Life Cycle Assessment of Urban Passenger Transportation

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Abstract

This paper describes a life-cycle analysis (LCA) performed for urban passenger transport (cars and urban buses) in United States for the years 2015–2050 in five-year steps. It is assumed that the only change made is the propulsion technology/fuel used and that the distance driven by all vehicles (within each mode) per year remains the same. The complete conversion to a single powertrain type is neither realistic or necessarily desirable, but the intention of this LCA is not to provide a forecast of greenhouse gas (GHG) and air pollution emissions or other factors; the system is too complex with more uncertainties. Instead, the intention is to compare the effect of applying the various technologies/fuels in order to discern their effect in a simplified manner and identify any possible limitations and allow further discussions on the ideal policy strategy.

Keywords: Life-cycle analysis, Urban passenger transport, Greenhouse gas, Urbanization

1. Introduction

Cities are facing unprecedented growth from rising population, migration, and urbanization. The United Nations (2011) anticipates global population to rise to 9.3 billion by 2050, by adding a net 2.3 billion new humans to the planet (a greater than 30 percent increase in population). Meanwhile, urban areas are projected to grow by 2.6 billion over the same period. In the next 35 years, cities will absorb all new population growth plus an influx from rural areas. From a global perspective, human populations are multiplying, and the urban regions are growing faster.

These new residents will require more living spaces, supporting infrastructure and efficiently meeting those needs is often a challenge of planning, design, and political will. Most of the research considers how city influences energy use and greenhouse gas emissions on a small scale. Only very little work aggregates the analysis to a larger city or regional level. This study extends the work by moving from neighborhoods to the entire country and from residential-only settings to more realistic land-use patterns. This paper describes a life-cycle analysis (LCA) performed for urban passenger transport (cars and urban buses) in the United States for the years 2015–2050 in five-year steps.

1.1. Literature Review

Changing from the use of internal combustion engine vehicles (ICEVs, i.e., conventional petrol- or diesel-fueled vehicles) offers potential GHG emissions savings. The literature contains estimates on how much this potential is, and what is essential in determining it. The advantage of EVs is 9%–29% less than petrol vehicles in European union [*Hawkins et al., 2013*], 30%–39% less in Portugal [*Garcia et al., 2015*], 10%–60% advantage in other studies. GHGs will be reduced by 40% with a 60% likelihood if battery electric vehicles (BEVs) displaces hybrid electric vehicles (HEVs) [*Abdul-Manan, 2015*].

From an LCA perspective, the significant difference between a BEV and its ICEV equivalent is a shift of emissions from those produced in use of fossil fuel to those from the production of vehicles. It follows that the major determinants of the overall effects of BEVs relate to the production of vehicles and their batteries, and the electricity used to power them. BEVs has heavy emissions in the production phase which significantly affects the lifetime CO2 emissions. [*Aguirre et al., 2012; Van Mierlo et al., 2017; Notter et al., 2010*] Most of the LCA studies reviewed focus primarily on assessing impacts through a storage capacity basis rather than accounting for the battery lifetime, which they suggest might lead to misleading conclusions. Battery manufacturing and the cell chemistry adopted to manufacture the battery are another significant determinant of the overall CO2 emissions [*Peters et al.,2017*].

Several studies examine various effects of different cell chemistries. Depending on the electricity used to power the EV in its use phase, battery manufacturing was found to contribute between 8% and 38% of the total life-cycle emissions (Poland and Sweden, with electricity CO2 emissions of with 650 and 20 g/kWh, respectively) [*Ellingsen et al., 2017*], or 15% at the European Union average electricity CO2 emissions (300 g/kWh) [*Messagie, 2017*]. Batteries cause 7%–15% of the environmental impacts of e-mobility [*Notter et al., 2010*], while the battery production phase accounts for 5%–15% of the fuel cycle GHGs of plug-in electric vehicles [*Ambrose and Kendall, 2016*]. The discrepancies in many of these results are primarily due to the differences in assumptions rather than the cell chemistries [*Peters and Weil, 2018*].

Material recycling is another significant contributor to the overall CO2 emissions related to high production emissions [*Van Mierlo et al., 2017*]. The most commonly noted determinant of the overall CO2 emissions of BEVs is the carbon intensity of the electricity used to power the vehicles [*Woo et al., 2017; Wu et al., 2017*]. Studies on finding optimum vehicle types in different US states based on the states' electricity generation (and driving patterns) finds that BEVs generally outperform ICEVs, although not for very efficient ICEVs compared to BEVs running on coal-fired electricity [*Onat et al., 2017*]. Similarly, another study in Romania concludes that increasing the use of EVs will not affect GHG emissions, given the country's carbon-intensive electricity generation [*Varga, 2013*]. A study in Malaysia, concluded that EVs produced higher well-to-wheel (WTW, i.e., all impacts from fuel production to delivery to the vehicle and final use in the vehicle) environmental impacts in seven out of 15 categories than ICEVs, primarily due to the composition of the electricity grid (40% coal) [*Onn et al., 2017*]. A study in Beijing, China, shows that BEVs can significantly reduce CO2 emissions, unlike previous assessments, primarily due to the shift from coal-based electricity generation to gas [*Shi et al., 2016; Ke et al., 2017*].

Given the significance of electricity emissions on the overall results and the temporal variation of electricity emissions, at what time of day BEVs are charged is significant [*Jochem et al., 2016*]. A renewable-dependent grid may not necessarily directly translate to low GHGs for EVs due to the high variability of such systems [*Faria et al., 2013*]. It is important to charge during off-peak hours to reduce the impacts of BEVs [*Rangaraju et al., 2015*]. However, a study performed by EPRI (as quoted in [31]) warns that an off-peak charging scheme might increase emissions of EVs, particularly if the grid is coal-based, by increasing the baseload (often coal-fired) electricity demand [*Huo et al.,2015*].

While electric motors are much quieter than their internal combustion engine (ICE) equivalents, above approximately 40 miles/h, other sources of noise (tire and aerodynamic) begin to become dominant, leading to little difference in the noise emissions of BEVs and ICEVs from that speed and above [*Jochem et al., 2016*]. A study on different fleet based LCAs observes that many of these studies have not integrated all stages of the life cycle. End-of-life treatment (i.e., recycling and/or reuse) is another influential, an oft-overlooked aspect of an LCA of vehicle technologies [*Garcia and Freire, 2017*]. While BEVs have definite benefits in terms of urban air pollutant emissions, and electricity-dependent benefits in terms of GHG emissions, these benefits are also accompanied by negative effects, such as human toxicity, water eco-toxicity, freshwater eutrophication, acidification, and metal depletion, amongst others [*Choma and Ugaya, 2017*].

