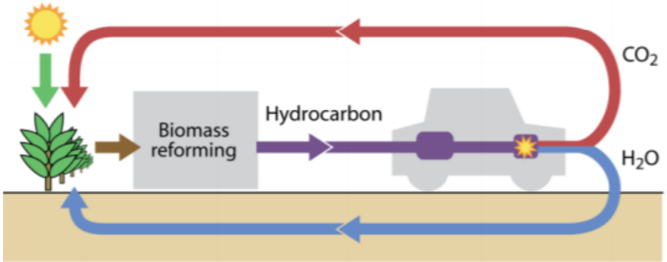


Figure 5. Theoretical Carbon cycle from Using Biomass to Produce Hydrocarbon fuels (Graves et al., 2011). Pollutants Eerived from Hydrocarbon Combustion and CO_2 Produced during Biomass Reforming are not Present in the Figure.

Monocultures that produce biofuel received a great deal of attention in the past decades as a renewable energy source alternative. There is a claim that crops grown for fuels may displace other agricultural activities or harm food production and its prices (Scharlemann & Laurance, 2008; Searchinger et al., 2008). Accordingly, it is not possible to infer that biomass biofuel is the ultimate "green" answer until a sound environmental analysis is considered.

1.4 Cutting-edge fuel technologies as a possible solution

Beyond the technologically well-established fuels (e.g., electricity, hydrocarbons, and hydrogen), microalgae seem to be a promising catalyzer to produce biofuels. Microalgae hold several prospective advantages, such as efficiency, production rate, volume, and fewer environmental impacts, which may severely disturb the energy and fuel market.

Another promising technology is the synthetic production of fuels from renewable sources. One example is the bacteria-assisted electrocatalysis technology (also called artificial-leaf) which allows the production of hydrocarbon fuels from solar energy. A further example is the high-temperature electrolysis in solid oxide cells. In the latter, renewable electricity surplus is used to produce a hydrogen gas which is then combined with CO_2 to produce fuel.

The idea of using produced surplus electricity from intermittent sources and transforming it into liquid fuels could also solve the previously mentioned storage of energy requirement. Again, the question remains: which is the best-suited option to Brazil taking into consideration financial, technological, and sustainability factors?

1.5 The uniqueness of this research

Previous studies within the Brazilian scenario scope did not cover a broad sustainability analysis. Lack of a holistic environmental impact analyses allied to life-cycle assessment (LCA) jeopardize an assertive decision of policies and strategic planning for the transportation sector.

The present study is intended to fill this gap. However, as a full life cycle assessment could entail a scope beyond that of this approach, the primary focus here is upon the fuel cycle (Figure 6 non-grey area), to match the feasibility of the current research timeframe.

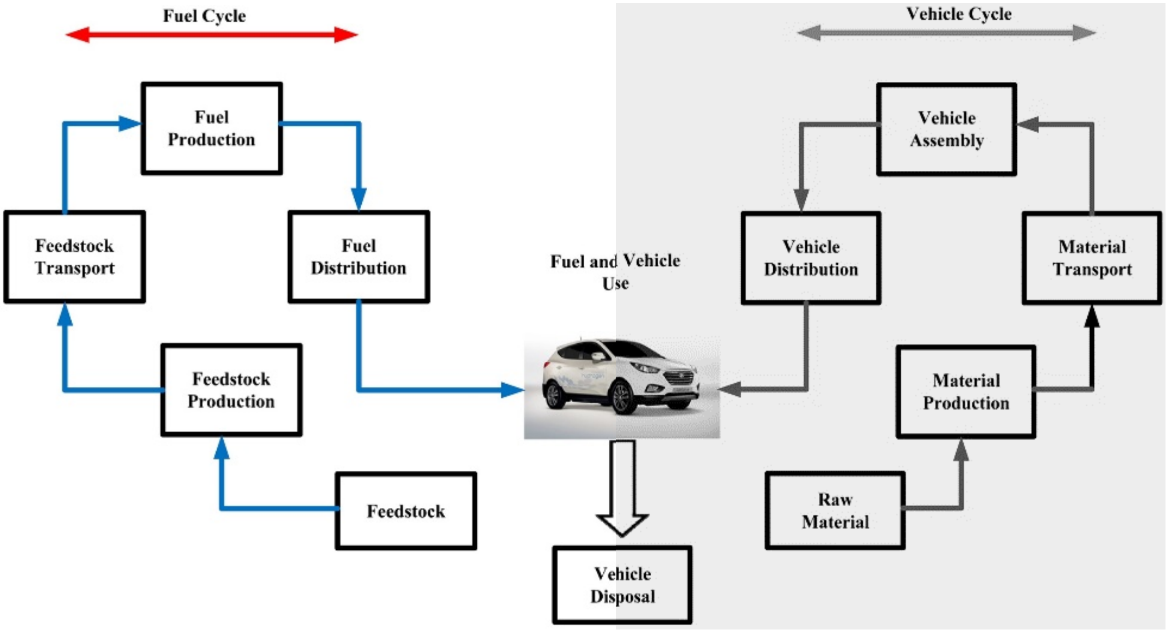


Figure 6. Life Cycle Assessment of a Vehicle. Adapted by Daniel Peon from Ahmadi & Kjeang (2017).

A chief focus is upon comparing the transportation fuel technologies currently available and investigating which provides the most suitable option for Brazil, taking into consideration financial, technological, and sustainability factors.

An index will be created for each factor. A table will be developed to present the indexes for each parameter and this will allow a visual comparison of the technologies. The indices developed attempt to include the main concerns of stakeholders.

Since all fuel production and distribution have a vast effect and a broad number of stakeholders, the results of this study may impact Brazilian decisionmakers positively (e.g., Environmental Ministry of Brazil, Ministry of Planning), as well as NGOs, and entities focused on environmental issues. The outcome of this study could also disrupt the transportation sector industries and its supply chain, not to mention the energy sector, including electricity production and distribution, oil and gas industries, and sugarcane producers; among others.

It is intended that the results of this work serve as an exceptional source, providing decisionmakers with a more integrative analysis when opting to develop a specific fuel technology or policy for the Brazilian transportation sector. Such a goal is aimed at that benefitting Brazil's most important stakeholder – its people.

2. Methodology

2.1 The boundaries

The first scope of boundaries is within the fuel technologies for cars in the light vehicle segment of the transportation sector in Brazil. The fossil-derived fuels are out of calculation in this section due to their intrinsic non-renewable characteristics allied with their notorious environmental impacts, being not suitable for a sustainable future of the Brazilian transportation. Nevertheless, gasoline powered vehicles are included in the overall technology comparison. Direct solar usage (e.g., solar vehicles) and other vehicle's fuel prototypes which cannot sustain the premise of 'a developed technology capable of substituting the existing ones' are not taken into consideration either.

Some social risks and consequences were not considered due to the need of narrowing down the scope of the study. Nevertheless, the author recognizes that the fuel change could lead to loss of public financial sums from oil royalties, loss of jobs in the transportation and energy sectors, and the loss of taxes and production for the conventional automotive sector among other socio-economic unforeseen costs. At the same time, many positive consequences are also unanticipated.

Some other factors are also not considered, such as the power of lobby and private sector financial interests in the decision-making process. These can generate sufficient inertia as to delay or even prevent implementation of immediately advantageous technology. Unforeseen events like a revolutionary fuel technology development are also not considered.

Regarding the economic factor index (which will be described in the metrics sub-chapter below), other pertinent parameters such as the return of investment and infrastructure investment were excluded as beyond the scope of the present study. Nevertheless, it is expected that these existing boundaries and assumptions will allow this research to make a valid and focused analysis of the technologies' impacts; ultimately enabling decisionmakers to have richer data in their hands. Hopefully leading to a sustainability embraced decision.

2.2 The assumptions

The author assumes that the pillars of economic, technological, and sustainability should frame the critical thinking informing fuel-technology assessment and choice. An underlying premise here is that sustainable environments promote improved public health conditions and thus, human well-being.

A further assumption is that the current economic scenario will not change significantly in the near future. This encompasses price of fuels, non-renewable and renewable biomass, and electricity, and natural resources.

In the author's best knowledge, among all the technologies researched, the ones selected for this research reflect the highest possibility of implementation within the proposed scope, time frame, and objectives. The author also assumes that technical efficiency is not the sole factor in contemporary decision-making processes, despite its appeal from an engineering point of view. Nevertheless, the author calculates the energy efficiency of each technology recognizing its expected importance in decision-making.

2.3 Literature inclusion and approach

To ensure source credibility, technical literature reviewed is restricted to peer-reviewed journals. In total, 125 scientific articles and reports issued from 1980 to 2018 were reviewed for this capstone project. The articles were examined as to their falsifiability, logic, comprehensiveness, replicability, and sufficiency-- the primary basis for critical thinking.

The objective of this review was to identify the findings regarding life cycle assessment relative to the environmental aspects and impacts of specific fuels technologies for automobiles. Additionally, the goal was to investigate the financial parameters of each technology, as well as its technological maturity.

Some parameters are considered essential and are irreplaceable, meaning that without them, the technology could no longer be considered for the comparison.

2.4 Metrics

2.4.1 The economic factor

For an economic evaluation, one essential parameter was considered: economic viability. In other words, the technology must be price-competitive with other fuels.

2.4.2 The technological factor

The technological evaluation approach is based on two parameters: technology maturity and technology efficiency. The first includes the viability and scalability of deployment (i.e., the capacity for implementation). This is an essential parameter. The latter, which concerns how efficient the process is, taking into account the laws of thermodynamics and the losses due to energy transformation. This is a quantitative factor which shall be used subjectively (e.g. as a "tie-breaker").

2.4.3 The sustainability factor

The review includes articles comparing fuel technologies using the life cycle assessment approach. Thus, the technologies are evaluated regarding their production, use, and waste life-cycles.

In the absence of data or when the available data scope is not appropriate, the author uses a matrix of environmental impacts (Appendix, Table 8). This matrix was produced by Marazza, Bandini, & Contin (2010) to indicate the plausible severity of each environmental aspect. The matrix makes a correlation between environmental stressors and environmental contexts (e.g., soil, atmosphere, ecosystems, etc.). The expected interaction between these components is a combination of temporal and spatial measure and is depicted in Table 9 of the Appendix.

Based on Table 2, a value of severity is associated to each interaction, varying from 0 ("no correlation"), to 1 ("local and rapidly reversible impact"), to 5 ("irreversible and spatially broad impact") (see Appendix, Table 10). The author chose to adapt this table with all its interaction results and it is presented below (Table 1).

In this study, the total value of the sustainability parameter will be inversely proportional to the sum of the severity of hazards value of all applicable interactions (environmental factors vs. environmental components). Therefore, the sustainability parameter is lower when the sum of all severity of hazards value associated with the fuel technology is higher.

2.4.4 An overall factor: the viability parameter

The final expected parameter is the viability parameter (V), which will be given by the following formula:

$\mathbf{V = E \times T \times S}$, where

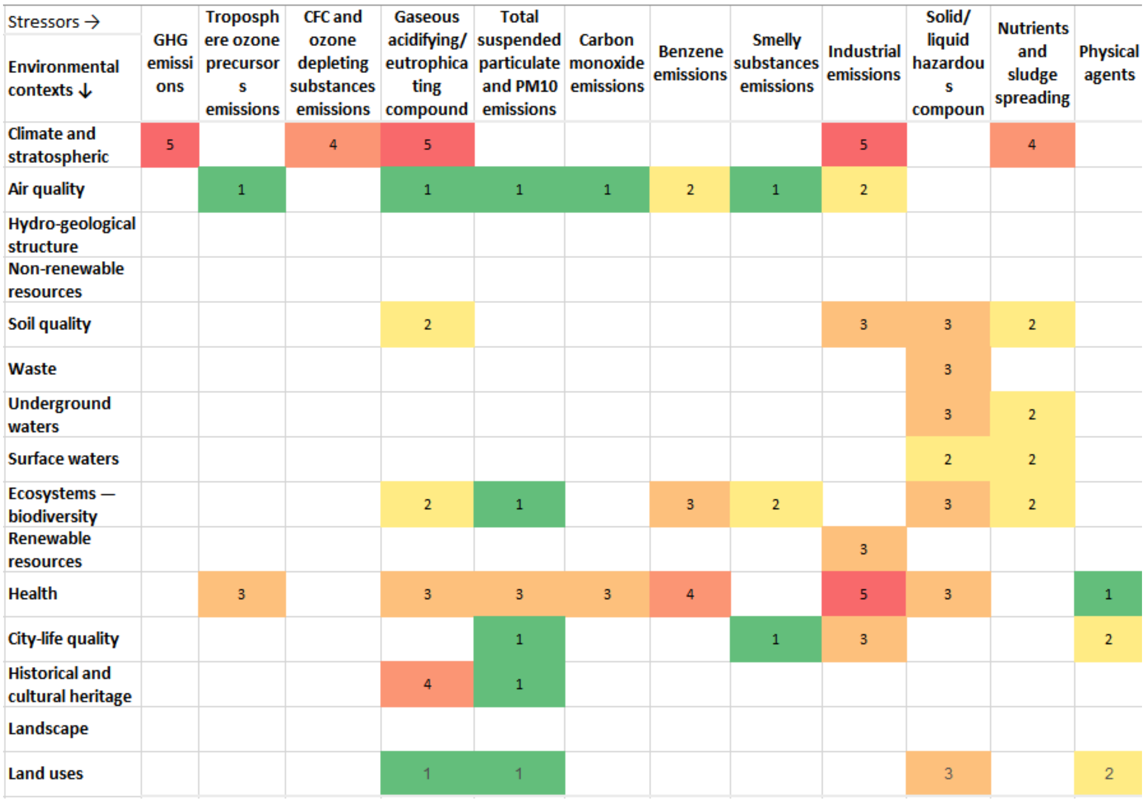
E= Economic factor (value 1 or 0)

T= Technological factor (value 1 or 0)

S = Sustainability factor = 1/ (Sum of all severity of hazards parameter) for each technology.

Through the viability parameter, it finally becomes possible to value and compare the sustainability of different technologies, taking into account the assumptions and boundaries of this study.

Table 1. The Matrix That Relates Environmental Pressures to Environmental Components (full version available in Appendix, Table 10) (Marazza, Bandini, & Contin, 2010). Adapted by Daniel Peon.



Stressors → Environmental contexts ↓	GHG emissions	Troposphere ozone precursors emissions	CFC and ozone depleting substances emissions	Gaseous acidifying/ eutrophicating compound	Total suspended particulate and PM10 emissions	Carbon monoxide emissions	Benzene emissions	Smelly substances emissions	Industrial emissions	Solid/ liquid hazardous compoun	Nutrients and sludge spreading	Physical agents
Climate and stratospheric	5		4	5					5		4	
Air quality		1		1	1	1	2	1	2			
Hydro-geological structure												
Non-renewable resources												
Soil quality				2					3	3	2	
Waste										3		
Underground waters										3	2	
Surface waters										2	2	
Ecosystems — biodiversity				2	1		3	2		3	2	
Renewable resources									3			
Health		3		3	3	3	4		5	3		1
City-life quality					1			1	3			2
Historical and cultural heritage				4	1							
Landscape												
Land uses				1	1					3		2

2.5 Rationale

The rationale for choosing the above-mentioned factors is informed by a multiplicity of stakeholders. Included are those that may suffer consequences, or have vested interest in fuel choice for light vehicle transportation. Sectors vary from private to public.

The reason behind choosing an economic factor lies in the inherent prerequisite of finance in a capitalist scenario, where projects and policies must attain to economic constraints. In addition, a technological maturity is necessary to ensure a large-scale deployment capability of a technology. The technology must be mature and capable enough to even substitute for another established technology if required.

Nevertheless, further in attending to the interest and financial concerns of the private and public sectors, the major focus must be the people. Sustainability is the factor most aligned with the people because its essence is to guarantee that the present development satisfies the current need without compromising future generations' ability to satisfy their own needs (Brundtland, 1987). Thus, quantification and ranking of technology alternatives in terms of their sustainability is critical.

