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ENVIRONMENTAL IMPACT ASSESSMENT OF ELECTRIFYING THE US FREIGHT TRANSPORTATION SECTOR

BY

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ABSTRACT

Increasing demand for energy generation processes has led to an increase in greenhouse gas (GHG) emissions. The scope of this paper is to study if road freight transportation electrification is convenient for the environment. The accumulation of GHGs in the atmosphere harms the planet. Anthropogenic emissions have to be reduced to maintain an equal quality of life and keep improving it. The freight transportation sector accounts for 11 % of the US total emissions. The freight transportation sector is divided mainly into light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs). In this paper, a diesel powered vehicle (DE) and an electric battery vehicle (BEV) have been proposed for each freight vehicle type. In order to study the convenience of electrification, the entire vehicle's lifetime environmental impact is considered. By considering the total vehicle's lifetime, the emissions due to vehicle production (chassis, engine, transmission, electric battery, electric motor and inverter), fuel production, fuel combustion, electric power generation (used to recharge the electric battery), vehicle's maintenance and end-of-life (EOL), are considered. The emissions in the electric power generation phase depend on the energy mix used. There are two parts to this study. One where a specific energy mix has been set, hence a conclusion of the environmental assessment can be presented. And a second part where a user can personalize the energy mix with a designed tool and get customized conclusions. The first part of the study has shown that LDVs electrification is convenient for the environment. However, there has to be an improvement in electric battery storage technology, i.e., full storage performance should be maintained for as long as possible (the study considers a replacement of the installed electric battery every 100,000 miles traveled), and an increase in renewable sources presented in the energy generation mix, before the HDVs are electrified.

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my supervisor Prof. Harrison Hyung Min Kim, who accompanied me through this thesis, suggesting new ideas all along, understanding my work, and giving me the advice to estimate the calculations in the best way possible. Thank you also to the rest of the ESOL lab group for having the opportunity to work with them, always kind and respectful throughout my thesis. Finally, a modest mention to my family, who without their support this could have not been possible.

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INTRODUCTION

There are two main sources of Greenhouse Gas (GHG) emissions. Those that come from natural processes such as volcanoes, water lands, forest fires, among others, and emissions due to human activity. After the Industrial revolution, anthropogenic emissions started to rise year by year. The Earth is capable of processing the emissions coming from itself. However, adding more and more emissions has caused the accumulation of these gases in the atmosphere. The accumulation of GHGs is causing an alteration of the environment. Climate change, endangered species, health issues, and more frequent natural disasters, are some of the most important issues that this environmental alteration is causing.

In order to mitigate or stop climate change, there have been several international treaties where emissions goals were set. The most important one was the Paris Agreement in 2016. The goal is to reduce GHG emissions to achieve a maximum global warming of 2 degrees Celsius, preferably 1.5, compared to preindustrial levels. The countries that aim to comply with the agreement, will have to achieve a net-zero emission scenario by 2050. On April 22nd of 2021, the US government rejoined and ratified this agreement.

In the US, the transportation sector is responsible for 36 percent of the CO_2 emissions. Its electrification would have a big impact on lowering the total emissions of the country. This sector has four main modes of transportation, e.g., air, water, road, and rail transport. The scope of this study is on-road transportation, more specifically, freight road transport. Freight road transportation is responsible for approximately 30 percent of the transportation emissions, i.e., approximately 11 percent of the overall emissions in the country.

Freight road transportation is responsible for moving and delivering all the goods around the country. There are two main types of vehicles used for this purpose, light-duty vehicles (i.e., commercial vans) and heavy-duty vehicles (i.e., semi-trucks). This study is going to focus on the environmental impact of their electrification compared to the already existing fuel-powered vehicles. Nowadays, the vast majority of freight vehicles are powered by diesel.

Electric vehicles' direct emissions are zero. Therefore, by just comparing the tailpipe emissions of a diesel model versus an electric model, the fleet's electrification is convenient. However, to estimate the real impact of electrification, the emissions throughout the whole vehicle's life have to be taken into account. These include the emissions in the manufacturing process for all the vehicle's components (engine, chassis, and electric battery, among others), the fuel production, the fuel combustion (i.e., direct emissions), the electric power generation (used to recharge the batteries), the maintenance of the vehicles, and processing and landfilling these vehicles. The recycling and waste management processes are out of the scope of this study.