The calculation of the overall GHG emissions from biofuel production is particularly reliant on the inclusion (or not) of direct (the effect of changing land from one use to growing biofuel feedstocks) indirect (increased land use for biofuel feedstocks causes land elsewhere to be converted to other uses) land-use change emissions, and how those are calculated. Particularly the inclusion (and calculation method) of LUC, especially indirect, emissions is difficult and subject to significant controversy [*Finkbeiner, 2014*]. However, the degree to which including LUC reverses the GHG advantages of biofuels depends on many factors and conditions [*Dunn et al., 2017*].

1.2. United States Biofuel Industries

The U.S. production of biodiesel was 156 million gallons in August 2019. Biodiesel production during August 2019 was 3 million gallons lower than production in July 2019. Biodiesel production from the Midwest region (Petroleum Administration for Defense District) accounted for 67 percent of the United States total. Production comes from 95 biodiesel plants with a capacity of 2.5 billion gallons per year.

Producer sales of biodiesel during August 2019 included 71 million gallons sold as B100 (100% biodiesel) and an additional 86 million gallons of B100 sold in biodiesel blends with diesel fuel derived from petroleum. There were a total of 1,198 million pounds of feedstocks used to produce biodiesel in August 2019. Soybean oil remained the largest biodiesel feedstock during August 2019, with 701 million pounds consumed. [*EIA, 2019*]

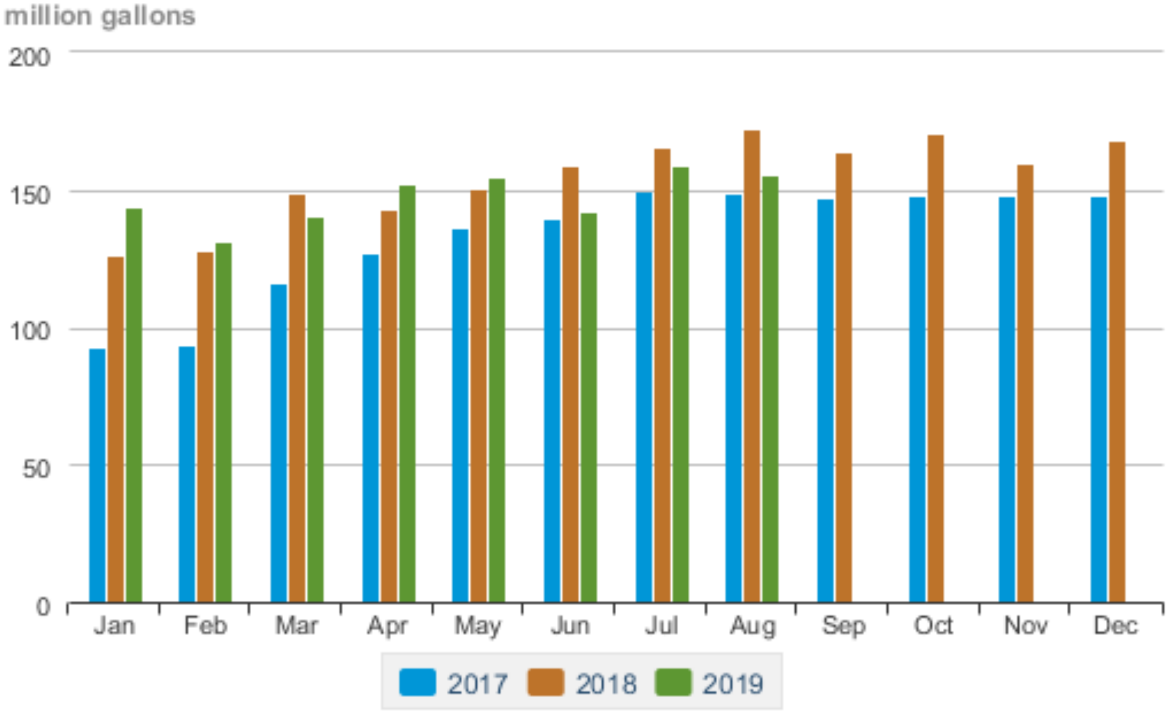

Figure 1. U.S. monthly biodiesel production 2017-2019

Source: U.S. Energy Information Administration, Form EIA-22M Biodiesel Monthly Survey

1.3. United States Electricity Sector

The United States uses many different energy sources and technologies to generate electricity. The sources and technologies have changed over time, and some are used more than others.

The three major categories of energy for electricity generation are fossil fuels (coal, natural gas, and petroleum), nuclear energy, and renewable energy sources. Most electricity is generated with steam turbines using fossil fuels, nuclear, biomass, geothermal, and solar thermal energy. Other major electricity generation technologies include gas turbines, hydro turbines, wind turbines, and solar photovoltaics. [*EIA, 2019*]