3. Results

3.1 Electric cars operated by batteries and fuel cells

3.1.1 Battery electric vehicles (BEVs) economic considerations

For electric vehicles, the currently developed electricity-based storage systems such as the expensive lithium-ion batteries, still need considerable space or add a great deal of weight to the vehicle: 5 to 8 times the volume or weight of gasoline for the same propulsion (Graves, Ebbesen, Mogensen, & Lackner, 2011). Such additional weight demands a lightweight material adaptation in the rest of the vehicle, adding costs and reducing its competitive ability in the marketplace (Dhameja, 2001; Hensley, Newman, & Rogers, 2012). Due to its high cost, few EVs are in circulation in Brazil, only 2027 imported ones, representing 0.0004% of the car fleet (DENATRAN, 2018).

In a Brazilian scenario, Ana Santos (2017) compared the economic viability of a very affordable imported electric vehicle (the Renault Zoe), to a similar combustion engine model (Renault Sandero) produced in Brazil. Even without considering the Brazilian taxes, the acquisition cost of the electric model is double the price of its conventional counterpart. Plus, the electric model has the added cost of a monthly battery fee, which is a sales strategy to reduce the vehicle acquisition price. Despite their higher final acquisition prices, electric vehicles have lower fuel and maintenance costs than regular combustion engine vehicles. But even considering the lower maintenance and lower energy consumption, still, in this scenario, the study concluded that the electric car is not economically viable for the consumer (Santos, 2017).

Another Brazilian study from the Getulio Vargas Foundation (Delgado, Costa, Febraro & Silva, 2017) used the vehicle cost calculator from the US Department of Energy to compare ownership costs between an electric vehicle (2016 Nissan Leaf BEV 2016; price: US $29,010) versus a combustion auto (2016 Toyota Corolla 2016 US $17,830). The cost of ownership per year for each vehicle includes fuel, tires, maintenance, registration, license, insurance, and loan repayment. Again, the electric vehicle had lower costs in maintenance and fuel, but, due to higher initial price, it fails in overall cumulative cost of ownership (Figure 7a). The only way to work around this situation is through subsidies. Using the California state subsidy (US$10,000), Figure 7b shows approximate parity the first 6 years, after which the electric vehicle grows increasingly more affordable (Delgado et al., 2017).

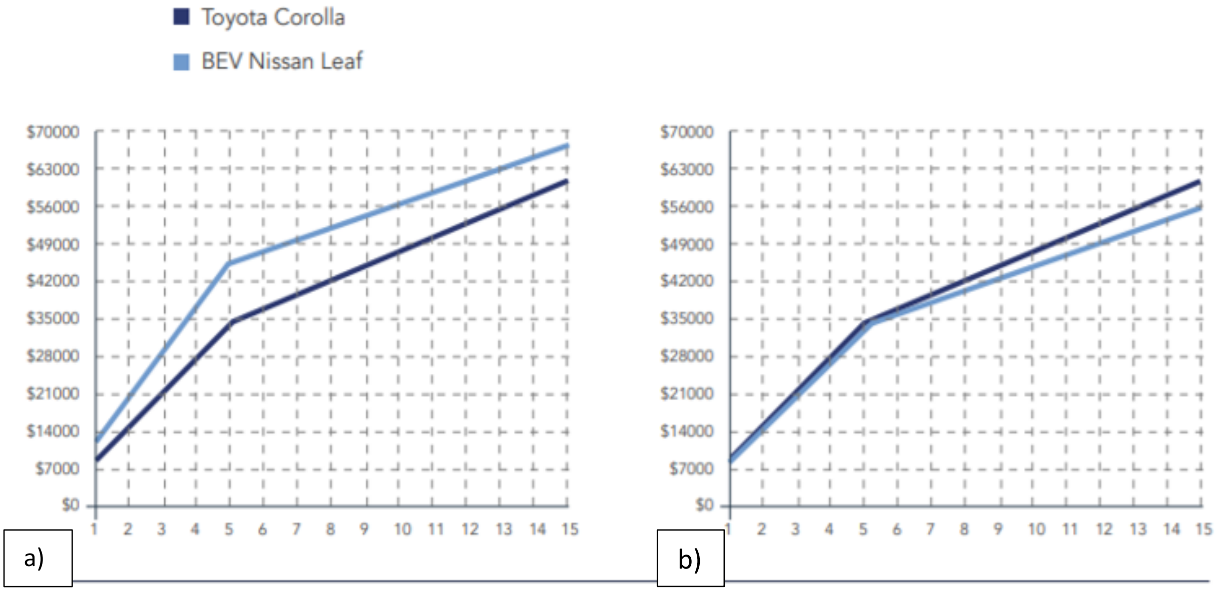


Figure 7a,b. Annual Cumulative Cost of Ownership of a Battery Electric Vehicle (BEV Nissan Leaf 2016) vs. a Combustion Vehicle (Toyota Corolla 2016). a) Without Acquisition Subsides; b): With Acquisition Subsides (Delgado et.al., 2017).

In Brazil, the subsidies are small and the national taxes on electric vehicles are exorbitant. Currently, the government has exempted two taxes: the importation tax, and the annual vehicle ownership tax in 7 of the 26 Brazilian states. Nevertheless, in the current legislation, additional taxes allow the taxation to surpass 120% of the cost of the electric vehicle (Jussani, Masiero e Ibusuki, 2014).

Partially due to the lack of incentives and high taxes, and since no hybrid/electric car is produced in Brazil, the current cheapest electric car available is the BMW i3 that is sold for 200,000BRL ($54,000USD – July/2018 exchange rate). For hybrids, the Honda Prius is sold for 126,600BRL ($34,000USD – July/2018 exchange rate). Considering the price of entry-level combustion cars in Brazil is approximately 30,000BRL, the hybrid and electric models cost between four and six times more. Therefore, without subsidy policies, electric cars are not price-competitive in Brazil. However, hidden economic benefits could indeed make this fuel technology the most financially advantageous for Brazil.

Despite electric car's current lack of price competitiveness, economies of scale are reducing the prices of batteries (see Appendix, Figure 16); and several countries are adopting subsidies and other measures to invest in this change (Chediak, 2017; Delgado et al., 2017). Considering a USD $3,50 fuel price per gallon, the breakeven point for lithium battery prices would be USD $100 per kWh, which could occur already in 2025 (Chediak, 2017). Further, in relation to the sustainability matter, possible economic reasons for adoption are the savings in oil consumption, the reduction in public health expenditures, and the energy independence that is derived from the use of electric cars.

Due to their higher efficiency, electric cars are a great solution to save overall energy consumption. In Brazil, Renato Baran (2012) investigated a scenario where electric vehicles would have a great acceptance, reaching 37.4% of the fleet in 2031. In this context, he concluded that the consumption of gasoline would reduce 41%, followed by a 42.1% increase in electricity consumption. Despite the increase in electricity demand, the overall energy consumption of this Brazilian sector would be reduced by 27.5%, thereby saving 31.6 million tons of petrol per year (Baran, 2012). The yearly savings in oil would reach $13 billion USD, which is equivalent to one third of Brazil's federal budget expenditure on public health per year (Ministério da Saúde, 2017).

A significant fleet of electric cars would allow a vehicle-to-grid scenario, where car batteries would store electricity during the day and could release it during peak demand periods, helping in the Brazilian electricity matrix stabilization without further investments in storage technologies to attend renewable energy intermittency. Nonetheless, stakeholders (i.e., utilities companies, interested private, and or public sector) should consider a cost-benefit analysis including the hardware required to support the vehicle-to-grid system (e.g., battery-to-grid converter).

Regarding infrastructure, a BEV charging network costs approximately one thousand dollars for a home-based charger, and costs between 10 to 100 thousand dollars USD for public stations (Plug In America, 2015). Building a gasoline station would cost approximately 1 million to 2 million USD a piece (National Petroleum Council [NPC], 2012). Additionally creation of a significant number of recharging stations would be required, mostly on roadsides. However, the lack of urban infrastructure (like recharging posts) is less of an impediment since consumers could use household electricity to charge their cars. The same is not true for fuel cell vehicles (FCV).

3.1.2 Hydrogen fuel cell vehicles (HFCVs) economic considerations and comparison with BEVs

Hydrogen public stations cost roughly 3-5 million dollars USD (Melaina and Penev, 2013). This is between 30 to 500 times more than electric public stations. Besides these infrastructure requirements, when economically comparing Hydrogen FCVs with BEV, the most relevant factors are the cost of the vehicles (coupled with fuel cells costs and its durability) and the cost of production of hydrogen.

A study based on the province of British Columbia, Canada (88% hydroelectricity grid and $0.08 CDN per kWh) compared the costs of gasoline vs. HFCVs, considering the maximum operating hours of the fuel cell and the total lifetime costs (Figure 8) (Ahmadi & Kjeang, 2017).

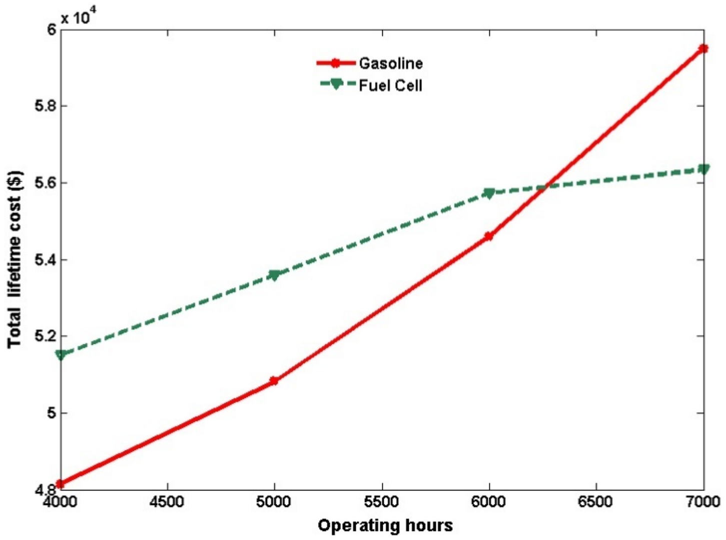


Figure 8. Estimated total lifetime cost of the gasoline and hydrogen fuel cell powered vehicles for different operating hours (Ahmadi & Kjeang, 2017)

The assessment concluded that the total lifetime cost of the FCV is $2,100 higher for the current 5500 hours of fuel cell durability. Therefore, until the cell durability reaches 6,300 hours, the FCVs in Canada would not be price-competitive (Ahmadi & Kjeang, 2017). Accordingly, it is possible to infer that in Brazil, the vehicle would also not be price competitive since the cost of electricity ($0.52BRL/KWh ≅ $0.18CND/KWh) is more than double than in Canadian comparison ($0.08CND/KWh) (ANEEL, 2018b).

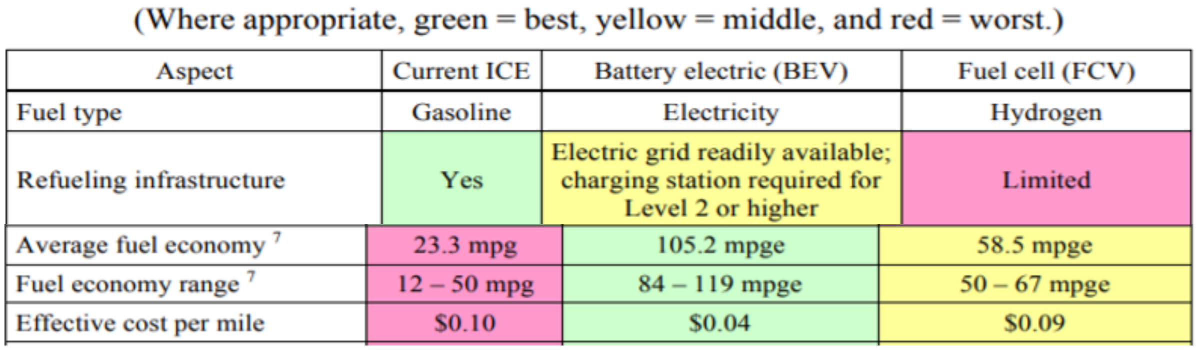
Regarding the fuel cell system costs, the cost needs to achieve a price between $40USD to $30USD per kW of energy, which is only attainable through high-volume manufacturing (see Figure 17 in the Appendix) (Huya-Kouadio, 2017). Moreover, the hydrogen storage tanks in vehicles use a considerable amount of expensive carbon fiber, which is another reason to believe that FCVs may not become cost competitive even with mass production of its components (Miotti, Hofer, & Bauer, 2017).

Regarding the cost of production of hydrogen based on current technology, solar to hydrogen transformation is not yet competitive with hydrogen from fossil energy (R. Shaner, A. Atwater, S. Lewis, & W. McFarland, 2016). Also, in short-term (up to 2030), cost of hydrogen produced by electrolysis from renewable energy is expected to continue to be non-competitive with natural gas cost (Moliner, Lázaro, & Suelves, 2016).

Due to all the factors mentioned above, per-mile costs for FCV are more than double those for BEVs (Schoettle & Sival, 2016).

The Table 2, put together by Schoettle & Sivak, (2016), summarizes some of the economic relevant aspects of these two fuel technologies.

Table 2. Relevant Aspects of the Fuel Sources for Internal Combustion Engine (ICE), Battery-Electric Vehicles (BEV) and Hydrogen Fuel-cell Vehicles (FCV) (Schoettle & Sivak, 2016).



(Where appropriate, green = best, yellow = middle, and red = worst.)

Aspect	Current ICE	Battery electric (BEV)	Fuel cell (FCV)
Fuel type	Gasoline	Electricity	Hydrogen
Refueling infrastructure	Yes	Electric grid readily available; charging station required for Level 2 or higher	Limited
Average fuel economy [7]	23.3 mpg	105.2 mpge	58.5 mpge
Fuel economy range [7]	12 – 50 mpg	84 – 119 mpge	50 – 67 mpge
Effective cost per mile	$0.10	$0.04	$0.09

3.1.3 Electric vehicles (EVs) - technical considerations

Regarding the electricity grid in Brazil, there is no need to greatly increase its production capacity to attend to the demand for more electric cars. If 25% of the Brazilian fleet were electric, only 14% consumption demand would be the increase, which is manageable under the currently existing infrastructure (Baran, 2012). Nevertheless, the development of public or private recharging stations throughout the country will surely contribute to increase the autonomy reliability of EVs. Furthermore, both BEV and FCV are well-developed technologies with the consolidated fleet in developed countries worldwide. To technically differentiate them, efficiency characteristics shall be compared.

BEV efficiency

To calculate the “well-to-wheel” efficiency of an electric vehicle, it is necessary to know how much of each energy source composes the electric grid. In Brazil, 70% of the electricity generation is from hydropower, followed by 20% from thermal (coal and natural gas), 9% from renewables (mostly biomass, and marginally, wind and solar) and 1% nuclear (EIA, 2016b). Furthermore, it is necessary to know how efficient in generating electricity these sources are.

Each of the electricity sources in Brazil has a specific energy conversion efficiency. Hydro in Brazil has an average 90% energy conversion efficiency (“Renewable Energy, Hydroelectric Power, benefits and cons of hydro energy,” n.d.). Thermal, about 30% and biomass to electricity may have a 20% efficiency (Moreira, 2002) (Biomass Energy Resource Center [BERC], 2017). Nuclear, about 33% (EIA, 2017). With these values at hand, the overall electric grid efficiency may be calculated as follow:

- From a hypothetical 100KW of electricity produced: 70KW would come from hydroelectricity, 20KW from thermal (coal and natural gas), 9KW from renewables (wind, sun, and biomass) and 1KW from nuclear.
- Applying the specific efficiencies: (90% of 70KW) + (30% from 20KW) + (20% from 9KW) + (33% from 1KW) = 56KW+6KW+1.8KW+0.3KW = 64KW of electricity generated.
- Furthermore, the distribution losses in Brazil are 16% (World Bank, 2014). Subtracting these losses from the energy generated (64KW), the final energy delivered is 54KW.