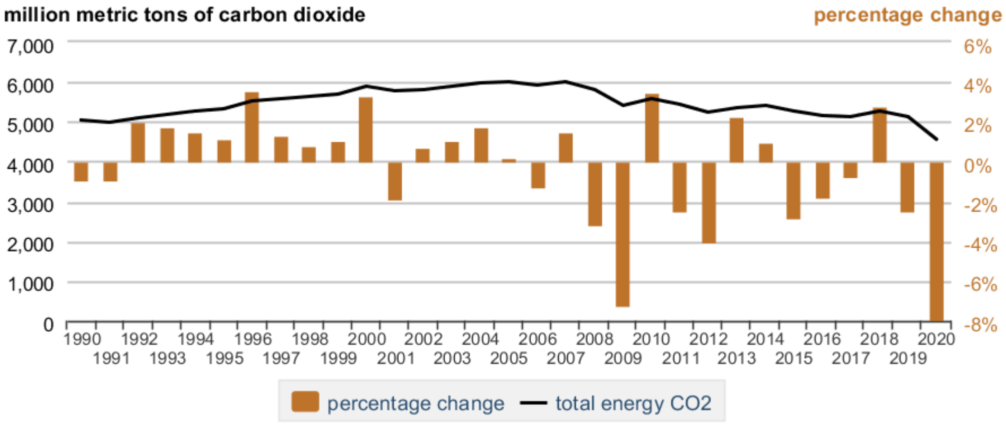
CHAPTER 1: US ENVIRONMENTAL SITUATION

1. US Historic Emissions

After the Industrial Revolution, anthropogenic emissions started to rise. This event led to the accumulation of GHGs in the atmosphere. Since then, year by year, as the economy grew, so did the emissions. Due to the accumulation of GHGs, it was noticeable that the environment started to be harmed. Countries, the US included, started using greener methods of energy generation. As Figure 1 shows, since 2006, there has been an overall decline in the total US CO_2 emissions. Overall processes are being optimized day by day, and research in greener energy generation methods has been key to the reduction in emissions.

Furthermore, it is shown in Figure 1, that 2020 was the year that saw the largest emission reduction in issuance in history. However, this is an anomaly due to the COVID-19 pandemic. COVID-19 caused lower domestic and international travel as well as an increase from home, which led to a sharp decrease in fuel consumption.

Figure 1 Annual emissions of and percentage change in energy-related carbon dioxide [1]