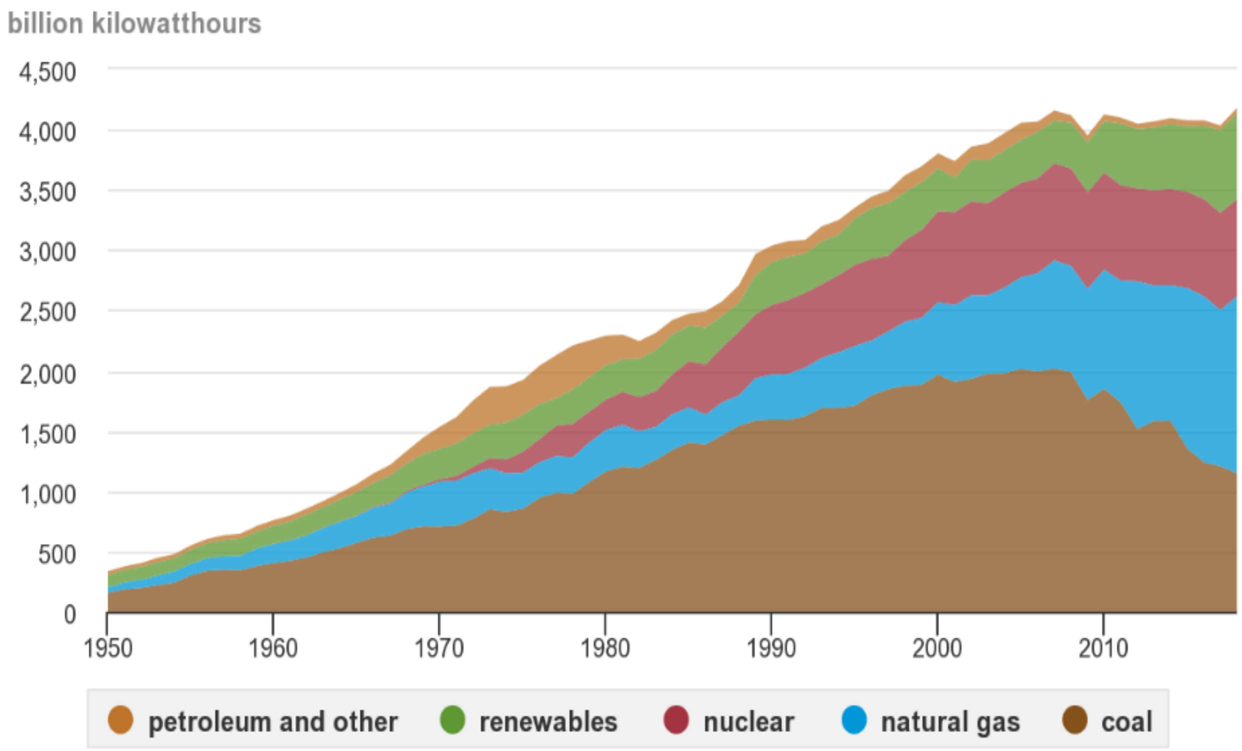

Figure 2. U.S. electricity generation by major energy source, 1950-2018

Source: U.S. Energy Information Administration, Monthly Energy Review, Table 7.2a

2. Methodology

The LCA presented here examines the effect of gradual adoption of either electric vehicles or biofuels by 2050 in (urban) passenger transport based on the projected proportions. The results are calculated in terms of CO2 emissions, electricity & fuel consumption, and the land area required to grow enough biofuel feedstocks.

The LCA considers passenger cars and urban buses. However, because the magnitude of results of motorcycles is negligible in comparison to the other modes, the results for motorcycles are omitted for brevity. The LCA is calculated in a five-year step ignoring the intervening years. An overview of the aspects and life phases considered in the LCA is shown in Figure 2 and further described in the section below.

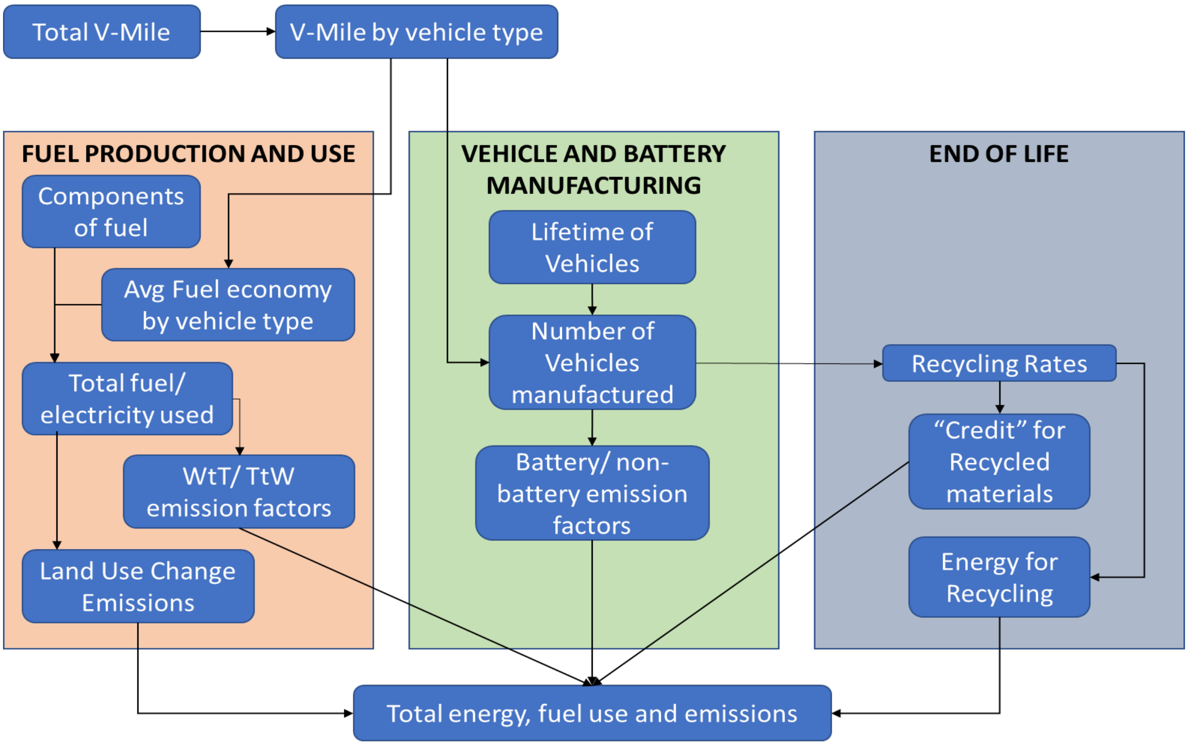

Figure 3. Schematic of the life-cycle analysis (LCA) methodology. WtT: well to tank; TtW: tank to wheel.

Based on the 2050 calculator tool (http://2050-calculator-tool-wiki.decc.gov.uk/pages/1)

2.1. Vehicle Use and Characteristics

2.1.1. Total National Vehicle Use

The total distance driven by all vehicles of each mode (cars, urban buses) per year in vehicle miles is calculated to allow free selection from different powertrain types. It is calculated from the total projected vehicle stock of each mode multiplied by the corresponding average distance driven per vehicle, using figures for both from Edmunds, 2019.