  Such value is 54% of the initial hypothetical value. Therefore, the average efficiency of primary energy to electricity conversion in Brazil is 54%.

  Electric vehicles have a 90% efficiency of electrical-to-kinetic energy conversion (Shah, 2009). Taking into consideration the Brazilian grid electric efficiency of 54%, electric vehicles overall primary energy to kinetic energy efficiency (“well-to-wheel” efficiency) is 48.6% in Brazil.

Combustion engines are 20% efficient on average (Shah, 2009). Nevertheless, refining oil to obtain gasoline is 85% efficient on average since 15% of energy is lost during conversion(Wang, 2008). The gasoline transportation and distribution could further reduce the well-to-pump efficiency to 81.6% to 83.9%, but as this value greatly varies depending on location (Dehagani, 2013). Accordingly, a more conservative approach will be adopted

(85%). Thus, the real "well-to-wheel" efficiency of combustion engines is 17% approximately. Thus, electric vehicles are almost three times more efficient than combustion engines vehicles in the Brazilian scenario.

Comparing BEVs and FCVs efficiency

A fuel cell takes more steps to convert energy, and it loses energy at each conversion step. Currently, the "well-to-wheel" efficiency of FCVs are between 22% to 29% (Sperling & Cannon, 2004). As calculated above, the BEVs achieve 48.6% "well-to-wheel" efficiency in Brazil, and are therefore approximately two times more than FCVs.

However, hydrogen fuel cells have a high capacity, which allows this type of vehicle to travel more miles between recharges than battery-operated vehicles. Low battery capacity and high recharging time limit electrical vehicles. Moreover, fuel cells do not degrade with age like batteries (Barcellona, Brenna, Foiadelli, Longo, & Piegari, 2015)

Therefore, technically, there is a draw between the two vehiche types. Hydrogen has better driving ranges and time to refuel values (see Table 3). However, BEVs are approximately two times more efficient than FCVs in using energy and need less infrastructure deployment.

Regarding safety, hydrogen is compressed as gas in high pressure (up to 10000psi) or kept liquid at an extreme cold temperature (lower than -250° C) (U.S. Department of Energy [DOE], 2015a). Nevertheless, the National Highway Traffic Safety Administration (NHTSA) has concluded they are no more dangerous as gasoline operated vehicles (Flamberg, Rose, and Stephens, 2010). The same conclusion was reached for battery operated vehicles (NHTSA, 2017).

3.1.4 Sustainability considerations

Battery electric vehicles (BEVs) - sustainability considerations

Despite using more natural resources during fabrication— mostly for battery and low weight chassis— electric vehicles generally have lower environmental footprints than combustion engined cars in regions where the electric grid is clean (Hawkins Troy R., Singh Bhawna, Majeau-Bettez Guillaume, & Strømman Anders Hammer, 2012) (Nordelöf, Messagie, Tillman, Söderman, & Mierlo, 2014). The reason is the weight of the use phase emissions for the overall LCA of electric vehicles.

Life cycle assessments were evaluated after 200,000 km of use for EVs on a clean grid scenario compared to internal combustion vehicles. EVs have lower global warming potential (GWP), terrestrial acidification, particulate matter formation, smog formation potential (releases of nitrogen oxides), and fossil resource depletion indices (Hawkins et al.,2012). Nevertheless, they are worse than internal combustion vehicles on indices of human toxicity, freshwater eco-toxicity, freshwater eutrophication, and mineral resource depletion indexes (Hawkins et al.,2012). However, the positive impacts of EVs are global and lasting while the negative latter are more local and non-permanent impacts.

Human toxicity potential (HTP), freshwater eco-toxicity potential, freshwater eutrophication, and mineral depletion potentials are produced principally by the supply chains involved in the manufacture of cars, occurring mostly in the discarding of sulfidic mine tailings and spoils from lignite and coal mining and additional copper and nickel requirements (Hawkins et al., 2012). As highlighted by Hawkins et al. (2012), "toxic emissions from the production chain of these metals mostly occur in the disposal of the sulfidic mine tailings, which accounts for roughly 75% of the HTP from the production phase". Waste and disposal treatment adds only a marginal contribution to these across all impact categories (Hawkins et al., 2012).

It is necessary to bear in mind that if the electric grid is mostly based on fossil fuels (lignite, coal, or petroleum combustion*)*, the battery operated electrics perform worse than conventional internal combustion engine vehicles in GWP (Hawkins et al., 2012). Fortunately, Brazil does have an electric grid that is roughly 80% clean (Energy Information Administration, 2016b).

Hydrogen fuel-cell vehicles - sustainability comparison

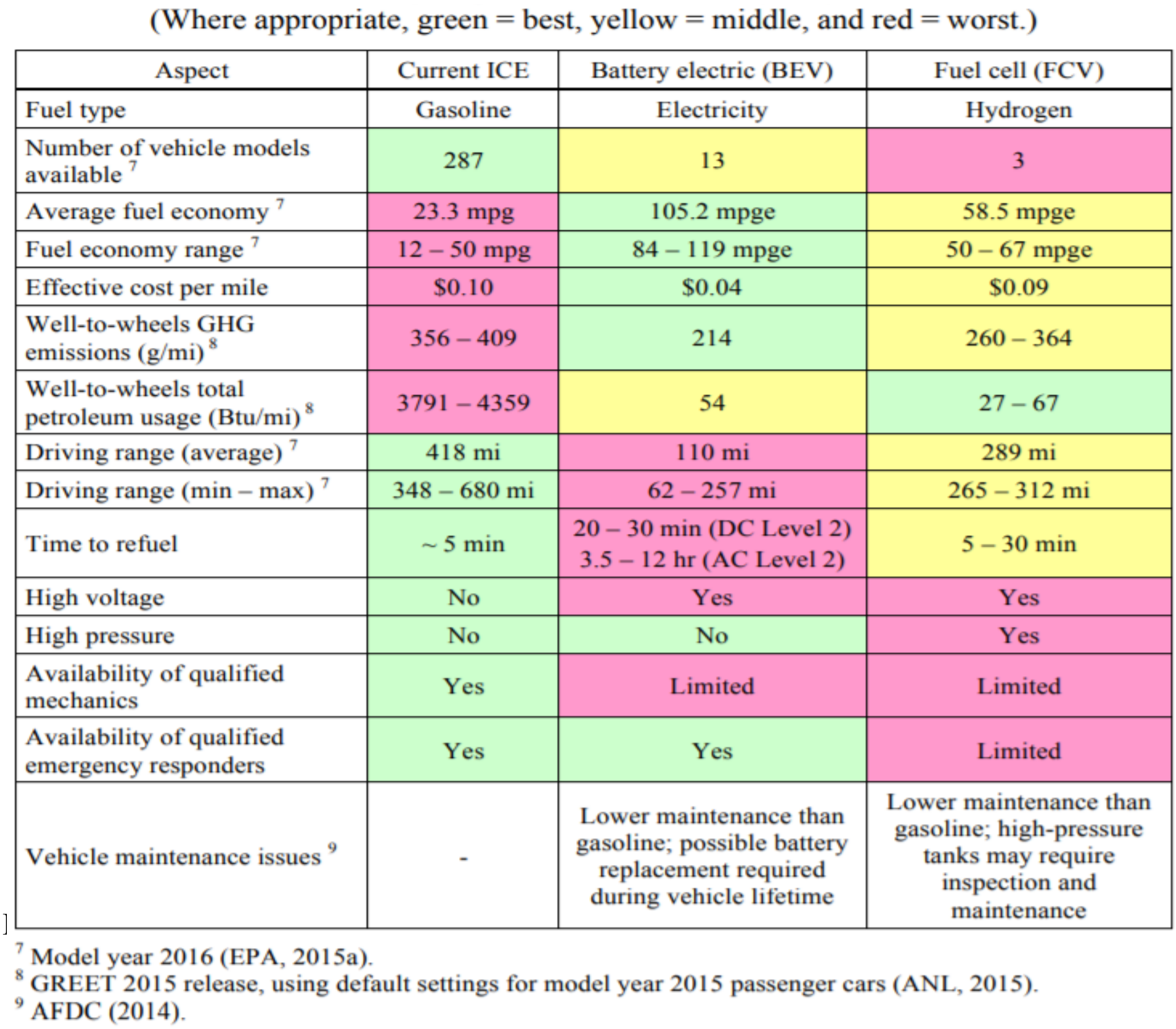
Hydrogen is a promising energy carrier for a sustainable future because when it is used as fuel the only subproducts are water and a small quantity of NOx (depending on hydrogen purity; Stolten, 2010). The most common and viable sources to produce hydrogen are electricity (electrolysis of water) and natural gas (through steam methane reformation) (Ahmadi & Kjeang, 2017) (DOE, 2015b). Miotti, Hofer & Bauer (2017) concluded that when producing hydrogen through natural gas reforming, FCVs are found to offer no GHG reductions, along with higher impacts in several other environmental categories. The fuel-cell requirement of the use of platinum also causes substantial environmental impacts. Mine tailings and spoils from platinum mining largely contribute to high indices of human toxicity, particulate matter formation, terrestrial acidification and photochemical oxidant formation (Miotti, Hofer, & Bauer, 2017).

Regarding energy use, the research of Ahmadi & Kjeang (2017) also calculated the energy use during the various life cycle stages of the gasoline and fuel-cell vehicles. Due to higher energy consumption for hydrogen production and distribution, along with the vehicle special materials manufacture, the life cycle energy use of a FCV was 21% higher than a gasoline car (Ahmadi & Kjeang, 2017). Nevertheless, the FCVs emit 72% less GHG emissions per km than a conventional gasoline vehicle (Figure 18 in Appendix) (Ahmadi & Kjeang, 2017). However, when compared to BEVs, FCVs consume 2.5–3.5 times more electricity per kilometer as BEVs (Miotti, Hofer, & Bauer, 2017).

3.1.5 Conclusion

A summary table from Schoettle & Sivak, (2016) comparing internal combustion engine vehicles (ICEs), BEVs, and FCVs, is shown below.

Table 3. Relevant Aspects of Vehicle Performance for ICEs, BEVs, and FCVs (Schoettle & Sivak, 2016).



(Where appropriate, green = best, yellow = middle, and red = worst.)

Aspect	Current ICE	Battery electric (BEV)	Fuel cell (FCV)
Fuel type	Gasoline	Electricity	Hydrogen
Number of vehicle models available [7]	287	13	3
Average fuel economy [7]	23.3 mpg	105.2 mpge	58.5 mpge
Fuel economy range [7]	12 – 50 mpg	84 – 119 mpge	50 – 67 mpge
Effective cost per mile	\$0.10	\$0.04	\$0.09
Well-to-wheels GHG emissions (g/mi) [8]	356 – 409	214	260 – 364
Well-to-wheels total petroleum usage (Btu/mi) [8]	3791 – 4359	54	27 – 67
Driving range (average) [7]	418 mi	110 mi	289 mi
Driving range (min – max) [7]	348 – 680 mi	62 – 257 mi	265 – 312 mi
Time to refuel	~ 5 min	20 – 30 min (DC Level 2) 3.5 – 12 hr (AC Level 2)	5 – 30 min
High voltage	No	Yes	Yes
High pressure	No	No	Yes
Availability of qualified mechanics	Yes	Limited	Limited
Availability of qualified emergency responders	Yes	Yes	Limited
Vehicle maintenance issues [9]	-	Lower maintenance than gasoline; possible battery replacement required during vehicle lifetime	Lower maintenance than gasoline; high-pressure tanks may require inspection and maintenance

[7] Model year 2016 (EPA, 2015a).
[8] GREET 2015 release, using default settings for model year 2015 passenger cars (ANL, 2015).
[9] AFDC (2014).

technology with a distribution network already in place (public electricity grid) . BEVs are increasing in numbers worldwide, moving into mass production and lower price. Their energy efficiency and low price of energy make it the more low-cost fuel technology. Its disadvantages of autonomy and recharging time are improving, but are still a concern.

The FCVs refuel faster than BEVs and have lengthier driving range. Nevertheless, FCVs lack of existing infrastructure (to produce and distribute hydrogen) together with their lower efficiency makes it a second choice when compared to BEVs. Also, the technological challenges of diminishing FCVs environmental impacts are equal, or bigger, than the ones associated within the life cycle of BEVs (Miotti, Hofer, & Bauer, 2017).

Therefore, BEVs are financially and technically viable. A further step entails calculation of their viability from a sustainability standpoint, enabling comparison in this regard with other promising fuel technologies.

3.2 Biofuel economic, technological, and sustainability evaluation in Brazil

3.2.1 Sustainability assessment of biofuels from sugarcane

The use of petrochemicals as fertilizers in monocultures for biofuel production more than double farm yields in Brazil and worldwide (Kheshgi, Prince, & Marland, 2000). However, such a “Green Revolution” has “transformed agriculture from solar based systems to a global petrol-dependent one” (Weiskel, 2017). However, the low-input advantages of sustainable crops are often offset by low-yields, going against traditional business models and demand.

In Brazil, most of the biofuel production is of ethanol from sugarcane (~28 billion liters) followed by biodiesel (~7 billion liters) (EPE, 2017). Ethanol-powered automobiles comprise approximately half of the existing fleet (DENATRAN, 2018).

Considering the LCA of ethanol, compared to oil-derived fuels (diesel/gasoline) in Brazil, ethanol combustion mitigates approximately 220 to 147 kg of CO_2eq emissions per metric ton of sugar cane (Macedo, Leal, & da Silva, 2004). This means that in Brazil, ethanol is at least three times less GHG intensive than gasoline (Macedo, Leal, & da Silva, 2004) (Oliveira, Vaughan, & Rykiel, 2005).

Nevertheless, despite being renewable and less GHG intensive than gasoline, ethanol is not a zero net emissions fuel. In 2004, Macedo, Leal and A.R. da Silva analyzed the full LCA for the Brazilian ethanol GHG emissions, including the release of CO_2 by:

> "(I) *flows associated with fuel use fossil fuels in the production of all agricultural inputs and industrial processes for the production of sugarcane and ethanol;* (II) *flows in the production of equipment (agricultural and industrial) and construction of buildings and facilities;"… "*(III) *the use of fuels Fossils in farming: cultural dealings, irrigation, harvesting, transportation of sugarcane, etc.;* (IV) *in the production of crop inputs (seedlings, herbicides, pesticides, fertilizers, etc.);* (V) *in the manufacture of equipment agricultural and spare parts and maintenance;* (VI) *in the manufacture of inputs for industry (lime, H2SO4, biocides, etc.);* (VII) *in the production and maintenance of equipment and in the construction of buildings and industrial facilities.*"

In addition to CO_2 release, the study also accounted for the release of soil N2O from nitrogen fertilization and other GHG emissions in the process of burning the sugar cane (pre-harvest), burning bagasse in boilers, and from the combustion of ethanol in the vehicles (Macedo, Leal, & da Silva, 2004). All these emissions were accounted for in the figure of 34.5 kg of CO_2eq per ton of sugarcane harvested (Macedo, Leal, & da Silva, 2004).

In another LCA study, the net emissions per ha of sugarcane harvested were 3122 kg of CO_2eq (Oliveira, Vaughan, & Rykiel, 2005). Considering an average production of 75 tons per ha, the emissions per ton of sugarcane harvested were then 41.6 kg of CO_2eq (NovaCana.com, n.d.). Therefore, the latter calculated value based on a different research finding also corroborates the conclusion that ethanol production contributes to the accumulation of GHG in the atmosphere.

Some researches that compare ethanol and gasoline do not take into consideration the full GHG life cycle assessment, and as a consequence, do not account for the emissions mentioned above. And even in the researches that account the full GHG assessment, the focus remains to highlight the smaller emissions of ethanol when compared to gasoline. However, what must be clear is that besides continuing to contribute to GHG emissions, ethanol is also not a "clean" energy source. In considering a full life cycle assessment for ethanol production in Brazil, major impacts other than GHG accumulation must be accounted.