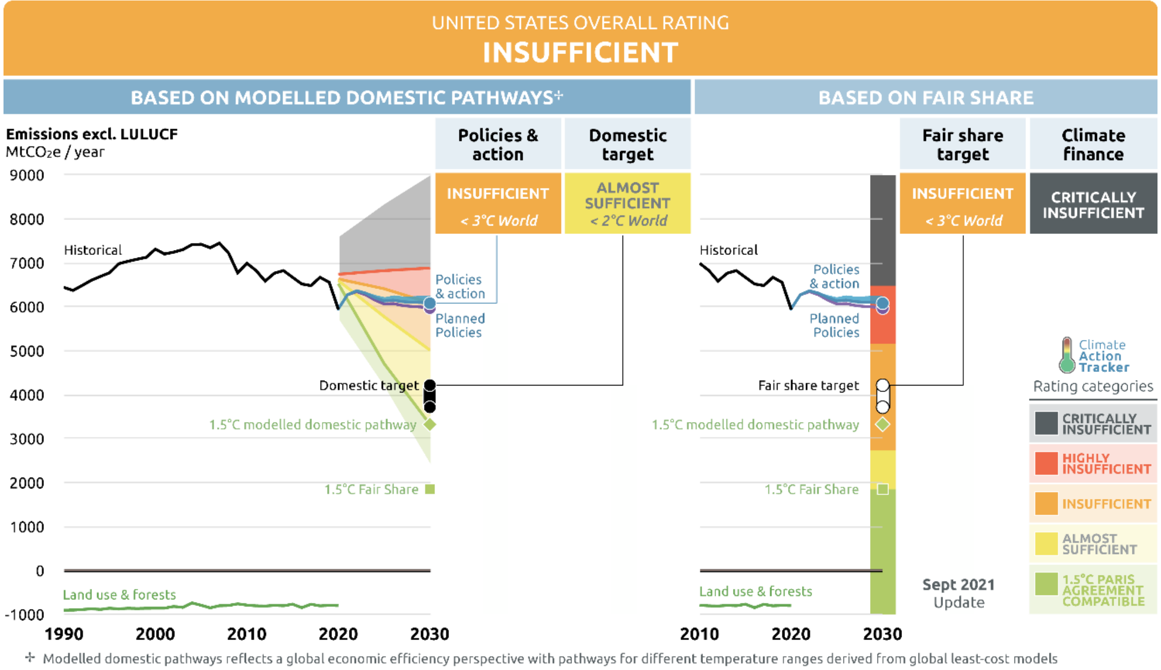
2. US Emission Goals Situation

As aforementioned, in April 2021, the US rejoined and ratified the Paris Agreement. The US country will have to achieve a net-zero economy by 2050. Furthermore, in order to help achieve the emission goals, President Joe Biden also committed to an economy-wide 50-52 % reduction of 2005 emissions levels by 2030 [2]. Actions such as replacing carbon-based energy generation technologies with renewable sources have been made to reduce the country's emissions. However, according to Climate Action Tracker, the United States' overall rating to follow the global emission goals is 'Insufficient', as shown in Figure 2.

Climate Action Tracker takes into consideration all the treaties ratified and approved policies by the selected country, and estimates the future emissions under different scenarios. One of those scenarios is without any more improvements than those that already exist today, i.e., continue developing life with today's technology. This is the reason to have the

‘Insufficient’ status. Further improvements must be made if the objective is to be met. The tracker also shows the paths that should be taken to comply with the Paris Agreement.

Figure 2 US emission status by Climate Action Tracker

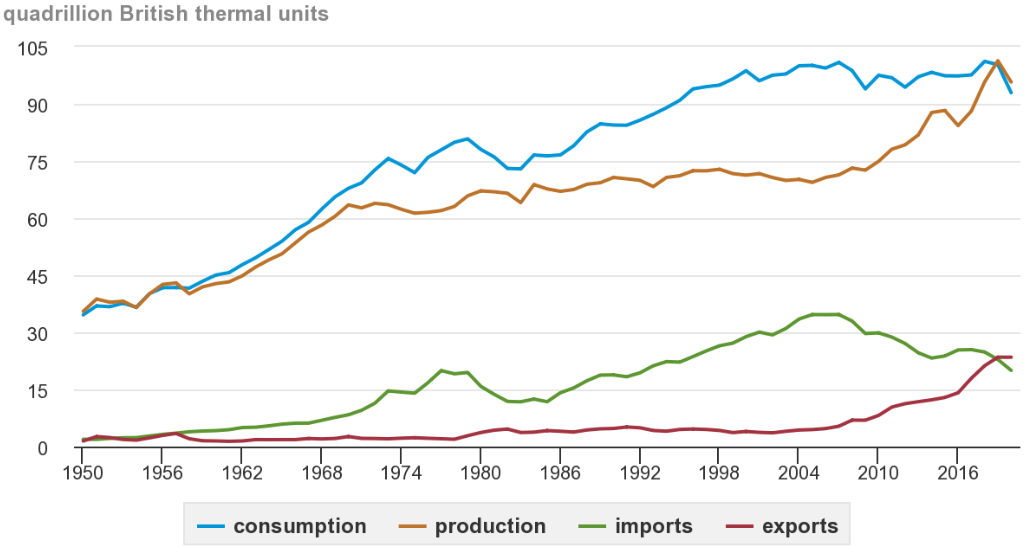


+ Modelled domestic pathways reflects a global economic efficiency perspective with pathways for different temperature ranges derived from global least-cost models

CHAPTER 2: US ENERGY SECTOR

Figure 3 shows the levels of consumption, production, and energy imported and exported for the past 70 years. Around the 70s, the consumption levels started to have a significant difference from the production levels. This explains the behavior in the imports curve. If the energy demanded (shown with the consumption curve) is higher than the energy produced by the US, then energy needs to be imported from outside of the US. These imports can be from neighboring countries or other parts of the world (e.g., China, and Saudi Arabia, among others).