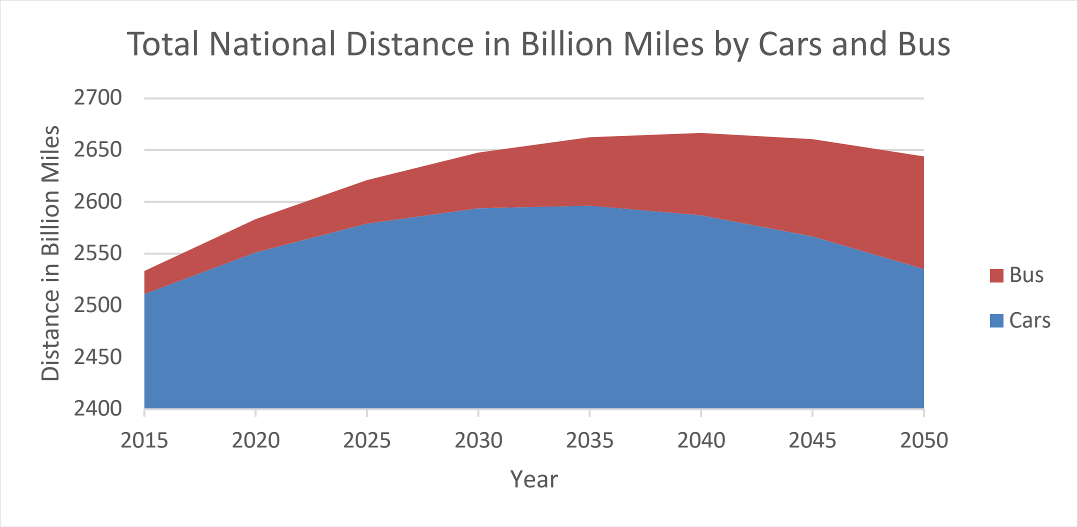

Figure 4. Total distance driven by the respective modes annually

2.1.2. Fleet and Fuel Composition

For every year, the composition of the fleets (cars and urban buses) is defined from the following powertrain types: electric, plug-in hybrid, hybrid, flex, petrol, diesel and compressed natural gas (CNG). Hybrids are assumed to be 'standard' hybrids without the facility to be charged from external sources, while electric is assumed to mean fully electric vehicles with only onboard batteries as energy storage. Values for the volume of fuels sold are available from 1950 to 2018 in "Highway Statistics, Table MF-202". The future values are calculated by extrapolating the development from 1950 to 2018. This model assumes all relevant vehicles can run on any proportion of bio or fossil fuel.

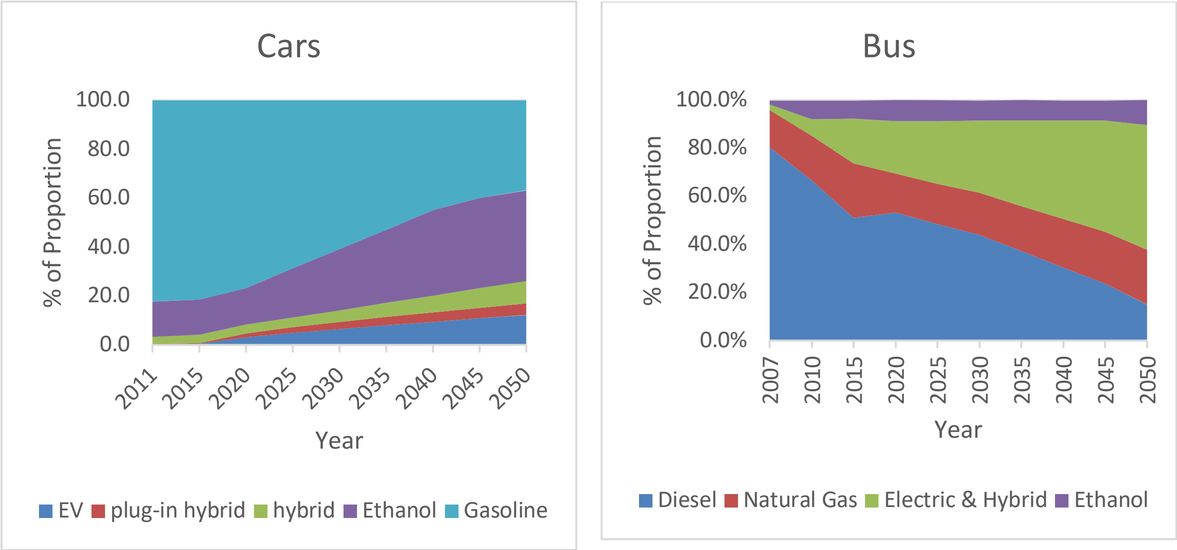

Figure 5. The proportion of vehicles in the Fleet by Powertrain Type

2.2. Fuel Production and Use Phase

2.2.1. Total Fuel Use Per Vehicle Type and Fuel Type

The total v-mile per mode and powertrain type is calculated based on the overall v-mile per mode and the powertrain proportions. The total use-phase energy, and thus fuel consumed by each vehicle type, is calculated from the v-mile and the corresponding on-road average fuel economy for each type. All relevant values here are provided by Edmunds and Environmental and Energy Studies Institute (EESI).

Table 1. Fuel Economy of Vehicle Fleet

FLEET	POWER TERRAIN	ENERGY REQUIRED PER MILE	SOURCE
CAR	EV	0.3 KWh	Edmunds
	Plug-in Hybrid	0.13 KWh + 0.012 gallon	
	Hybrid	0.025 gallon	
	Flex	0.04 gallon	
BUS	CNG	0.6 gallon	EESI
	Electric & Hybrid	0.1 KWh + 0.3 gallon	
	Flex	0.4 gallon	

2.2.2. *Well-to-Wheel (WtW) Emissions*

For each fuel type, the well-to-tank (WtT) and Tank-to-Wheel (TtW) CO2 emissions (per gallon) are given by NAFA, 2009. The full fuel cycle is the combination of the WtT and TtW, which is also commonly referred to as a Well-to-Wheels (WtW). WtT includes Feedstock extraction, transport, storage, processing, and distribution, while TtW includes Refueling, consumption, and evaporation. These figures do not contain land-use emissions. The CO2 coefficients are drawn mainly from the U.S. EPA Climate Leaders' guidance for mobile combustion sources. The factor for electricity is from the U.S. Energy Information Agency.

Table 2. Carbon Dioxide Coefficients

Power terrain	**Units**	**Kg CO2**
Motor Gasoline	Gallons	8.81
Diesel Fuel	Gallons	10.15
LPG	Gallons	5.79
Ethanol	Gallons	5.56
Biodiesel	Gallons	9.46
Compressed Natural Gas (CNG)	Scf	0.054
Electricity	KWh	0.6078

2.2.3. *Electricity System*

The energy generation and CO2 emissions are provided by EPA from the year 2008 to 2018, which are used to extrapolate and forecast. The worst-case scenario is the default used, which is the renewables energy production is still the same. The model does not account for any effects of large additional loads in the short or long term, and the total generation capacity is used only as a comparison; a more complicated model accounting for the characteristics of the electricity generation system is beyond the scope of this study.