As example, a non-LCA GHG footprint comparison between ethanol and gasoline in Brazil highlights the lower GHG emissions and the consequential smaller forest area required to absorb CO_2 (approximately 6 million ha smaller than the gasoline required area) (Oliveira, Vaughan, & Rykiel, 2005). However, if we take in consideration that monocultures of sugarcane erode the soil 5.2 times faster than soil formation and destroy entire ecosystems, erosion and biodiversity would require 34.4 million ha additional area in order to counterbalance such impacts (Oliveira, Vaughan, & Rykiel, 2005). Therefore, it is important to take all possible impacts in consideration when comparing fuels.

In such monocultures, water use is also intense, due to applied irrigation methods. In fact, it is more intensive than petrol refining (King & Webber, 2008). The water use may vary from 2500 to 500 liters per ton of milled sugarcane, only to clean it of soil matter, not being treated before wasting it, and therefore harming the local basins (Rosillo-Calle & Cortez, 1998). Ethanol production also contributes to acidification, eutrophication, and photochemical oxidation (Cavalett, Chagas, Seabra, & Bonomi, 2013).

Native forests located nearby the plantations are often reached by preharvest burning of sugarcane, a practice that also harms the air quality of nearby cities (Godoi et al., 2004) (Oliveira, Vaughan, & Rykiel, 2005).

Moreover, the practice of monoculture farming is not beneficial for biodiversity. It can destroy entire ecosystems and reduce genetic diversity, leading to a higher susceptibility to diseases and dependency on pesticides and similar petrochemicals (Greene, 2006). Also, if the monoculture expansion occurs through deforestation, or even over non-degraded lands, the environmental losses may be extremely severe (Searchinger et al., 2008).

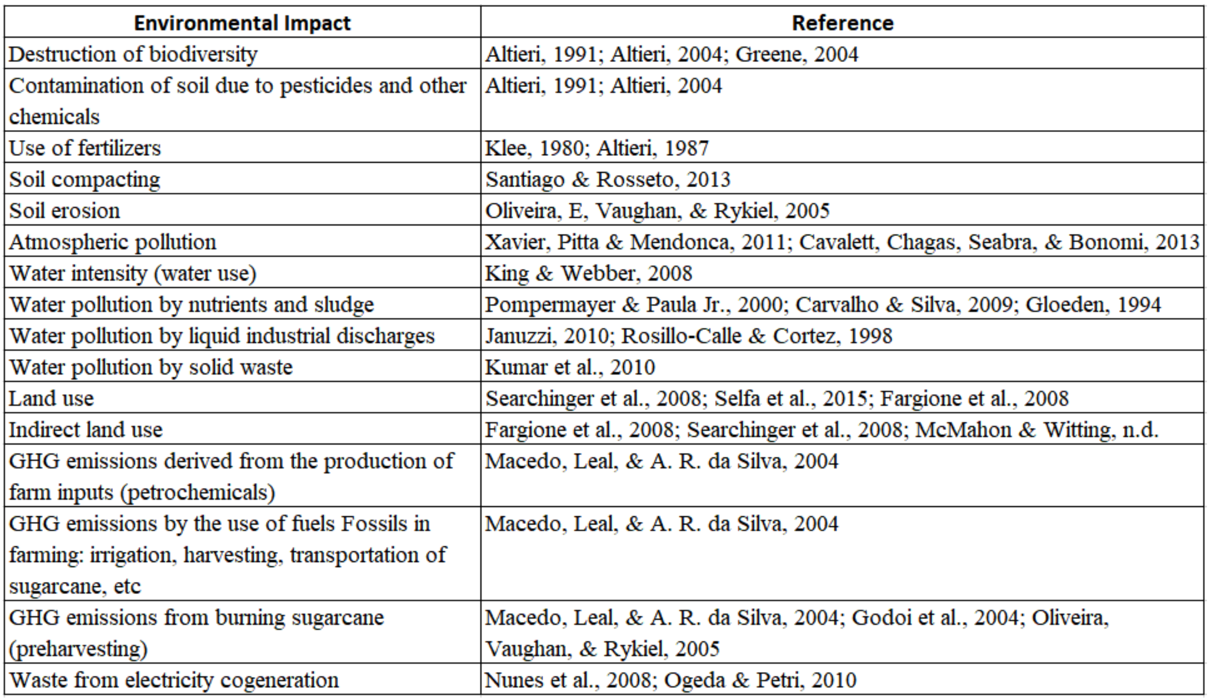
Brazil claims to be a good example of sugarcane production using only 1% of arable lands, distant from forests, and producing 50% of light-vehicle fuel needs (De Azevedo & Galiana, 2009). However, much of this land taking was justified as underutilized, degraded or abandoned lands as part of a simplification effort (Selfa et al., 2015). These are political concepts that aim to obscure the area biodiversity complexity (Bailis and Baka 2011; Borras, Fig, & Saurez, 2011) (Selfa et al., 2015). Besides using degraded lands, converting any other type of covered land into crop fields for biofuels creates a “carbon debt” which releases 17 to 420 times more carbon dioxide than the predicted reductions/savings from substituting fossil fuels (Fargione et al., 2008).

In addition to direct land use, indirect land use may also occur due to biofuel production. For instance, deforestation in some part of the globe could occur to plant a specific crop due to its market demand or a reduction in production, which in turn causes the use of agricultural lands for biofuels in Brazil. In fact, emissions from ethanol could be worse than for fossil fuels when considering indirect land use change (Fargione et al., 2008) (Searchinger et al., 2008) (McMahon & Witting, 2011).

Vinasse, a liquid substance that remains from ethanol process, is also a fertilizer. It is applied in high quantities on the soils of sugarcane farms in Brazil, infiltrating and altering physiochemically the local groundwater, resulting in high concentrations of aluminum, chloride, manganese, and other chemicals (Gloeden, 1994). The high biochemical oxygen demand of vinasse might also be affecting adjacent groundwater and rivers (Oliveira, E, Vaughan, & Rykiel, 2005). The Table 4, a concept adapted from Pugliese, Lourencetti, & Ribeiro (2017), summarizes the main environmental impacts mentioned in this chapter.

Outside the environmental realms, the social impacts derived from ethanol production from the monocultures of crops affect small farmers and poor communities, leading to loss of access to land and native resources, loss of income, and food insecurity intensification (Selfa et al., 2015).

Table 4. Summary of Environmental Impacts of Biofuel Production and Consumption in Brazil and its Respective References.



Environmental Impact	Reference
Destruction of biodiversity	Altieri, 1991; Altieri, 2004; Greene, 2004
Contamination of soil due to pesticides and other chemicals	Altieri, 1991; Altieri, 2004
Use of fertilizers	Klee, 1980; Altieri, 1987
Soil compacting	Santiago & Rosseto, 2013
Soil erosion	Oliveira, E, Vaughan, & Rykiel, 2005
Atmospheric pollution	Xavier, Pitta & Mendonca, 2011; Cavalett, Chagas, Seabra, & Bonomi, 2013
Water intensity (water use)	King & Webber, 2008
Water pollution by nutrients and sludge	Pompermayer & Paula Jr., 2000; Carvalho & Silva, 2009; Gloeden, 1994
Water pollution by liquid industrial discharges	Januzzi, 2010; Rosillo-Calle & Cortez, 1998
Water pollution by solid waste	Kumar et al., 2010
Land use	Searchinger et al., 2008; Selfa et al., 2015; Fargione et al., 2008
Indirect land use	Fargione et al., 2008; Searchinger et al., 2008; McMahon & Witting, n.d.
GHG emissions derived from the production of farm inputs (petrochemicals)	Macedo, Leal, & A. R. da Silva, 2004
GHG emissions by the use of fuels Fossils in farming: irrigation, harvesting, transportation of sugarcane, etc	Macedo, Leal, & A. R. da Silva, 2004
GHG emissions from burning sugarcane (preharvesting)	Macedo, Leal, & A. R. da Silva, 2004; Godoi et al., 2004; Oliveira, Vaughan, & Rykiel, 2005
Waste from electricity cogeneration	Nunes et al., 2008; Ogeda & Petri, 2010

3.2.2 Technological assessment of biofuels from sugarcane in Brazil

Biofuels from sugarcane in Brazil are a well-developed technology, with infrastructure and supply chain well-built, currently attending half of the current private vehicle fuel needs. However, its energy efficiency shortcomings are not mainstream knowledge.

Energy efficiency of biofuels

Fuels derived from crops are very low-efficiency. Biomass requires too much land (1-2 additional orders of magnitude) to produce the same amount of energy than other sources (Graves et al., 2011). Current average petroleum dependent fertilized agriculture efficiency in producing biomass from solar energy is less than 1% (Walker, 2009; Zhu, 2010).

The energy balance from the Brazilian sugarcane ethanol shows that an input of 42.4 GJ per ha produces 150.4 GJ of energy in the form of ethanol (Oliveira, Vaughan, & Rykiel, 2005) - 3.5 ratio of energy produced per energy input. Giampietro, Ulgiate and Pimentel (1997) have projected that more than 10 GJ per cubic meter of ethanol is necessary to cleanse biological oxygen demand from distillery wastes. This additional requirement reduces the ethanol energy balances to a 2.84 ratio.

The possible energy surplus acquired by cogenerating electricity in sugarcane distilleries is often used as an argument for supporting the ethanol program. However, even considering all possible electric power generated in distilleries in Brazil, this amount wouldn’t be significant, not surpassing 0.25% of the hydroelectricity generation capacity of the country (Oliveira, Vaughan, & Rykiel, 2005).

3.2.3 Conclusion after evaluating biofuels in Brazil

Biofuels derived from sugarcane (and other crops such as corn, soybean, etc.) have been associated with deforestation, competition with food production, high water intensity, high petrochemical input, and biodiversity menace (Brennan & Owende, 2010) (Gouveia & Oliveira, 2009) (Costa & De Morais, 2011).

Therefore, monocultures to produce biofuel have a highly negative environmental impact. Associated land use should be ceded to more promising endeavors, such as to more efficient energy conversion systems. Giving the scale needed and considering all of the impacts, biofuel production from biomass monoculture needs to have its sustainability parameter measured and compared to other suitable technologies.

An alternative approach would be to use algae for fuel production. However, despite its land use advantage via aquaculture, algae may have significant environmental impacts in water use and GHG emissions (Clarens, Resurreccion, White, & Colosi, 2010).

3.3 The algae-based biofuels

Macro and microalgae might be the answer since they have growth rates higher than crops; can persevere on any type of land, even degraded land; do not disturb the food supply chain; do not require large amounts of petrochemicals (e.g., fertilizers, pesticides), and might be climate neutral in emissions (Chisti 2007; Gouveia and Oliveira 2009; DOE 2010; Singh et al. 2011; Ellis & Miller, 2016).

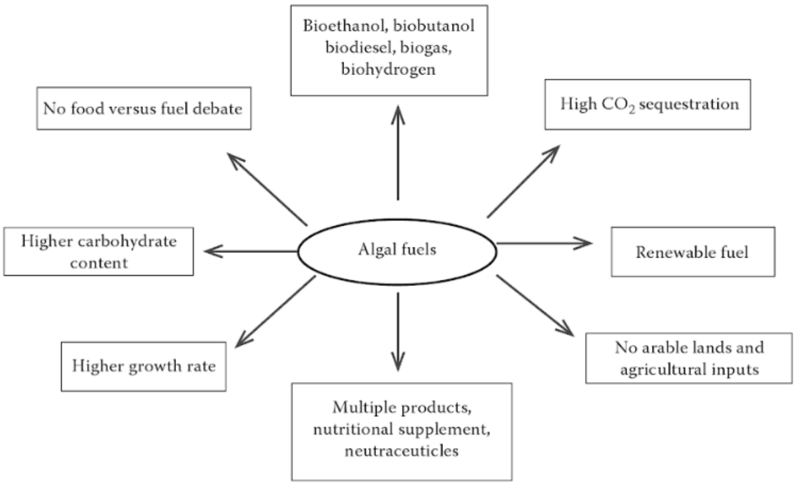


Figure 9. Algal Feedstock as a Source of Biofuels (Kim & Lee, 2015- pg 202)

3.3.1 Sustainability assessment of algae biofuel

Singh and Olsen (2011) critically reviewed the LCA of algal biofuels (including ethanol). They concluded that algae sequester a significant quantity of carbon from the atmosphere and may thrive, even using industrial and municipal wastewaters, ultimately treating them. Despite its advantages, the study concluded that biofuel created from algae is not appealing in economic terms. However, Sivakumar et al. (2012) also argue that algal biodiesel is long-term sustainable and may contribute to energy security.

The Natural Resources Defense Council produced, in 2009, an overview of the environmental externalities of process and technologies related to algae biofuel production. Table 5 compiles the main environmental benefits and concerns from their review.

Table 5. Environmental Benefits and Concerns. Adapted by Daniel Peon (Natural Resources Defense Council [NREL], 2009).

Benefits	***Concerns***
Treatment of wastewater	It is too water intense if not used concomitantly with water treatment.
Multi-interchangeable pathways of production	Environmentally responsible alternatives could be passed over in favor of more cost- or time-efficient processes
Minimizes water, energy, and land usage	Extensive land transformation and changes in water and air quality could impact local or regional hydrology, native habitats, and migratory patterns
Reduces water, soil, biodiversity, and air quality degradation	Materials toxicity could have long-term impacts on biodiversity, soil and water quality, and/or aquifer recharge
Circular economy linking algal biofuel production with other industries waste	Processing facilities that are not co-located will require increased storage and transport, and thus increased land and energy usage

3.3.2 Technology assessment of algae biofuel

The flowchart below (Figure 10) shows a general refinery process concept for algae. Another interesting concept is the cogeneration of biofuels from microalgae, while treating sewage, reducing GHG emissions and eutrophication of water bodies. Alternatively, seaweed (marine macrophytic algae) and its *in situ* marine aquaculture has all the previously mentioned advantages of microalgae plus bioremediation, land sparing for food production, as well as no water consumption concern.

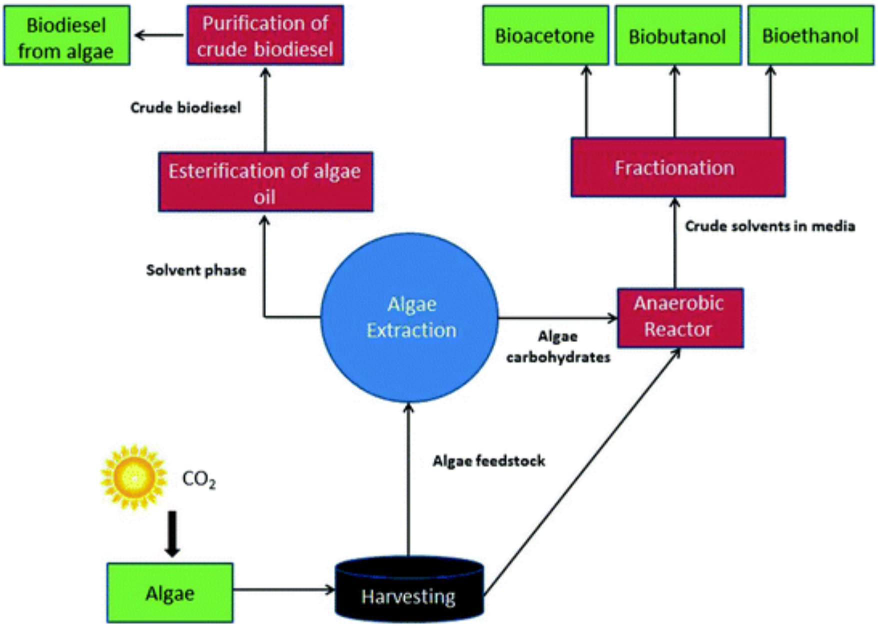


Figure 10. A Microalgae-based Biorefinery Concept for Producing Multiple Products from a Single Feedstock. Modified from Anthony et al. (2013).