Figure 3 US primary energy overview, 1950 – 2020 [3]



1. US Energy Production

Figure 4 shows how in 20 years the US energy generation industry has drastically changed. Nowadays, the highest energy production source comes from natural gas. A much greener and cheaper source than coal. As opposed to 2000, when coal was the primary source. Moreover, the renewables are in a constant increase and will continue doing so in order to comply with the emissions goals. However, fossil fuels (e.g., coal, natural gas, and crude oil) still dominate the US energy production sector. Figure 5 shows a more detailed version of Figure 4 for the year 2020. Figure 5 is a column for every source used in the US for energy production.

As shown in Figure 5, in 2020, natural gas, crude oil, and coal are the primary sources of energy production in the US.

Figure 4 US primary energy production by major sources, 1950 – 2020 [3]

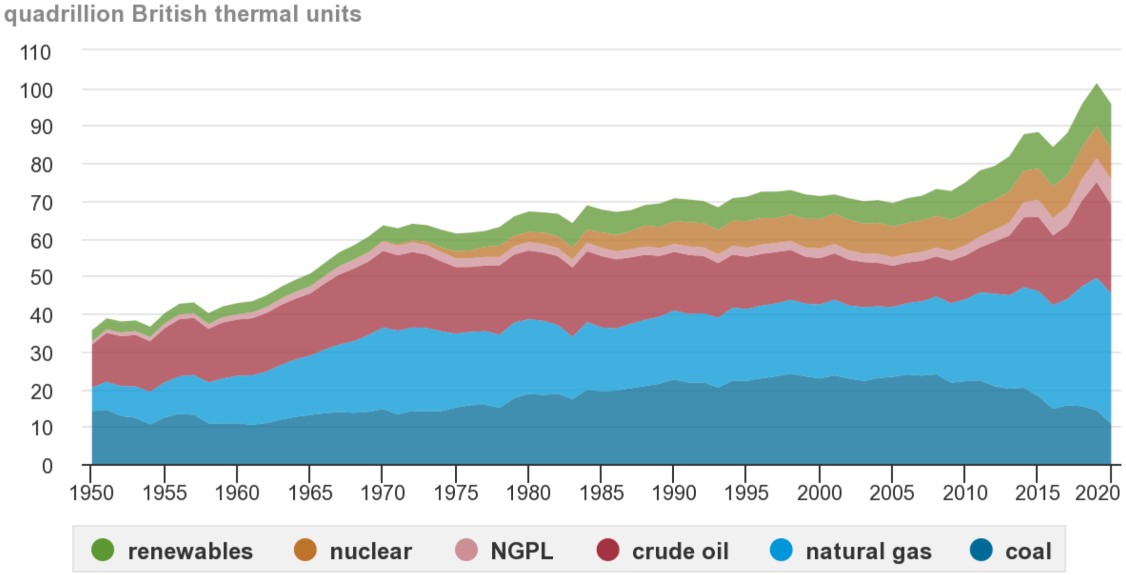
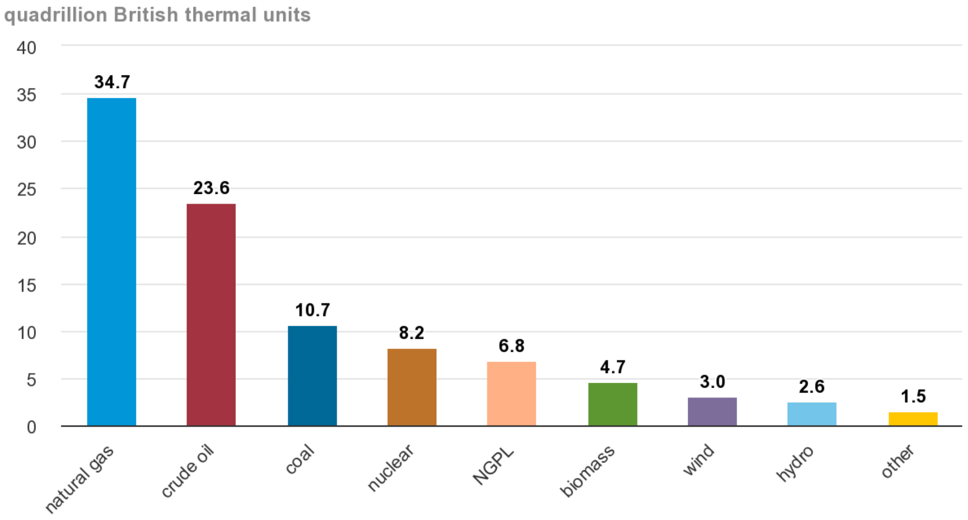