Table 3. Electricity Generation and CO2 Emissions Intensities

Year	**Generation (1000 MWh)**	**CO2 Emission intensities (Metric ton/MWh)**
2010	4,125,060	1.35
2015	4,077,601	1.37
2020	4,245,039	1.32
2025	4,283,160	1.30
2030	4,319,823	1.29
2035	4,355,451	1.28
2040	4,390,305	1.27
2045	4,424,564	1.26
2050	4,458,351	1.25

2.2.4. Land-Use Change Emissions

A direct land-use change (LUC) emission model is used to calculate the LUC emissions. It is assumed that the land area for all other crops remains the same, with all changes in biofuel use directly affecting the land used to grow the feedstocks, and that this land comes from (or returns to) various forest types according to the volume of biofuel needed in each year. A more complicated model involving intermediate steps and economic elasticities is beyond the scope of this analysis. Firstly, the land area required to grow the requisite fuel feedstocks is calculated using figures for the yield of ethanol (sugarcane) per land area [American Farmland Trust, 2015].

Table 4. Biofuel Yields and Applied Values for LUC Emissions of CO2 for Various Biomes

Aspect		**Value**
Biofuel yields per land area of cropland (gallons/ha)	Ethanol	1100
	CNG	105
CO2 emissions from LUC (Metric Ton/ha)	Corn	2.5
	Rice	5.2
	Tomatoes	4.0

2.3. Vehicle and Battery Manufacturing Phase

For computational efficiency and because of a lack of equivalent model data pre-2015, a fleet model could not be implemented, so the number of vehicles manufactured per year is calculated by assuming each year is closed regarding vehicles, i.e., all vehicles used in a year would be manufactured in that year and disposed of at the end of the same year. The scenarios thus prescribe a fleet proportion, not sales proportions of the various powertrain types. The number of vehicles for each year is calculated by dividing the total v-mile for each powertrain type by the total lifetime (in miles) of that type. For cars, the lifetime (200,000 miles) is assumed for all vehicle types [*Messagie, 2017*]. Besides, the lifetime CO2 emissions for cars are adopted from [*Nordelöf et al., 2019*], and for buses from [*Lajunen and Lipman, 2016*], the lifetimes (different by powertrain type) are assumed with a correction factor for the lifetime of non-diesel buses.

Table 5. Battery Life and Number of Batteries Required for Vehicles in the Fleet

Vehicle Type		**Vehicle Life (mile)**	**Battery Size (kWh)**	**Batteries in Vehicle Life**	**Battery Round Trip Efficiency**
CAR	Flex	200,000			
	Hybrid		1.5	1.5	
	EV		30	1.5	0.88
BUS	Diesel	400,000			
	CNG				
	Electric		99.5	2.5	0.88

Battery manufacturing emissions are calculated from the overall capacity of batteries required for all hybrid and electric vehicles and their respective battery capacities (and the rate of battery replacement). The average current battery manufacturing emissions intensities is .15 MT/kWh and the average Lifetime CO2 emission for the vehicle fleet is applied [*Yao and Moawad, 2019*]. The default assumption for the battery and vehicle manufacturing calculations is that both are manufactured from raw materials and disposed of with recycling at the end of life.

Table 6. Lifetime CO2 Emissions and Energy for Production of Vehicle Fleet

Power Terrain		**Estimated emission in production (Metric tons of CO2)**	**Energy for production (KWh)**
CAR	Flex	29.5	10000
	Hybrid	27.5	10000
	Plug-in hybrid	25.7	10000
	EV	27.7	10000
BUS	Diesel	562.8	50000
	CNG	643.2	50000
	Electric	140.7	50000

2.4. End-of-Life Phase

LCA treats each year as a closed system, so all vehicles used in any year also come to the end of their lives in that year. Five aspects of the end of life are considered: non-battery recycling emissions, non-battery materials credit, battery recycling emissions and materials credit, and a battery reuse credit. Reusing batteries and recovering materials through recycling effectively reduces the manufacturing emissions, but they are considered as credits in this manner to allow separate (calculation) and presentation of these and the default manufacturing emissions.

Table 7. End-of-Life Data and Sources

Aspect		**Figure**	**Source**
Energy for recycling	Vehicle	0.43 MJ/kg	Kukreja, 2018
	Battery	469 MJ/kWh	
Mass (metric ton)	Car	1.2 MT	Dallmann and Façanha, 2017
	Bus	7.5 MT	Lajunen, 2012
Extra emissions for all-virgin materials in vehicle production		15–20%	Nealer et al., 2015

Reduction in emissions by using recycled battery materials	23–43%	EEA, 2018
	10–17%	Nealer et al., 2015
Current recycling rate	5%	Zacune, 2013

Recycling emissions considers the energy required to recycle the respective parts and is calculated by multiplying the total mass of vehicles and the capacity of batteries to be recycled by the respective factors for the energy required to recycle them. It is assumed the energy for this comes from the electricity network, so the relevant CO2 emission intensity of the electricity system for that year is applied. The vehicle recycling materials credit is included at current levels of recycling and use of recycled materials. The credit is zero, as it is assumed to be included in current calculations of vehicle manufacturing emissions.

The battery recycling materials credit is calculated according to the 10%–17% and 23%–43% reductions given for the use of recycled materials in battery manufacturing. The base assumed reduction is 26.5%—the mid-point between the 10% and 43% outer figures. The actual emission credit figure is calculated from the total battery manufacturing emissions in the relevant year, multiplied by the 26.5% and the assumed proportion of battery recycling.

The calculation of end-of-life credits applies an assumed proportion of battery reuse and recycling. Both are assumed to increase linearly to 99% by 2050, from 5% and 0% in 2015 for recycling and reuse, respectively. This assumes that the greater use of batteries as per the scenarios will create an ever-greater economic and environmental imperative on the more efficient use of batteries and materials. As batteries can be both reused and recycled, both credits can be applied.

Table 8. Recycling and Reuse Rates as Applied in the LCAs

Aspect	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Recycling rate	0.05	0.19	0.32	0.46	0.59	0.73	0.86	0.99
Reuse rate		0.17	0.33	0.46	0.60	0.73	0.87	0.99

3. Life Cycle Analysis for Business as Usual Scenario (BAU)

3.1 Calculate the Total Miles for Each Power Terrain

Business as usual is a scenario where the future is assumed to have the current execution of standard functional operations without any major changes. For the BAU scenario, the 2015/2020 proportions of ethanol (15% in 2015, 57% subsequently) and biodiesel (10% in 2015) are applied, while the vehicle proportions are provided from figure 5. The total distance is obtained from figure 4. The total mile by each power terrain is calculated as the product of total miles driven in the year and the proportion of each power terrain in that year.