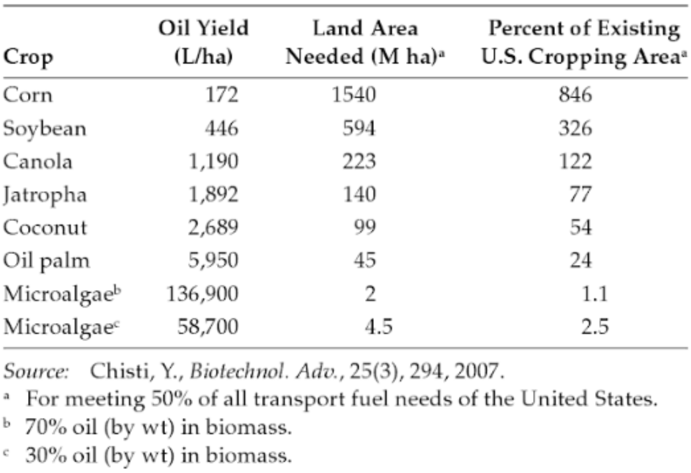
Despite concluding that microalgae biofuels have several advantages over biofuels from crops, associated technology still needs improvement in: best-species selection, efficiency of harvesting and drying technology, costs of separation and oil extraction, as well as energy and nutrient recovery in biorefineries (Franco et al., 2013; Wijffels & Barbosa, 2010).

Energy efficiency

A study in the United States showed that crops could not replace petroleum for fuel due to fuel demands and biofuel yield (Kim & Lee, 2015). However, microalgae production could prove competitive in this regard, as shown in the Table 6 below.

In comparison to crops, microalgae may produce between 30 to 100 times more energy/ha (Demirbas, 2010; Ellis & Miller, 2016). Therefore, not only biodiesel may be largely produced by algae. Ethanol can be produced at a level from 10 to 30 times more per hectare than corn, wheat, sugar beet, cassava, or switchgrass (Nguyen, 2012).

Table 6. Comparison of productivity of biodiesel sources (Kim & Lee, 2015).



Crop	Oil Yield (L/ha)	Land Area Needed (M ha)[a]	Percent of Existing U.S. Cropping Area[a]
Corn	172	1540	846
Soybean	446	594	326
Canola	1,190	223	122
Jatropha	1,892	140	77
Coconut	2,689	99	54
Oil palm	5,950	45	24
Microalgae[b]	136,900	2	1.1
Microalgae[c]	58,700	4.5	2.5

Source: Chisti, Y., *Biotechnol. Adv.*, 25(3), 294, 2007.

[a] For meeting 50% of all transport fuel needs of the United States.

[b] 70% oil (by wt) in biomass.

[c] 30% oil (by wt) in biomass.

3.3.3 Economic assessment

Studies around the economic feasibility of algae systems show similar conclusions. Singh and Gu (2010) reviewed the issues of cultivation, the biorefinery, and LCA of biofuel production from algae. According to them, a key factor for economic success is to reduce operational and maintenance costs and maximize oil production.

In a recent 7-year complete techno-economic analysis of different algae biofuel technologies, the Natural Resources Defense Council [NRDC] (2017) accessed the cost-competitiveness and established cost targets for diverse algal biofuel process scenarios. The project scope included the cost of biomass production, harvesting and conversion, and minimum fuel selling price (MFSP).

The research pointed that theoretically, the critical productivity rate is at least 30g/m2/day, where the costs of biomass production reach \$430/US dry ton, in a lower limit with a system cost of \$30,000/acre in a large-scale pound project (>5000acres). Nevertheless, the article states that, even if pounds were free, other production costs still add up to produce biomass for no less than \$300-\$400/ton.

In a more realistic design case scenario for 2022, it would be possible to reach a 25g/m2/day productivity rate, reaching a biomass cost of \$494/ton, which translates to an MFSP of \$4.7/GGE. A competitive \$3/GGE MFSP would require a <\$230/ton biomass cost, which is not possible in current farm-based models. Therefore, to be competitive, algae multiple co-products (other than biofuels, such as succinic acid, bioplastics, and sterol-derived surfactants) must be combined and commercially explored (NRDC, 2017).

In conclusion, despite showing great promise in all researched parameters, the economic viability of this technology is still not practical within the time scope of this research.

3.4 The biofuel synthesis derived from bacteria (artificial leaf).

3.4.1 Technology assessment

Bacteria-assisted electrocatalysis is a technology currently in very rapid development. Its low energy input demand allows it to be coupled to solar panels to allow storage of liquid energy wirelessly (Torella et al., 2015).

This technology uses photovoltaic processes to split water and generate hydrogen as a food for an autotroph microorganism. The other necessary component in this solution is CO_2, increasingly abundant in the atmosphere. The microorganism then consumes the CO_2 and the produced H2, ultimately producing biomass and biofuel.

To produce H2, the system splits water into O_2 and Hydrogen ions using a cobalt phosphate electrode, followed by a cobalt-phosphorus (Co-P) alloy that transforms the H+ into H2 molecules, both under a low 3V applied voltage (see Fig. 11) (Liu, Colón, Ziesack, Silver, & Nocera, 2016). A metabolically engineered type of the Raistonia eutropha bacteria performs the biomass and fuel synthesis (isopropanol).

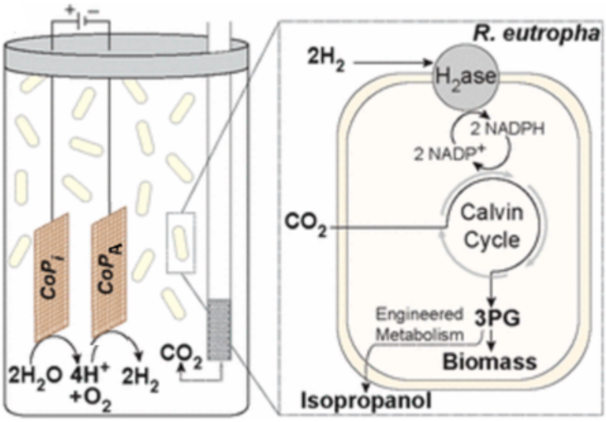


Figure 11. The bacteria-assisted electro-catalysis method with a COPi anode and COPa alloy cathode. Adapted by Daniel Peon. (Torella et al., 2015).

The isopropanol has a heat content similar to the gasoline (Lewis 2007). However, it cannot be used directly in gasoline engines. Isopropanol can be directly used in diesel combustion engines if it is blended with diesel in an optimal 30% isopropanol ratio, increasing the engine thermal efficiency while reducing in 25% its CO_2 emissions from combustion (Krishnamoorthi & Malayalamurthi, 2016).

Under optimal conditions, the system CO_2 reduction efficiency achieves 50% when producing “liquid fuel alcohols:” absorbing 180 grams of CO_2 out of 230m3 of air, and producing 60g of isopropanol per kilowatt-hour of electricity (Liu et al., 2016). If the system is coupled to a photovoltaic device, under natural conditions, it has a CO_2 reduction efficiency of approximately 10% (Liu et al., 2016). Thus, its efficiency hits the 10% threshold required to be considered practical and accessible (Barber & Tran, 2013). This means the solar to fuel conversion is currently ten times more efficient than natural photosynthesis. Therefore, the so-called “artificial leaf” can store electricity in the form of biofuels and is 40 times more efficient than the most productive monocultures for ethanol, using much less area while being more environmentally friendly (Kheshgi, Prince, & Marland, 2000).

Nevertheless, such a biosynthetic system is more suitable as a distributed solution, where each household could make use of such a device to produce its biofuel during electricity surpluses. Taking into consideration the capability of coupling with photovoltaics panels, such a wireless artificial leaf device could be used in remote areas of Brazil, synthesizing biofuels whenever there is a surplus of energy. It could help as extra income or fuel savings for rural families where there is otherwise no incentive for capturing abundant excess energy (e.g. given the intensity of year-long sunlight incidence).

3.4.2 Conclusion on viability of the bacterial synthetic fuel

It is important to keep in mind that a technology be practically feasible when considering its transportation fuel demand. For bacterially-assisted technology, achieving such feasibility requires that it become scalable as a portable device. Its lifetime is not yet calculated, but the “self-healing” characteristic of its electrodes’ suggests feasibility for short-term commercialization. The costs related to this technology still require evaluation, probably being most impacted by the material cost of its cobalt-phosphate electrode. More studies in materials and efficiency could make such device even more economically viable.

In conclusion, both the technological and economic parameters for biofuels are currently impracticable, because the technology is neither scalable nor economically viable at present. Still, with greater efficiency, the system may become a strong competitor as a sustainable fuel solution technology.

3.5 Synthetic fuel generation from clean and renewable electricity surplus

3.5.1 First economic assessment for selecting most promising technology

Carbon-neutral fuels can be produced based on capturing CO_2 from the atmosphere in conjunction with water splitting, using the electricity derived from clean and renewable sources, as seen in Figure 12.

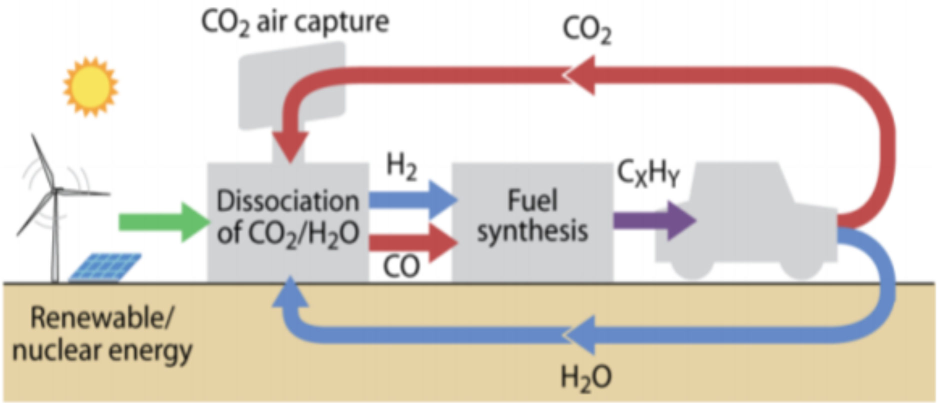


Figure 12. Carbon Neutral Fuel Synthesis from CO_2 and H2O Electrolysis using Renewable Electricity (Graves et al., 2011).

Using direct energy or remaindered electricity from clean sources to generate biofuels could be a promising solution to the sustainable fuel challenge posed by transportation. Such an approach is very practical because it does not demand significant changes in infrastructure, vehicle production, or consumer behavior while attending the storage challenges faced by both sectors.

The production of synthetic hydrocarbon fuel has three main stages: collection of energy and oxides (water and CO_2), dissociation of oxides, and fuel synthesis (Graves et al., 2011). There are many pathways to the production, as seen in Figure 13. However, this paper's scope will focus only on the cost-effective and sustainable ones, assuming a large-scale scenario wherein clean, renewable electricity is offered, in both constant and intermittent scenarios.

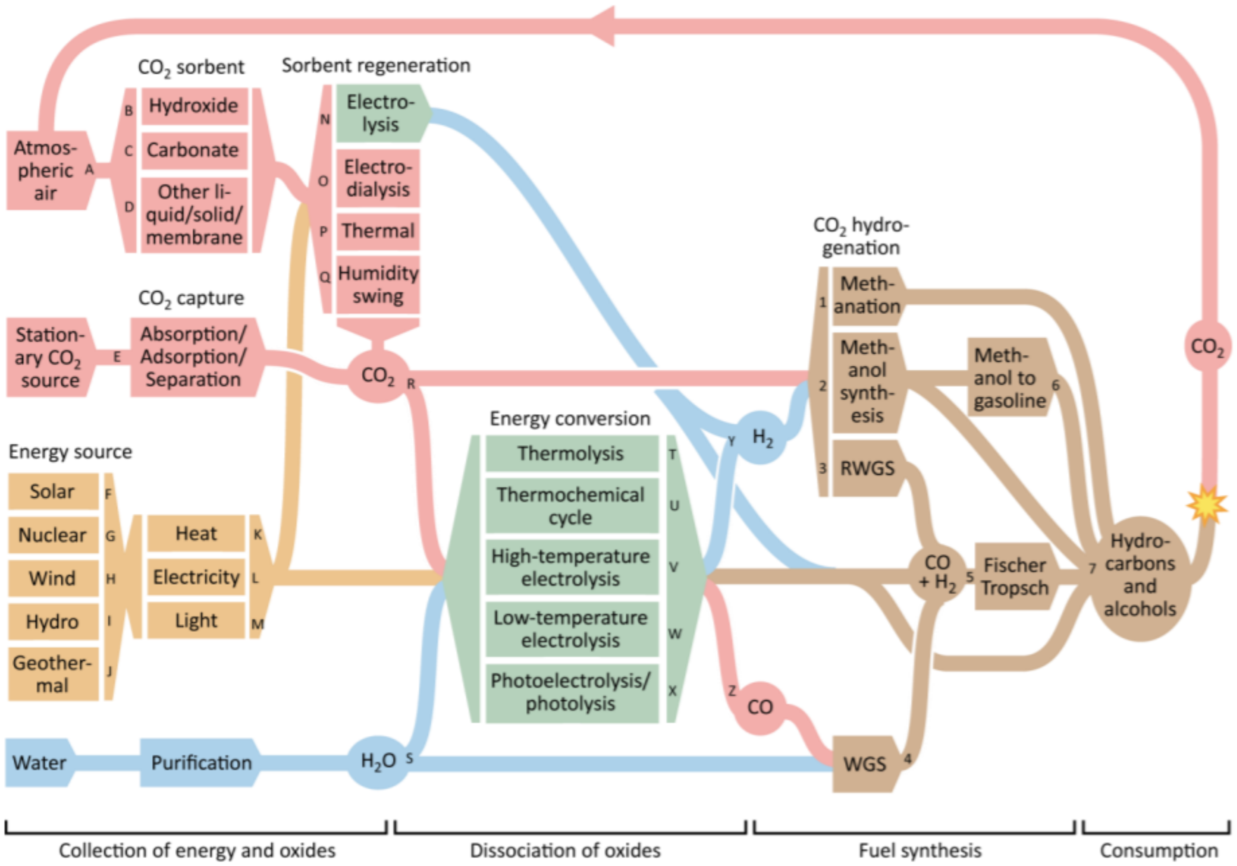


Figure 13. The Diverse Paths to Synthetic Fuel Generation from CO₂ and H2O Conversion (Graves et al., 2011).

The dissociation of oxides (CO_2 and H2O) is the stage where most of the energy is converted (green color in Figure 14) (Graves et al., 2011).

Graves et al. (2011) identified that ‘thermolysis’ economic viability is jeopardized by the cost of reactors; while ‘thermochemical cycle’ is threatened by expensive materials, energy losses, and side reactions. Electrolysis is the most economically attractive solution among all conversion technologies involving dissociation of oxides. It uses electricity to dissociate water or carbon dioxide, and its sub-products are released into the cell electrodes (cathode and anode). Electrolysis can be achieved via three main physical approaches: high-temperature, low temperature, and photolysis. Graves et al. also evaluated that low-temperature electrolysis is currently low in efficiency, therefore being less competitive. Photolysis currently demands expensive materials for direct dissociation of water and CO_2 (Li, Ciston, & Kanan, 2014). Its catalyst materials require rare or high technologic conductors (nanotechnology), which keeps this solution from being market competitive in the short term (Sharma et al., 2015).

Nevertheless, the high-temperature electrolysis with solid oxide cells presents the most sustainable and economically feasible technology, which will be further detailed below.

3.5.2 The technology of high-temperature electrolysis in solid oxide cells

Technical assessment

High-temperature electrolysis is thermodynamically advantageous, promoting high reaction rates, and presenting the highest efficiency (~100%) in transforming electricity to a CO and H2 mixture (syngas) (Graves et al., 2011).