Figure 5 US primary energy production by major sources, 2020 [3]



2. US Energy Consumption

Figure 6 shows all the energy consumption levels for every energy generation source in the US. As stated in the figure, petroleum-based sources have been dominating since the Industrial Revolution. The latter does not take into account biofuels. The US government considers biofuels as a net-zero source, thus, a renewable resource. As aforementioned, the COVID-19 pandemic led to a vast decrease in domestic and international travel, as well as an increase in working from home. This episode caused a decrease in fuel consumption.

Figure 6 US primary energy consumption by major sources, 1950 – 2020 [3]

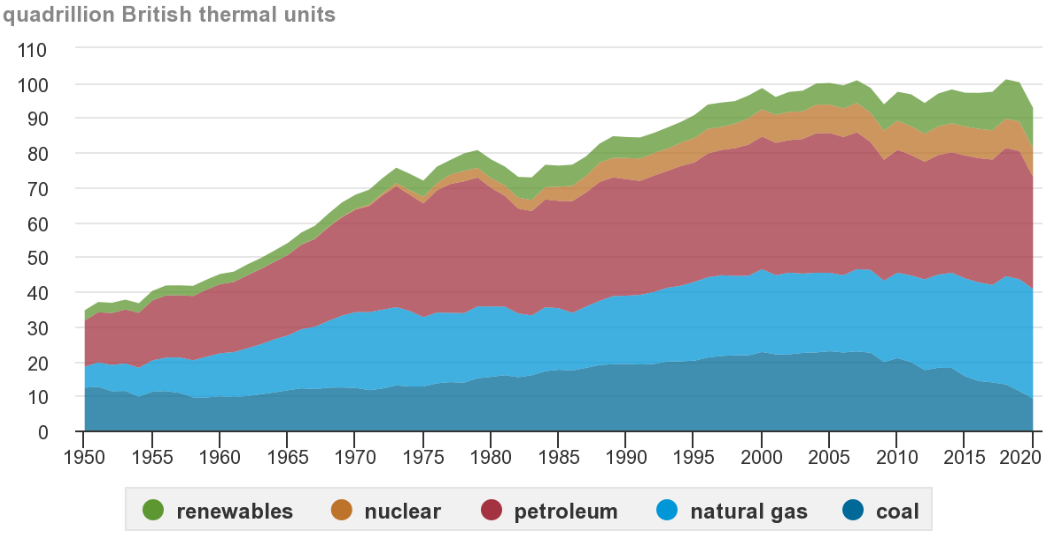


Figure 7 shows the 2020's energy consumption mix. The different sources are listed with the percentages according to their share in the US energy sector. It is possible to observe how coal continues to be an important source of energy even though it has decreased to a large extent.

Figure 7 US primary energy consumption by energy source, 2020 [3]