Sample Calculation:

Total Vehicle miles of cars in 2015 = 2,511,192,454,042.35 miles

Proportion of EV in 2015 = 0.5%

*Total EV vehicle mile in 2015 = 2511192454042.35 * 0.5% = 12,555,962,270 miles*

Table 9. Total Miles driven by the Fleet for Different Power Terrain

YEAR	CAR					BUS			
	Billion Miles					Billion Miles			
	EV	plug-in hybrid	hybrid	Ethanol	Gasoline	CNG	Electric & Hybrid	Ethanol	Diesel
2015	12.56	10.04	82.87	359.10	2046.62	5.06	4.10	1.71	11.36
2020	80.62	38.27	89.29	385.24	1959.38	3.59	4.89	1.91	11.84
2025	128.95	56.74	105.74	515.82	1771.83	3.70	5.84	1.91	10.78
2030	170.43	72.63	124.52	648.52	1577.20	3.91	6.65	1.89	9.78
2035	207.73	85.69	148.01	781.58	1373.61	4.16	7.90	1.89	8.29
2040	243.20	98.32	175.93	908.13	1161.68	4.44	9.13	1.87	6.78
2045	277.19	110.36	205.32	949.63	1024.06	4.75	10.34	1.84	5.29
2050	306.74	121.68	235.76	935.43	935.43	5.08	11.53	2.29	3.33

3.2 Calculate the Total Fuel and Energy Used by Power Terrain

The total energy required in a year is calculated as the product of total miles driven by each power terrain as calculated in tables 9 and 10 and the fuel economy of the vehicle fleet given by table 1. The fuel economy for ethanol is assumed to be the same as petrol cars and diesel buses, assuming ethanol is mixed only with these fuel types and not used with any other fuels. It is assumed that the fuel economy will not change over the entire analysis period for simplicity.

Sample Calculation:

Total EV vehicle mile in 2015 = 12,555,962,270 miles

Average Fuel economy of EV vehicle = 0.3 KWh/ mile

Total Plug-in Hybrid vehicle mile in 2015 = 10,044,769,816 miles

Average Fuel economy of Plug-in Hybrid vehicle = (0.13 KWh + 0.012 Gallon)/ mile

*Total energy required for EV vehicles in 2015 = (0.3 * 12555962270) + (0.13 * 10044769816)*

= 3766788681 + 1305820076 = 5,072,608,757 KWh

Table 10. Total Fuel and Electricity Used by the Fleet for Different Power Terrain

YEAR	CAR Electricity (KWh)	CAR Gasoline (gallons)	CAR Ethanol (gallons)	BUS Electricity (KWh)	BUS Diesel (gallons)	BUS Ethanol (gallons)	BUS CNG (gallons)
2015	5.07	84.06	14.36	0.41	4.54	0.68	3.03
2020	29.16	81.07	15.41	0.49	4.74	0.76	2.15
2025	46.06	74.20	20.63	0.58	4.31	0.76	2.22
2030	60.57	67.07	25.94	0.66	3.91	0.76	2.34
2035	73.46	59.67	31.26	0.79	3.32	0.76	2.49
2040	85.74	52.05	36.33	0.91	2.71	0.75	2.67
2045	97.50	47.42	37.99	1.03	2.12	0.74	2.85
2050	107.84	44.77	37.42	1.15	1.33	0.92	3.05

** Value in Billions*

3.3 Calculate Emission in Fuel Use

The fuel emission is generally calculated by different measures, which include but not limited to greenhouse gas emissions, particulate matters, pollutants, and so on. But for the simplicity of the model, CO2 emissions are the only measurement used for this entire analysis. The CO2 emissions factor for hydrocarbon fuels is given in table 2, which is assumed to be the same for the entire analysis period. Table 3 gives the emission factor for electricity, and table 4 gives the emission factor for land-use change. The emissions are calculated as the product of the emission factor and the total fuel usage.

Sample Calculation:

Total energy required for EV vehicles in 2015 = 5,072,608,757 KWh

CO2 emission factor = 0.6078 kg of CO2/ KWh

*CO2 emitted by EV vehicles fuel in 2015 = 0.6078 * 5072608757 / 1000 = 3,083,131.60 MT of CO2*

Note: 1 Metric Tons (MT) = 1000 kg

Total ethanol required in 2015 = 14,364,020,837.12 gallons

Biofuel yields per land area of cropland = 1100 gallons/hectare

CO2 emissions factor for LUC = 2.5 MT/hectare

*CO2 emitted by ethanol in 2015 = 2.5 * 14364020837.12 / 1100 = 32,645,501.90 MT of CO2*

Table 11. Fuel Use Emissions in Metric Tons

Year	CAR			BUS		
	WtW*	**LUC***	**Total***	**WtW***	**LUC***	**Total***
2015	823.49	32.65	856.14	78.88	73.80	152.68
2020	817.60	35.02	852.62	72.99	52.97	125.96
2025	796.40	46.89	843.29	69.39	54.65	124.03
2030	771.95	58.96	830.91	66.47	57.51	123.99
2035	744.19	71.05	815.24	61.93	61.11	123.05
2040	712.60	82.56	795.16	57.44	65.17	122.61
2045	688.23	86.33	774.56	53.18	69.58	122.76

2050	668.02	85.04	753.06	48.17	74.68	122.85

**Value in million*

3.4 Calculate Energy and Emission in Manufacturing

As mentioned earlier, it is assumed that the total number of vehicles manufactured every year is hard to calculate and incorporate in the LCA. Hence, it is assumed the number of vehicles manufactured every year is calculated as the total miles driven in the year divided by the lifecycle of the vehicle. Total emission and energy factors in manufacturing are given in tables 5 and 6. It is calculated as the product of the number of vehicle/batteries manufactured and the corresponding factor.