The fuel production in this process derives from the capture of CO_2 from the atmosphere, co-electrolysis of this carbon dioxide with water at a high temperature in a solid oxide cell electrolyzer, and finally synthesis by regular Fischer-Tropsch synthesis, a common practice set of chemical processes for generating liquid fuels from syngas (CO and H2). Figure 14 demonstrates such a system.

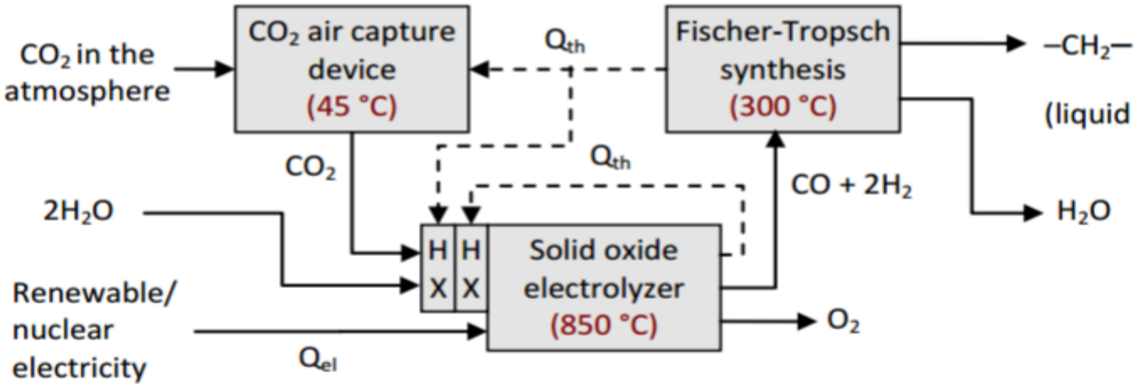


Figure 14. Flowchart for Fuel Generation from CO_2 and H2O Through High-temperature Electrolysis in Solid Oxide Cells (Graves et al., 2011).

The dissociation of carbon dioxide and water that occurs in the solid cell electrolyzer has a demonstrated reaction of 90% conversion (or higher) (Cable, Setlock, Farmer, & Eckel, 2011). In such a system, the efficiency from electricity to fuel synthesis would be approximately 70% (Graves et al., 2011).

Economic assessment

Figure 15 graphs the summary of the economic analysis of this technology. The synthetic gasoline total cost, including the costs of: CO_2 capture, fuel synthesis, dissociation investment, operating and overall maintenance, is represented by the y-axis; while the renewable electricity price by the x-axis.

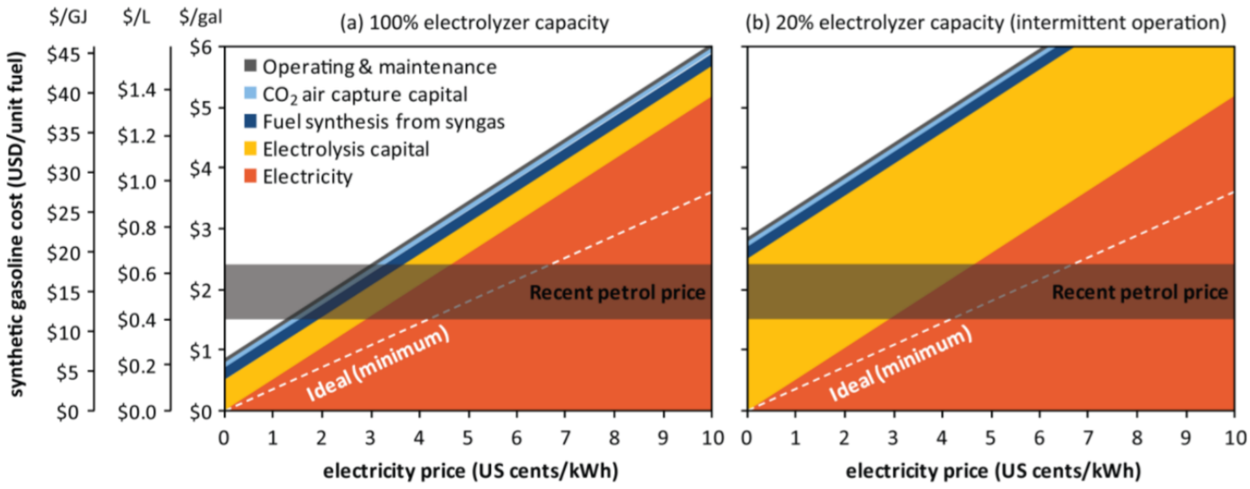


Figure 15. Economic Evaluation of the High-temperature Oxide Cell Electrolysis System. Adapted by Daniel Peon (Graves et al., 2011).

The graph on the left (continuous operation) shows that for electricity prices higher than U$0.03 per kWh and petrol price below U$2.30 per gallon, the synthetic gasoline cost is not competitive.

If the electricity costs are lower, below U$0.03 per kWh, and the system operates 100% of the time, using constant energy (e.g. hydroelectric, nuclear, geothermal) the synthetic gasoline total cost would be approximate U$0.53/L (U$2/gal) or U$15/GJ, which is a very competitive market price. Such price is evidence of the economic feasibility of this solution. Furthermore, the synthetic fuel could be even more competitive through mass production of this system, not to mention its environmental appeal and geographical independence advantage when compared to the strict supply chain demanded by fossil fuels. If oxide cells achieve greater durability at high currents, they can operate under intermittent sources achieving precisely the same attractive fuel production costs as the full time operating electrolyzer scenario mentioned above (Graves et al., 2011).

However, if it only uses electricity from intermittent sources, assuming it will work only 20% of the time (a more realistic scenario), the capital cost is multiplied by five, precluding the system from operating competitively (graph on the right) (Graves et al., 2011). Therefore, according to this research methodology criterion, the economic viability of the technology is null and should not be considered as an option for implementation within the current time frame.

3.6 Formula application

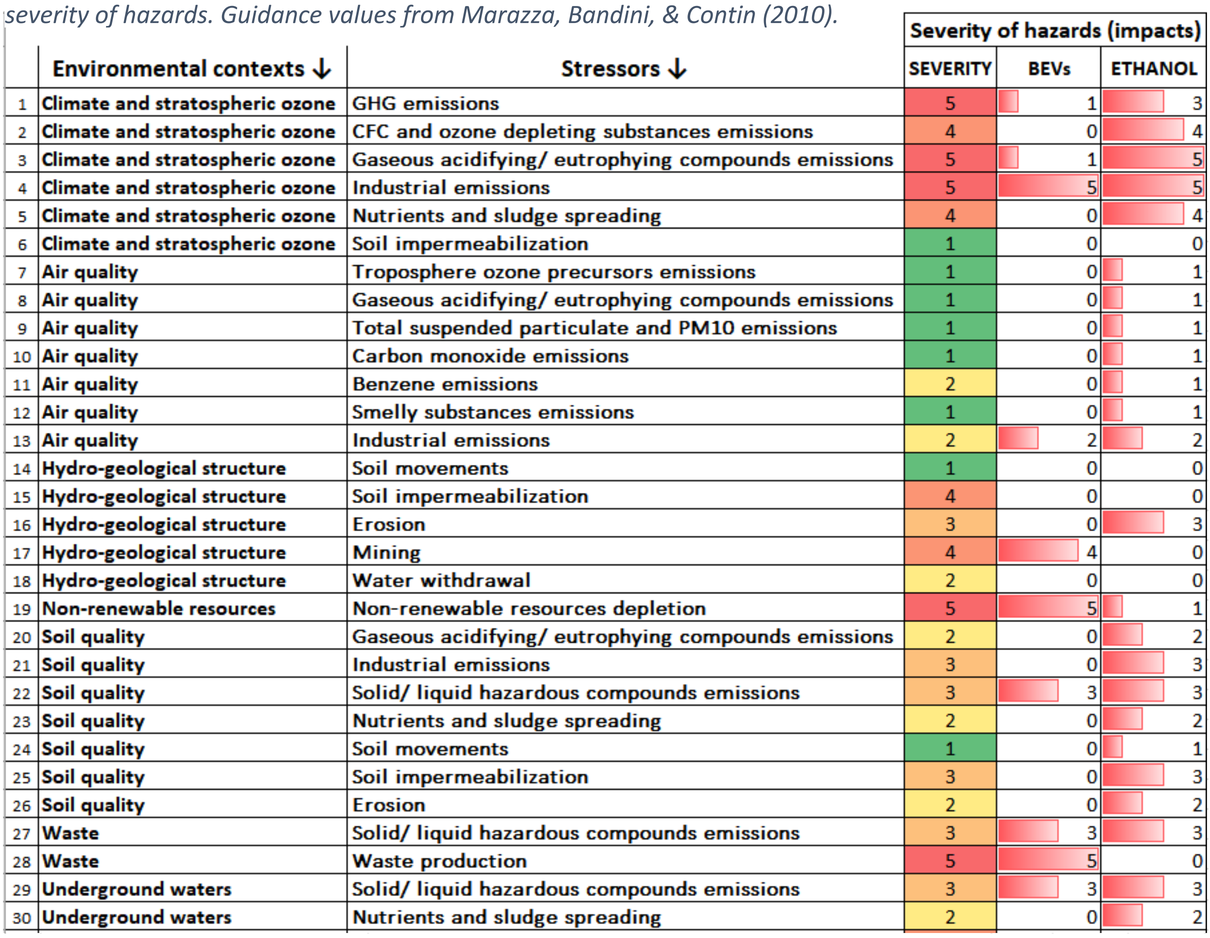
Sustainability and viability parameter results

Through the analysis of the findings and the implementation of the formula presented in the Methodology chapter above, the algae biofuel technology and high-temperature electrolysis in solid oxide cells technology had both a 0 value for economic viability. The artificial-leaf technology had a 0 value for both technology and economic viability. Therefore, these technologies viability parameters are equal to zero.

Sustainability impacts for the battery and ethanol fuel technologies were analyzed and appear in Table 7. Table 1 was adapted into the Table 7 to provide a better visual comparison. The values justifications are included in the Table 14 in the Appendix section.

In conclusion, the sum of the severity of hazards of the BEV technology is 74. The sustainability factor value is 1/74. The final viability factor value is = 0.0135. For ethanol, the sum of the severity of hazards is 147. The sustainability factor value is 1/147. The final viability factor value is = 0.0068. Therefore, since the viability value of the battery vehicle technology is the highest, this is deduced to be the preferential technology for a sustainable transportation sector in Brazil.

Table 7. BEVs and Ethanol sustainability assessment results through valuation of severity of hazards. Guidance values from Marazza, Bandini, & Contin (2010).



			Severity of hazards (impacts)		
	Environmental contexts ↓	**Stressors ↓**	**SEVERITY**	**BEVs**	**ETHANOL**
1	**Climate and stratospheric ozone**	GHG emissions	5	1	3
2	**Climate and stratospheric ozone**	CFC and ozone depleting substances emissions	4	0	4
3	**Climate and stratospheric ozone**	Gaseous acidifying/ eutrophying compounds emissions	5	1	5
4	**Climate and stratospheric ozone**	Industrial emissions	5	5	5
5	**Climate and stratospheric ozone**	Nutrients and sludge spreading	4	0	4
6	**Climate and stratospheric ozone**	Soil impermeabilization	1	0	0
7	**Air quality**	Troposphere ozone precursors emissions	1	0	1
8	**Air quality**	Gaseous acidifying/ eutrophying compounds emissions	1	0	1
9	**Air quality**	Total suspended particulate and PM10 emissions	1	0	1
10	**Air quality**	Carbon monoxide emissions	1	0	1
11	**Air quality**	Benzene emissions	2	0	1
12	**Air quality**	Smelly substances emissions	1	0	1
13	**Air quality**	Industrial emissions	2	2	2
14	**Hydro-geological structure**	Soil movements	1	0	0
15	**Hydro-geological structure**	Soil impermeabilization	4	0	0
16	**Hydro-geological structure**	Erosion	3	0	3
17	**Hydro-geological structure**	Mining	4	4	0
18	**Hydro-geological structure**	Water withdrawal	2	0	0
19	**Non-renewable resources**	Non-renewable resources depletion	5	5	1
20	**Soil quality**	Gaseous acidifying/ eutrophying compounds emissions	2	0	2
21	**Soil quality**	Industrial emissions	3	0	3
22	**Soil quality**	Solid/ liquid hazardous compounds emissions	3	3	3
23	**Soil quality**	Nutrients and sludge spreading	2	0	2
24	**Soil quality**	Soil movements	1	0	1
25	**Soil quality**	Soil impermeabilization	3	0	3
26	**Soil quality**	Erosion	2	0	2
27	**Waste**	Solid/ liquid hazardous compounds emissions	3	3	3
28	**Waste**	Waste production	5	5	0
29	**Underground waters**	Solid/ liquid hazardous compounds emissions	3	3	3
30	**Underground waters**	Nutrients and sludge spreading	2	0	2

31	**Underground waters**	Soil impermeabilization	4	0	0
32	**Underground waters**	Liquid industrial discharges	3	0	3
33	**Underground waters**	Mining	5	5	0
34	**Underground waters**	Water withdrawal	2	0	0
35	**Surface waters**	Solid/ liquid hazardous compounds emissions	2	0	2
36	**Surface waters**	Nutrients and sludge spreading	2	0	2
37	**Surface waters**	Eutrophicating discharges	1	0	1
38	**Surface waters**	Liquid industrial discharges	2	0	2
39	**Surface waters**	Water withdrawal	1	0	1
40	**Ecosystems — biodiversity**	Gaseous acidifying/ eutrophying compounds emissions	2	0	2
41	**Ecosystems — biodiversity**	Total suspended particulate and PM10 emissions	1	0	1
42	**Ecosystems — biodiversity**	Benzene emissions	3	0	1
43	**Ecosystems — biodiversity**	Smelly substances emissions	2	0	2
44	**Ecosystems — biodiversity**	Solid/ liquid hazardous compounds emissions	3	3	3
45	**Ecosystems — biodiversity**	Nutrients and sludge spreading	2	0	2
46	**Ecosystems — biodiversity**	Vibrations	1	0	0
47	**Ecosystems — biodiversity**	Soil movements	1	0	0
48	**Ecosystems — biodiversity**	Soil impermeabilization	4	4	4
49	**Ecosystems — biodiversity**	Light pollution	1	0	0
50	**Ecosystems — biodiversity**	Eutrophicating discharges	2	0	2
51	**Ecosystems — biodiversity**	Liquid industrial discharges	2	0	2
52	**Ecosystems — biodiversity**	Erosion	1	0	1
53	**Ecosystems — biodiversity**	Ground occupation	4	0	4
54	**Ecosystems — biodiversity**	Mining	2	2	0
55	**Ecosystems — biodiversity**	Water withdrawal	1	0	1
56	**Renewable resources**	Industrial emissions	3	3	3
57	**Renewable resources**	Use of renewable resources	3	3	3
58	**Renewable resources**	Water withdrawal	1	0	1
59	**Health**	Troposphere ozone precursors emissions	3	0	3
60	**Health**	Gaseous acidifying/ eutrophying compounds emissions	3	0	3
61	**Health**	Total suspended particulate and PM10 emissions	3	0	3
62	**Health**	Carbon monoxide emissions	3	0	2
63	**Health**	Benzene emissions	4	0	1
64	**Health**	Industrial emissions	5	5	5
65	**Health**	Solid/ liquid hazardous compounds emissions	3	3	3
66	**Health**	Physical agents	1	0	1
67	**City-life quality**	Total suspended particulate and PM10 emissions	1	0	1
68	**City-life quality**	Smelly substances emissions	1	0	1
69	**City-life quality**	Industrial emissions	3	3	0
70	**City-life quality**	Physical agents	2	0	2
71	**City-life quality**	Vibrations	2	0	0
72	**Historical and cultural heritage**	Gaseous acidifying/ eutrophying compounds emissions	4	0	1
73	**Historical and cultural heritage**	Total suspended particulate and PM10 emissions	1	0	1
74	**Historical and cultural heritage**	Vibrations	3	0	0
75	**Landscape**	Soil movements	1	0	0
76	**Landscape**	Soil impermeabilization	4	0	0
77	**Landscape**	Light pollution	1	0	0
78	**Landscape**	Erosion	3	0	0
79	**Landscape**	Ground occupation	4	0	4
80	**Landscape**	Mining	4	4	0
81	Land uses	Gaseous acidifying/ eutrophying compounds emissions	1	0	1
82	Land uses	Total suspended particulate and PM10 emissions	1	0	1
83	Land uses	Solid/ liquid hazardous compounds emissions	3	3	3
84	Land uses	Physical agents	2	0	2
85	Land uses	Soil movements	1	0	1
86	Land uses	Liquid industrial discharges	2	2	2
87	Land uses	Erosion	3	0	3
88	Land uses	Ground occupation	3	0	3
89	Land uses	Mining	2	2	0
	TOTAL	**Sum of severity of hazards**		**74**	**147**

4. Discussion

The results of this analysis have shown that cutting-edge technologies are not yet ready to economically compete with fossil fuels in Brazil. Nor does biofuel produced by algae. Nonetheless, these technologies are up-and-coming and can change the energy sector in the long run. Therefore, future analysis is required.