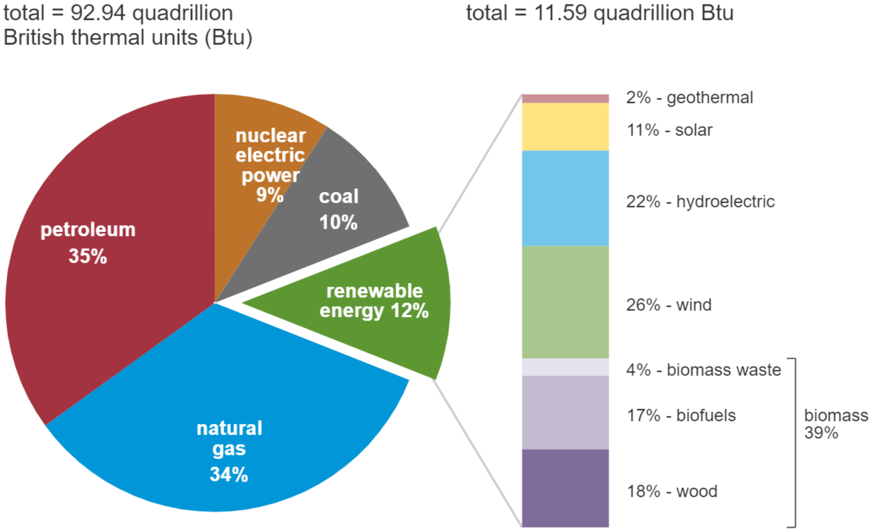
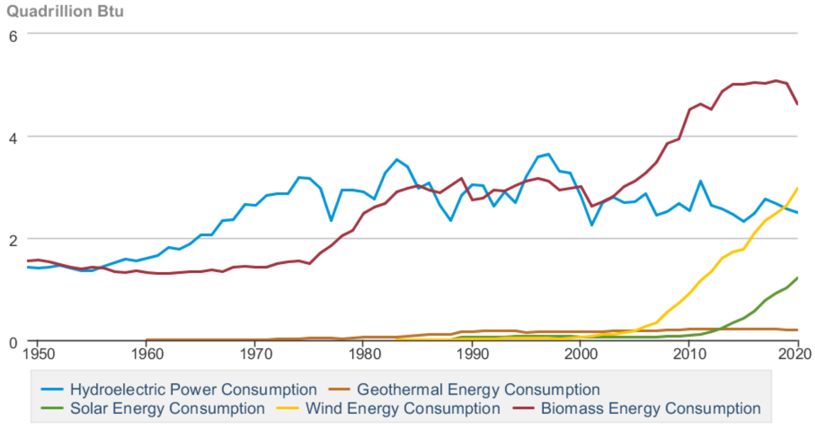


Figure 8 is a breakdown of all the energies that the US government has classified as renewables. It is seen how important biomass energy is for the US. Biomass includes wood, waste, and biofuels. Biomass predominates among the zero-emissions sources.

Figure 8 Primary energy consumption by renewable source [3]



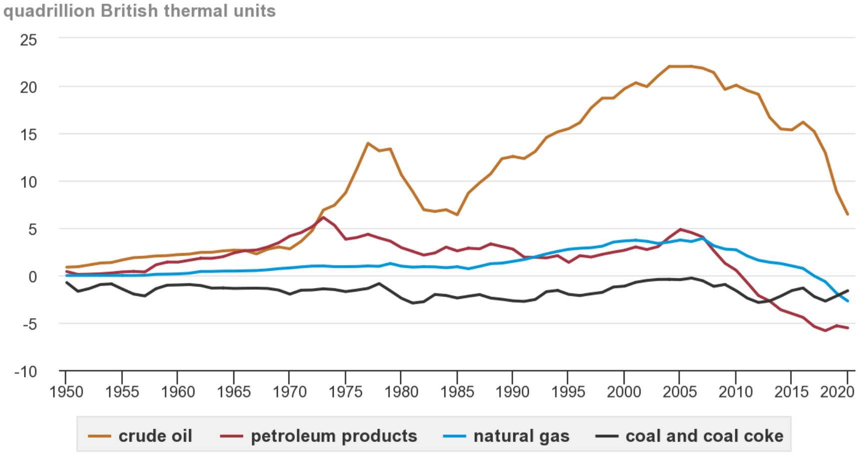
The US energy mix has predominated by fossil fuels for more than 100 years. However, this trend is changing over time. By having a look at the previous energy levels graphs, it is possible to extract that for 2019 and 2020 the energy production exceeded the consumption. This behavior could potentially be caused because of the COVID-19 pandemic. Besides that, this study is going to focus on the consumption data. After all, consumption is the basis for planning how much production to carry out on U.S. soil, how much to import and how much to export. Furthermore, consumption levels are the demand that needs to be supplied. Consumption governs the energy system.

3. US Energy Imports and Exports

As aforementioned, for the past 60 years, energy imports have been higher than energy exports. Until recently, around 2020, when the US has been exporting more energy.

As seen in Figure 9, from the 70s to today, the most important energy source imported has been crude oil. However, 2020 levels of crude oil imports have been the lowest since the 80s. On the one hand, the US has lowered the required demand for crude oil by transferring the energy needs to greener energy sources. On the other hand, the US is getting crude oil from their lands. That is one of the reasons why the exports have surpassed the imports in 2020.