Sample Calculation:

Total EV vehicle mile in 2015 = 12,555,962,270 miles

Average vehicle life = 200,000 mile

Number of EV vehicle manufactured in 2015 = 12555962270 / 200000 = 62,780 EV Cars

Average emission in production = 27.7 MT of CO2/car

Average energy required for production = 10,000 KWh/car

CO2 emission due to EV vehicle manufacturing in 2015 = 62780 27.7 = 1,739,006 MT of CO2*

*Energy required to manufacture EV vehicles in 2015 = 62780 * 10000 = 627,800,000 KWh*

Average battery size for EV vehicle = 30 KWh/car

Average number of batteries in EV vehicle life cycle = 1.5/car

Average emission factor for batteries manufacturing = 0.15 MT/KWh

*CO2 emission due to batteries manufactured for EV vehicles in 2015 = 62780 * 30 * 1.5 * 0.15/0.88*

= 48150 MT of CO2

Table 12. Energy and Emission in Manufacturing

Year	CAR							BUS					
	Emission (Million Metric Tons of CO2)						Energy (Billion KWh)	Emission (Million Metric Tons of CO2)					Energy (Billion KWh)
	Vehicle				Battery			Vehicle				Battery	
	EV	plug-in hybrid	hybrid	Flex	EV	Hybrid		Hybrid	CNG	Electric & Hybrid	Flex	Hybrid	
2015	1.74	1.29	11.40	355.08	0.48	0.02	125.56	0.02	8.09	1.43	18.30	0.43	5.56
2020	11.18	4.91	12.28	346.07	3.09	0.07	127.64	0.07	5.74	1.71	19.26	0.52	5.56
2025	17.89	7.28	14.54	337.66	4.95	0.11	128.95	0.11	5.93	2.05	17.76	0.62	5.56
2030	23.64	9.32	17.13	328.52	6.54	0.14	129.66	0.14	6.25	2.33	16.33	0.70	5.56
2035	28.81	10.99	20.36	318.11	7.97	0.16	129.83	0.16	6.65	2.76	14.25	0.84	5.56
2040	33.73	12.61	24.20	305.50	9.33	0.19	129.36	0.19	7.11	3.19	12.10	0.97	5.55
2045	38.45	14.15	28.24	291.32	10.63	0.21	128.33	0.21	7.60	3.62	9.99	1.10	5.56
2050	42.54	15.61	32.43	276.14	11.76	0.23	126.75	0.23	8.13	4.03	7.87	1.22	5.56

3.5 Calculate Emissions on End-of-Life

The end-of-life emissions are based on the recycling rate, reuse rate, and the corresponding emission factors are given in tables 7 and 8. The recycling rate for a battery is assumed to reach almost 100% by the year 2050. Hence the emissions for the batteries' life cycle gradually decrease over time. If virgin materials are used in the production of vehicles, there will be extra emission, and the use of recycled materials also increases gradually over time.

Sample Calculation:

Average energy for recycling cars = 0.43 MJ/kg

Average weight of a car = 1.2 MT

Note: 1 KWh = 3.6 MJ

*Energy required for recycling EV vehicles in 2015 = 62780 * 1.2 * 1000 * 0.43 / 3.6 = 8,998,466 KWh*

Extra emissions for all-virgin materials in vehicle production = 17.5%

CO2 emission due to EV vehicle manufacturing in 2015 = 1,739,006 MT of CO2

Recycle rate in 2015 = 5%

*Extra emission for using Virgin Materials = 1739006 * 0.175 * 0.05 = 15,216 MT*

Energy for battery recycling = 469 MJ/KWh

Reduction in emissions by using recycled battery materials = 21.5%

Average battery size for EV vehicle = 30 KWh/car

Average number of batteries in EV vehicle life cycle = 1.5/car

Average energy required for recycling batteries of EV vehicles in 2015 = 469 MJ/KWh

*CO2 emission due to recycling batteries of EV vehicles in 2015 = 62780 * 30 * 1.5 * 469 * 0.785 * 0.95 /3.6 = 274,471,609.56 KWh*

Table 13. Energy and Emission on end-of-life

Year	CAR			BUS		
	Energy for recycling vehicles (Billion KWh)	Extra Emission for using virgin materials in production (Million MT of CO2)	Energy for recycling battery (Billion KWh)	Energy for recycling vehicles (Million KWh)	Extra Emission for using virgin materials in production (Million MT of CO2)	Energy for recycling battery (Million KWh)
2015	1.80	61.43	0.32	49.77	4.63	281.18
2020	1.83	53.08	2.05	49.78	3.79	335.45
2025	1.85	44.91	3.27	49.80	3.06	401.27
2030	1.86	17.89	4.32	49.77	1.18	456.47
2035	1.86	26.48	5.27	49.80	1.66	542.34
2040	1.85	17.77	6.16	49.75	1.06	626.69
2045	1.84	8.47	7.02	49.77	0.48	709.68
2050	1.82	0.64	7.77	49.79	0.04	791.40

4. Results

The total energy, fuel, and emission in the lifecycle of cars are shown in figure 6. With almost 20% of electrification, the total energy over the life cycle is doubled. And since the flex-fuel is assumed to be a 50% ethanol blend in 2050 compared to 15% in 2015 is the reason for the reduction in gasoline consumption. The main point to be noted here is the CO2 emission, which almost remains the same throughout the analysis. The main reason is that the emissions transfer from the fuel phase to the manufacturing and end-of-life phase for the “clean energy sources." EVs have definite benefits in terms of urban air pollutant emissions and electricity-dependent benefits in terms of GHG emissions, these benefits, however, are accompanied by negative effects during its manufacture, which accounts for the environmental burden caused by the production of a Li-ion battery.