The biofuel of Brazilian sugarcane has several hidden impacts that, when quantified, reveal its magnitude. The quantification also made possible the direct comparison of sustainability parameters with the other technology that proved viable, the BEV. This experiment evidenced that battery electric cars are the most sustainable answer while economically and technically feasible for the question: what is the best fuel for private transportation in Brazil, considering the financial, technological and sustainability factors?

This result differs from what is currently being adopted by the Brazilian transport energy policy, which believes that ethanol is the best solution and intends to continue to invest heavily in the production of biofuels (EPE, 2017).

The final result of this research could guide the planning of public policies of the transportation and energy sectors. The extra results obtained from the literature review and comparison could also serve as a basis for further studies aiming at comparing the addressed fuel technologies; principally biofuels from sugarcane and battery-operated electric cars.

The design of this study included values of severity to sustainability impacts regarding its temporal and spatial performance, based on Marazza, Bandini, & Contin (2010). Therefore, the design determined and influenced the results.

This work was limited to the five presented technologies. And the scope was also reduced to the most significant actors in the Brazilian transportation sector (i.e., light vehicles). However, heavy vehicles have a substantial share of fuel consumption and environmental impacts. Future researchs should, therefore, target and include them.

Other issues raised are in regard to the economic feasibility of algae for sewage treatment. Although it is currently not financially viable to produce biofuels competitively with petroleum derivatives, algae could be applied to Brazilian water treatment more economically than current treatment stations. To attest that this is so, further studies are needed on this topic.

5. Conclusion & Recommendations

The widespread and growing scientific concern about climate change and natural resource scarcity have created a scenario where energy efficiency and environmental preservation are essential to a sustainable future. The enormous fossil fuel demand of the transportation sector makes it a priority target for the latter objective. In envisioning a sustainable future, this study included economic and technologic parameters and analyzed the private transportation sector in Brazil.

The Brazilian light vehicle fleet is expected to double by 2050 (EPE, 2015) (DENATRAN, 2018). Biofuels produced in current monoculture models are not sustainable on the scale needed to support this growth. Despite the still existent intrinsic environmental impacts from all technologies evaluated in this paper, the battery-operated electric vehicle is the most suitable and reachable solution. An additional positive impact of the adoption of electric cars by Brazil is the possibility to use the batteries of the vehicles as a distributed energy resource, applying "vehicle-to-grid" technology. This would positively influence energy planning and allow transition to an energy sector abundant in intermittent renewable sources of energy.

Brazil is the 9th largest vehicle producer globally (International Organization of Motor Vehicle Manufacturers [OICA], 2018). If the Brazilian government chooses to invest in the development and manufacturing of electric vehicles, it could feed not only internal demand but also external demand, increasing export sales. Moreover, a significantly expanding fleet proportion of electrical vehicles would allow Brazil to save high quantities of oil and its byproducts from internal consumption. The billions of gallons of saved oil could then be exported, turning into many billions of dollars in savings, improving the Brazilian trade balance deficit, and allowing more investments in health and education sectors. In this fashion, emission-free electric cars could also significantly benefit the nation's economy.

Air pollution in crowded urban areas affects the health and well-being of its inhabitants. Harmful gases are a direct consequence of the combustion of fuels and biofuels in vehicles (Rocha, 2013). The effects in human beings, such as chronic respiratory diseases, increases the Disability-Adjusted Life Year (DALY) and consequently harms the country's economy and productivity (DALY is a metric to quantify the burden of disease from mortality, morbidity, and disability and its impact on productivity and national GDP) (Homedes, 1996). Besides lowering the GDP, air pollution introduces direct costs to public health. The Laboratory of Experimental Atmospheric Pollution of the University of Sao Paulo has calculated the municipal expenditures associated with bad air quality of six Brazilian metropolises. Together, they spent roughly 1 billion dollars USD per year.

Furthermore, the use of clean, renewable electricity instead of a GHG-intensive fuel to supply electric vehicles can accrue carbon credits. As an example, if the City of Sao Paulo substitutes electric cars for 6% of its fleet, the sale of associated carbon credits (approximately 490.000 tons of CO_2) would sum 8.4 million EUR ($9.8 million USD, Jul/18) (Pacca, 2007; Bravo, Meirelles, & Giallonardo, 2014). In sum, such a technology could help transition Brazilian society's most intensive carbon sectors towards a more economically viable and sustainable future.

However, as history usually occurs with technological transitions, the role of the state, its agenda and policies play a fundamental role. EVs price competitiveness remains constrained by high battery prices. The transition depends on popular demand and on national leaders to foster the necessary shifts for inclusion, development, and propagation until the technology is well-established and its price reduced.

Among the policies that would allow this evolution are: financial incentives for EV acquisition, GHG regulations, fuel high-efficiency regulation, vehicle taxes proportional to energy efficiency, restitution of taxes to companies that provide EV's charging stations, an increase in charging stations infrastructure, EV access to otherwise restricted transit areas (e.g., bus, carpools and other lanes), and parking fee exemptions. Besides offering subsidies that reduce the nominal value of vehicles and their exemption from licensing fees and other taxes, almost all countries where EVs market participation is now above 0.5% (China, Denmark, France, Germany, Japan, the Netherlands, Norway, Portugal, Sweden, the United Kingdom and the USA) provide direct or fiscal incentives for the installation of domestic recharge stations (IEA, 2016b).

In conclusion, this study has shown that battery electric fueled car technology is the best economic and technological option for the near term sustainable future of the private transportation sector in Brazil. Considering that the Brazilian car fleet will change significantly increase in the next decades, instead of producing conventional or hybrid cars and having to change the future fleet, Brazil has the opportunity to grow its fleet already with this technology, which would be strategically more effective for its economy and the sustainability of present and future generations.

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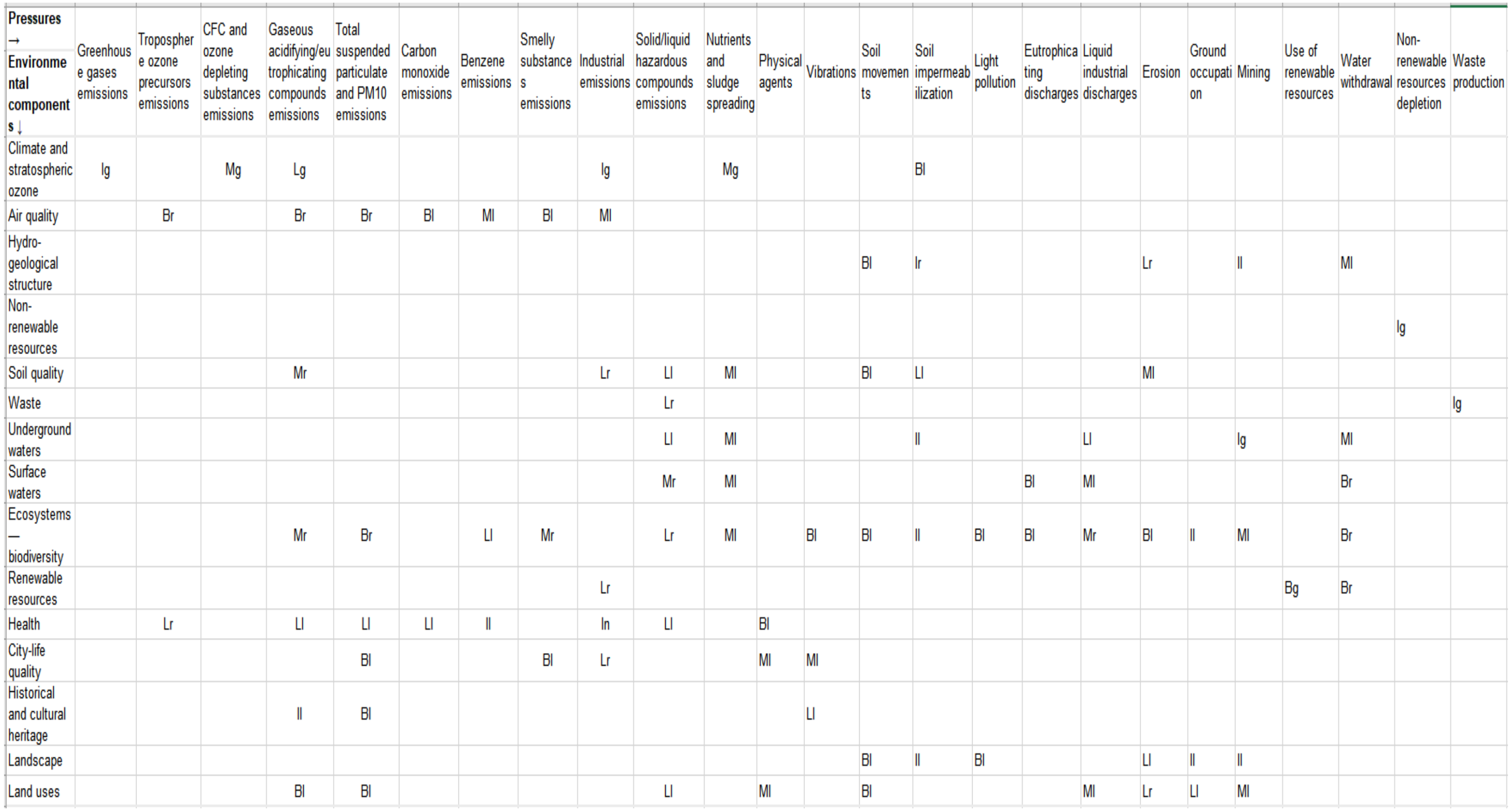
Appendix

Table 8. The matrix which relates environmental pressures to environmental components (Marazza, Bandini, & Contin, 2010).



Pressures → Environmental components ↓	Greenhouse gases emissions	Tropospheric ozone precursors emissions	CFC and ozone depleting substances emissions	Gaseous acidifying/eutrophicating compounds emissions	Total suspended particulate and PM10 emissions	Carbon monoxide emissions	Benzene emissions	Smelly substances emissions	Industrial emissions	Solid/liquid hazardous compounds emissions	Nutrients and sludge spreading	Physical agents	Vibrations	Soil movements	Soil impermeabilization	Light pollution	Eutrophicating discharges	Liquid industrial discharges	Erosion	Ground occupation	Mining	Use of renewable resources	Water withdrawal	Non-renewable resources depletion	Waste production
Climate and stratospheric ozone	Ig		Mg	Lg					Ig		Mg				Bl										
Air quality		Br		Br	Br	Bl	Ml	Bl	Ml																
Hydro-geological structure														Bl	Ir				Lr		Il		Ml		
Non-renewable resources																								Ig	
Soil quality				Mr					Lr	Ll	Ml			Bl	Ll				Ml						
Waste										Lr															Ig
Underground waters										Ll	Ml				Il			Ll			Ig		Ml		
Surface waters										Mr	Ml						Bl	Ml					Br		
Ecosystems — biodiversity				Mr	Br		Ll	Mr		Lr	Ml		Bl	Bl	Il	Bl	Bl	Mr	Bl	Il	Ml		Br		
Renewable resources									Lr													Bg	Br		
Health		Lr		Ll	Ll	Ll	Il		In	Ll		Bl													
City-life quality					Bl			Bl	Lr			Ml	Ml												
Historical and cultural heritage				Il	Bl								Ll												
Landscape														Bl	Il	Bl			Ll	Il	Il				
Land uses				Bl	Bl					Ll		Ml		Bl				Ml	Lr	Ll	Ml				

Table 9. The scoring of the environmental impact of each environmental component, according to the temporal and spatial dimension of the impact (Marazza, Bandini, & Contin, 2010).

	Temporal scale			
Spatial dimension	**B— short**	**M — medium**	**L — long**	**I — irreversible**
l — local	1	2	3	4
r — regional	1	2	3	4
n — national	2	3	4	5
g — global	3	4	5	5


Cheaper Batteries

Lithium-ion battery prices just keep falling. They're down 24% from 2016 levels.

Note: Figures are volume-weighted averages
Source: Bloomberg New Energy Finance survey of more than 50 companies

Figure 16. *Economies of scale reducing the prices of batteries* (*Chediak, 2017).*