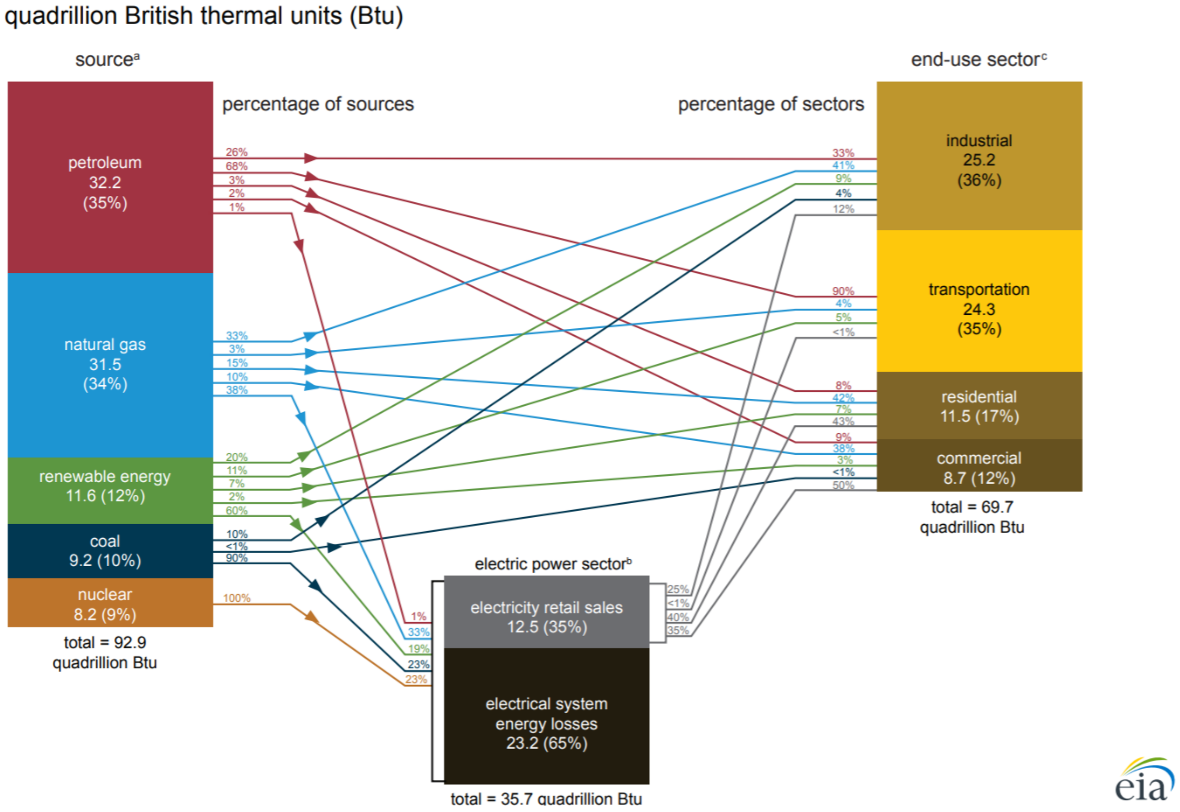
Figure 9 US energy net imports by major source, 1950 – 2020 [3]



4. US End-Use-Sectors Energy Consumption

Figure 10 shows how the energy consumption levels are used in five main sectors. These are electric power, industrial, transportation, residential and commercial. The last four are denominated as end-use sectors.

Figure 10 US energy consumption by source and sector, 2020 [3]



The electric power needed in 2020 is a total of 35.74 quads. A 65% of that amount is energy lost due to generation, transmission, and distribution processes. The other 35% corresponds to the energy consumed for electricity production sold to the end-consumers. In 2020, the US required 12.5 quads to generate the demanded electricity. The figure shows how every source of energy has a share in this sector. Being the most important one natural gas. Once the electricity is produced, it is distributed to the consumers. The consumers may be from the industrial, commercial, residential, or transportation sectors. However, the dominant consumer is private households (i.e., residential) with a demand of 40% of the total electricity. The electricity is used then for refrigeration, heating, lighting, and cooking, among other uses.