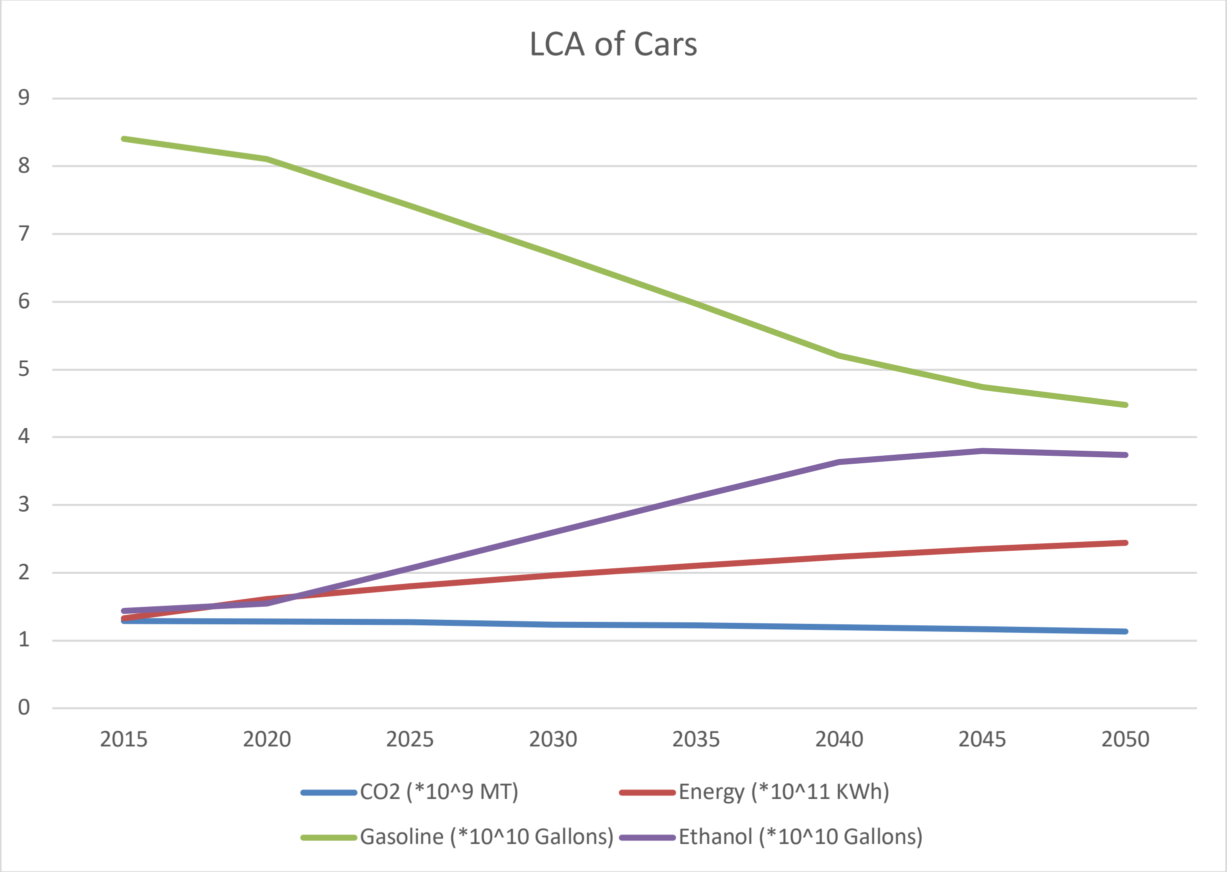

Figure 6. Life cycle analysis of cars

In the case of busses, the total electrification is predicted to be 50% by 2050, which brings down the consumption of hydrocarbon fuels. But again, the total emissions remain almost the same. The emissions in the manufacturing phase are almost one-third of fuel production and use irrespective of the power terrain. This might change if we conduct a sensitivity analysis study with an electricity source. However, the environmental impact can be minimized only by reducing the number of vehicles on the road.

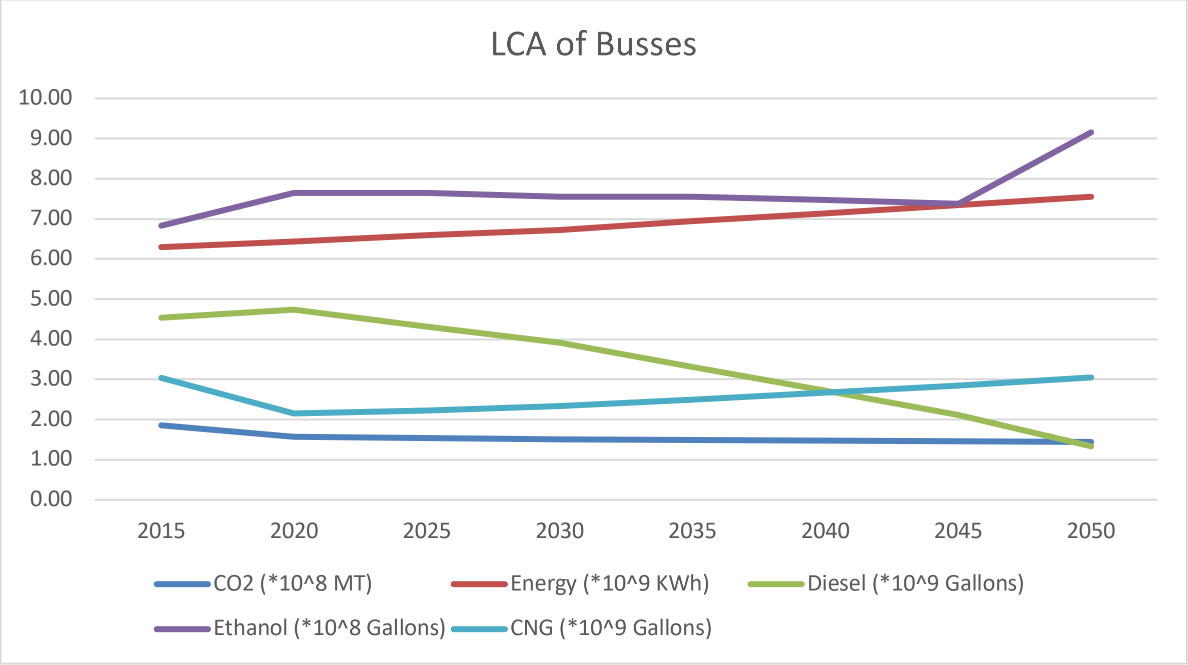

Figure 7. Life cycle analysis for Busses

Overall, of the two modes examined in this LCA, cars have the greatest effect on the results—CO2 emissions, electricity consumption, and land-use for biofuel feedstocks—albeit to differing degrees. Despite cars being smaller and having lower emissions per distance driven than buses, their collective total distance driven is much, much higher, accounting for their greater overall effect.

LUC emissions, as calculated here, is a major contributor to the overall CO2 emissions of the biofuel. Electrification can potentially yield significant benefits in terms of emission reduction. However, the amount of benefit depends greatly on the electricity system's average emission intensity. Another characteristic of the electricity system to note is the total generation capacity. More electrification demands a significant amount of electricity for transportation.

The takeaway from this analysis is that adapting to new technology will not always result in a sustainable future. Proper planning considering the situation is necessary to achieve future goals. Any changes for the future must be analyzed for all the impacts before adopting it.

Some recommendations for the future would be to study the LCA of EVs with renewable energies and conducting more sensitivity analysis. It is obvious that biofuels are not an alternative fuel, as they leave a huge impact on the environment. Electrification of Busses has some positive effects which should be studied closer with different scenarios of electricity sources. Encouraging public transportation use could also result in significantly less impact. Unless proper investment is not made on renewable energy sources in the power grid, tax rebates on EVs is not a good policy to be adopted by any government. The impact in-vehicle use phase can be minimized by reducing the number of trips by better town planning strategies.

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