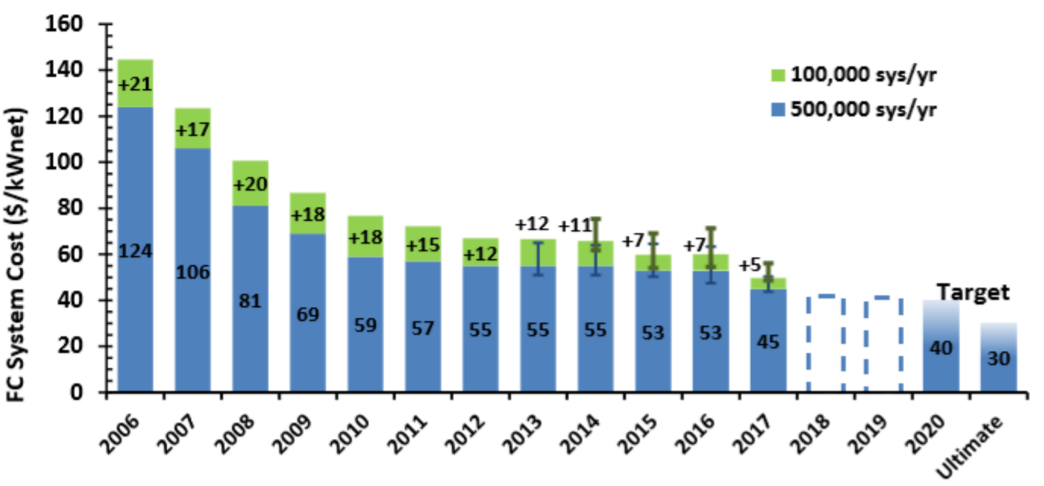
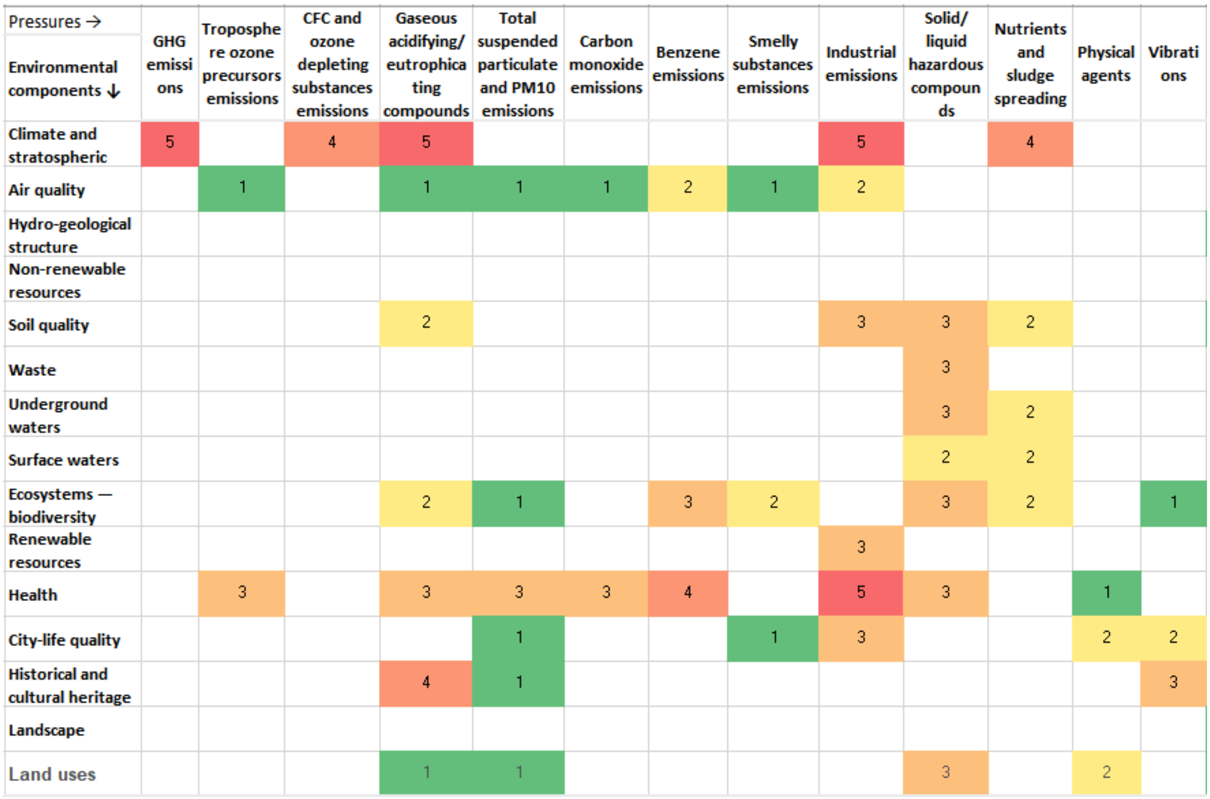
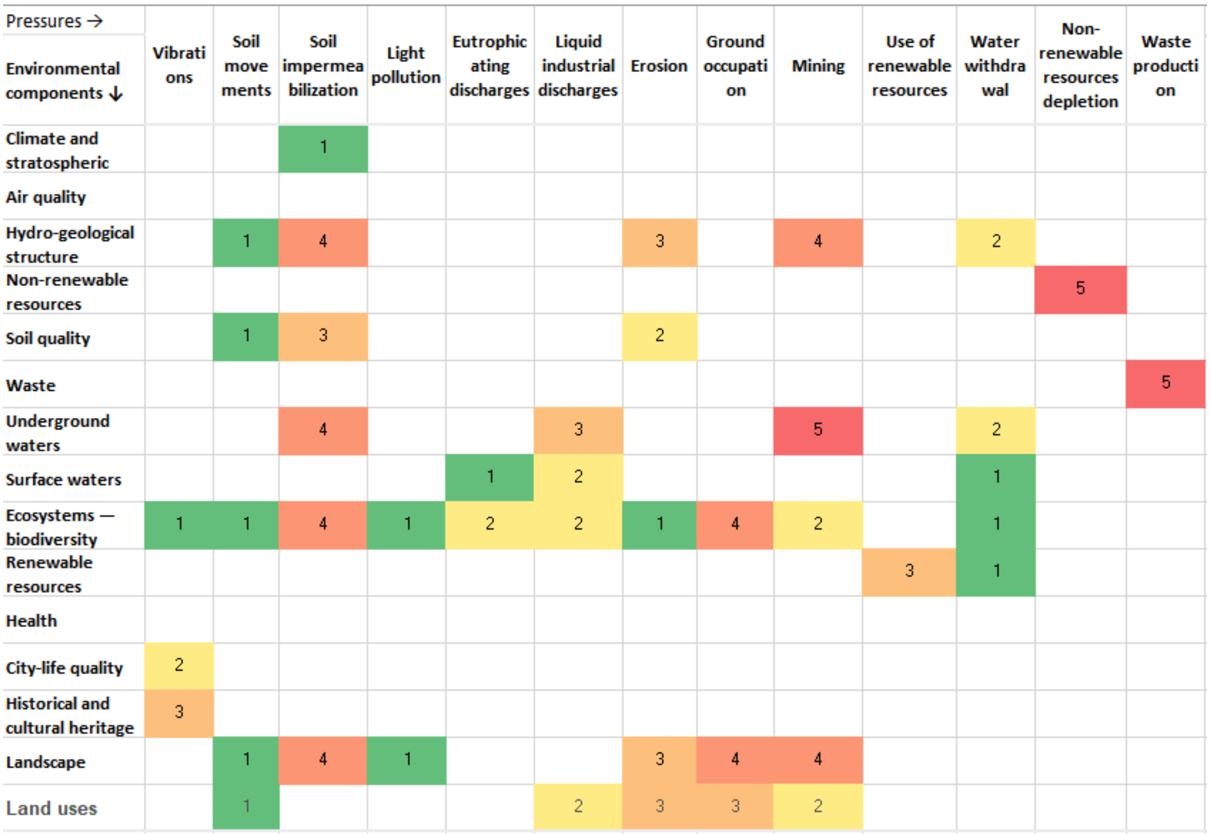


Figure 17. Modeled cost of fuel system over time. 80-kWnet PEM fuel cell system based on projection to high-volume manufacturing (Huya-Kouadio, 2017).

Table 10. Adapted table showing the severity value associated associated with each interaction, varying from 0 to 5, where 0 means "no correlation" and 5 means "irreversible and spatially broad impact"



Pressures → Environmental components ↓	GHG emissions	Troposphere ozone precursors emissions	CFC and ozone depleting substances emissions	Gaseous acidifying/ eutrophicating compounds	Total suspended particulate and PM10 emissions	Carbon monoxide emissions	Benzene emissions	Smelly substances emissions	Industrial emissions	Solid/ liquid hazardous compounds	Nutrients and sludge spreading	Physical agents	Vibrations
Climate and stratospheric	5		4	5					5		4		
Air quality		1		1	1	1	2	1	2				
Hydro-geological structure													
Non-renewable resources													
Soil quality				2					3	3	2		
Waste										3			
Underground waters										3	2		
Surface waters										2	2		
Ecosystems — biodiversity				2	1		3	2		3	2		1
Renewable resources									3				
Health		3		3	3	3	4		5	3		1	
City-life quality					1			1	3			2	2
Historical and cultural heritage				4	1								3
Landscape													
Land uses				1	1					3		2	



Pressures → Environmental components ↓	Vibrations	Soil movements	Soil impermeabilization	Light pollution	Eutrophicating discharges	Liquid industrial discharges	Erosion	Ground occupation	Mining	Use of renewable resources	Water withdrawal	Non-renewable resources depletion	Waste production
Climate and stratospheric			1										
Air quality													
Hydro-geological structure		1	4				3		4		2		
Non-renewable resources												5	
Soil quality		1	3				2						
Waste													5
Underground waters			4			3			5		2		
Surface waters					1	2					1		
Ecosystems — biodiversity	1	1	4	1	2	2	1	4	2		1		
Renewable resources										3	1		
Health													
City-life quality	2												
Historical and cultural heritage	3												
Landscape		1	4	1			3	4	4				
Land uses		1				2	3	3	2				

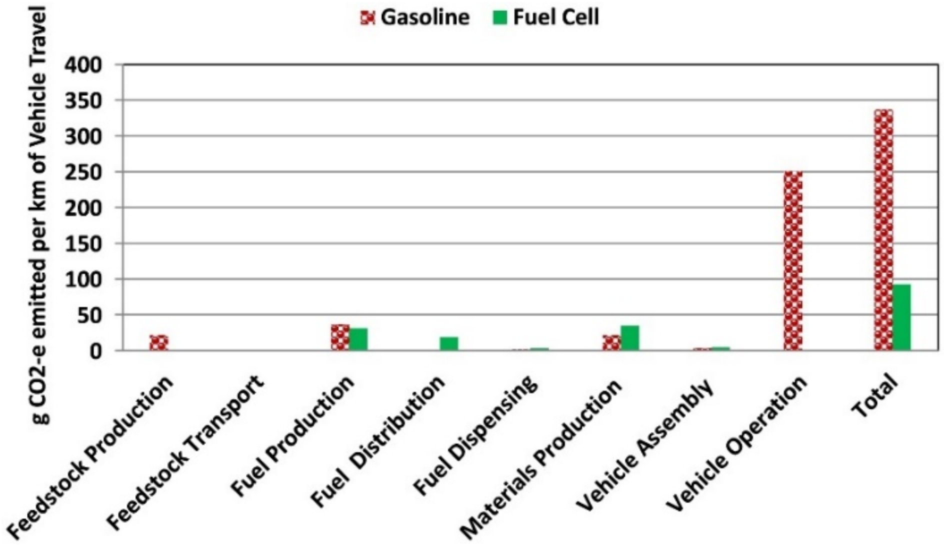


Figure 18. Equivalent carbon dioxide-based greenhouse gas emissions calculated for the gasoline and hydrogen fuel cell powered vehicles (Ahmadi & Kjeang, 2017).

Table 11. Justifications and comments for values non-identical to guidance. BEVs and Ethanol sustainability assessment results through valuation of severity of hazards. Guidance values from Marazza, Bandini, & Contin (2010).

	Environmental components ↓	Pressures ↓	Severity of hazards Guide ↓	BEVs	ETHANOL	Comments/Justifications
1	**Climate and stratospheric ozone**	GHG emissions*	5	1	3	BEVs emission related to grid. Ethanol emissions 3 times smaller than gasoline
2		CFC and ozone depleting substances emissions	4	0	4	
3		Gaseous acidifying/ eutrophicating compounds emissions	5	1	5	BEVs only in production. Ethanol produces acidifying gases
4		Industrial emissions	5	5	5	
5		Nutrients and sludge spreading	4	0	4	
6		Soil impermeabilization	1	0	0	Author could not find relation between technology, environment component and pressure
7	**Air quality**	Troposphere ozone precursors emissions	1	0	1	
8		Gaseous acidifying/ eutrophica ting compounds emissions	1	0	1	
9		Total suspended particulate and PM10 emissions	1	0	1	
10		Carbon monoxide emissions	1	0	1	
11		Benzene emissions	2	0	1	Ethanol combustion produce small quantities of benzene emissions
12		Smelly substances emissions	1	0	1	
13		Industrial emissions	2	2	2	
14	**Hydro-geological structure**	Soil movements	1	0	0	Author could not find relation between technology, environmental component and pressure
15		Soil impermeabilization	4	0	0	Author could not find relation between technology, environmental component and pressure
16		Erosion	3	0	3	
17		Mining	4	4	0	
18		Water withdrawal	2	0	0	Ethanol usually use surface water
19	**Non-renewable resources**	Non-renewable resources depletion	5	5	1	BEVs: Lithium and other minerals. Ethanol: Petrochemicals dependent
20	**Soil quality**	Gaseous acidifying/ eutrophica ting compounds emissions	2	0	2	
21		Industrial emissions	3	0	3	
22		Solid/ liquid hazardous compounds emissions	3	3	3	BEVs: Mining of lithium. Ethanol: Petrochemicals
23		Nutrients and sludge spreading	2	0	2	
24		Soil movements	1	0	1	
25		Soil impermeabilization	3	0	3	
26		Erosion	2	0	2	
27	**Waste**	Solid/ liquid hazardous compounds emissions	3	3	3	BEVs: Mining of lithium. Ethanol: Vinasse
28		Waste production	5	5	0	BEVs: Electronic waste

Continuation of Table 11

29	**Underground waters**	**Solid/ liquid hazardous compounds emissions**	3	3	3	**BEVs: Mining of lithium. Ethanol: Vinasse**
30		**Nutrients and sludge spreading**	2	0	2	
31		**Soil impermeabilization**	4	0	0	**Author could not find relation between technology, environmental component and pressure**
32			3	0	3	
33		**Mining**	5	5	0	
34		**Water withdrawal**	2	0	0	**Ethanol usually use surface water**
35	**Surface waters**	**Solid/ liquid hazardous compounds emissions**	2	0	2	
36		**Nutrients and sludge spreading**	2	0	2	
37		**Eutrophicating discharges**	1	0	1	
38		**Liquid industrial discharges**	2	0	2	
39		**Water withdrawal**	1	0	1	
40	**Ecosystems — biodiversity**	**Gaseous acidifying/ eutrophicating compounds emissions**	2	0	2	
41		**Total suspended particulate and PM10 emissions**	1	0	1	
42		**Benzene emissions**	3	0	1	
43		**Smelly substances emissions**	2	0	2	
44		**Solid/ liquid hazardous compounds emissions**	3	3	3	
45		**Nutrients and sludge spreading**	2	0	2	
46		**Vibrations**	1	0	0	**Author could not find relation between technology, environmental component and pressure**
47		**Soil movements**	1	0	0	**Author could not find relation between technology, environmental component and pressure**
48		**Soil impermeabilization**	4	4	4	
49		**Light pollution**	1	0	0	**Author could not find relation between technology, environmental component and pressure**
50		**Eutrophicating discharges**	2	0	2	
51		**Liquid industrial discharges**	2	0	2	
52		**Erosion**	1	0	1	
53		**Ground occupation**	4	0	4	
54		**Mining**	2	2	0	
55		**Water withdrawal**	1	0	1	
56	**Renewable resources**	**Industrial emissions**	3	3	3	
57		**Use of renewable resources**	3	3	3	
58		**Water withdrawal**	1	0	1	
59	**Health**	**Troposphere ozone precursors emissions**	3	0	3	
60		**Gaseous acidifying/ eutrophica ting compounds emissions**	3	0	3	
61		**Total suspended particulate and PM10 emissions**	3	0	3	
62		**Carbon monoxide emissions**	3	0	2	
63		**Benzene emissions**	4	0	1	
64		**Industrial emissions**	5	5	5	
65		**Solid/ liquid hazardous compounds emissions**	3	3	3	
66		**Physical agents**	1	0	1	
67	**City-life quality**	**Total suspended particulate and PM10 emissions**	1	0	1	
68		**Smelly substances emissions**	1	0	1	
69		**Industrial emissions**	3	3	0	
70		**Physical agents**	2	0	2	
71		**Vibrations**	2	0	0	**Author could not find relation between technology, environmental component and pressure**
72	**Historical and cultural heritage**	**Gaseous acidifying/ eutrophicating compounds emissions**	4	0	1	
73		**Total suspended particulate and PM10 emissions**	1	0	1	
74		**Vibrations**	3	0	0	**Author could not find relation between technology, environmental component and pressure**
75	**Landscape**	**Soil movements**	1	0	0	**Author could not find relation between technology, environmental component and pressure**
76		**Soil impermeabilization**	4	0	0	**Author could not find relation between technology, environmental component and pressure**
77		**Light pollution**	1	0	0	**Author could not find relation between technology, environmental component and pressure**
78		**Erosion**	3	0	0	**Author could not find relation between technology, environmental component and pressure**
79		**Ground occupation**	4	0	4	
80		**Mining**	4	4	0	
81		**Gaseous acidifying/ eutrophica ting compounds emissions**	1	0	1	
82		**Total suspended particulate and PM10 emissions**	1	0	1	
83		**Solid/ liquid hazardous compounds emissions**	3	3	3	
84		**Physical agents**	2	0	2	
85		**Soil movements**	1	0	1	
86		**Liquid industrial discharges**	2	2	2	
87		**Erosion**	3	0	3	
88		**Ground occupation**	3	0	3	
89		**Mining**	2	2	0	
	TOTAL	**Sum of severity of hazards**		**74**	**147**	