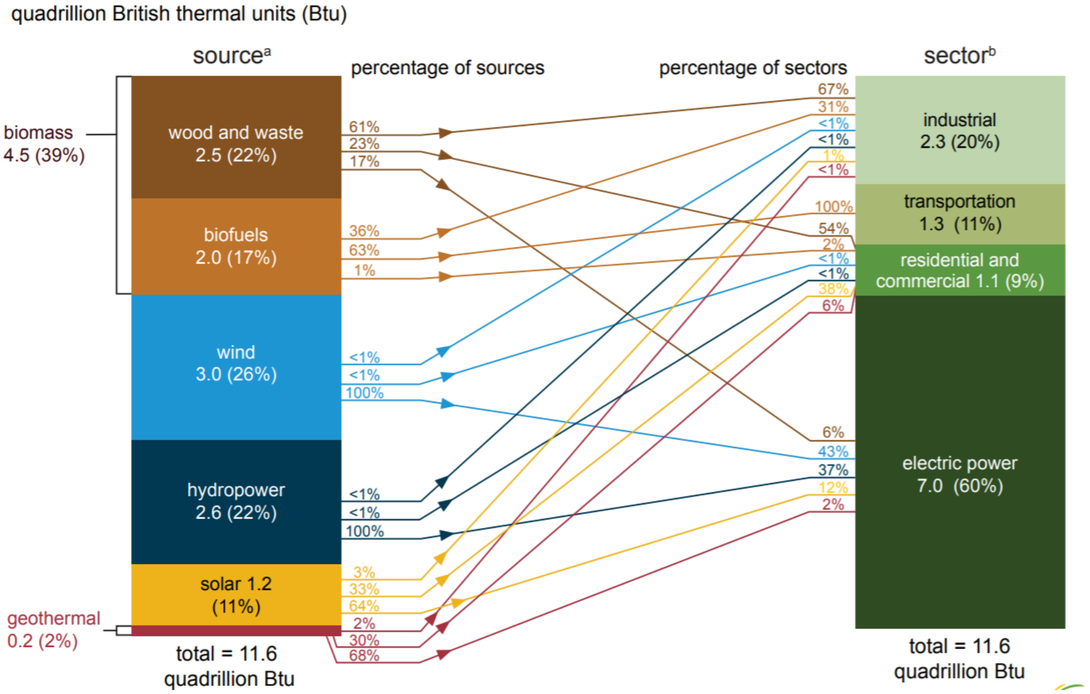
The industrial sector is mainly supplied by petroleum and natural gas sources. The total energy consumed by this sector was 25.24 quads in 2020. That amount corresponds to 36% of energy needs by the end-use sectors. Making this sector the most energy demanded among the end-use sectors.

The second most energy demanded end-use sector is transportation. Transportation includes all the energy used by automobiles, motorcycles, buses, trucks, trains, subways, all other rail vehicles, aircrafts, and all waterborne vehicles that are used to transport people and freight. As seen in the figure, the main source of energy comes from petroleum, e.g., the internal combustion engines used in vehicles. 90% of the person and freight transport vehicles are powered by fossil fuel-based resources. Figure 11 shows that less than 1 percent of the US transport vehicles are electric. The 5% shown in the above figure for transportation by renewables comes entirely from biofuels. Biofuels are a much greener and fully degradable source than fossil fuels. Biofuels do not make a vehicle electric, although biofuels can make them net-zero emissions. This net-zero emissions characteristic has a significant dependence on the manufacturing process to prepare the bio mixture. Furthermore, there are as well vehicles powered by natural gas. The total energy consumption of this sector sums up to 24.25 quads.

The most important energy source for the residential sector is electricity. It accounts for 43% of the total energy required by this sector. Natural gas plays an important role as well with a 42% share. Residential units use energy for space heating, cooling, refrigeration, and cooking, among others. The total energy consumed by all these appliances in all the US private households is 11.53 quads.

The commercial sector includes all the businesses, governments, private and public organizations, and sewage treatment facilities, along with others. This sector's energy source division follows a similar trend as the residential, where electricity has the highest energy share. The total consumption by all these entities ascends to 8.67 quads.

Figure 11 US renewable energy consumption by source and sector, 2020 [3]



5. US Electric Power Sector

By looking at Figure 10 and Figure 11, it is possible to calculate how the US is producing the energy used to generate electricity in the power sector. The combination of the different technologies is referenced as the US Average energy mix. This mix is the combination of all the energy mixes used in all the locations around the country to produce electric power.

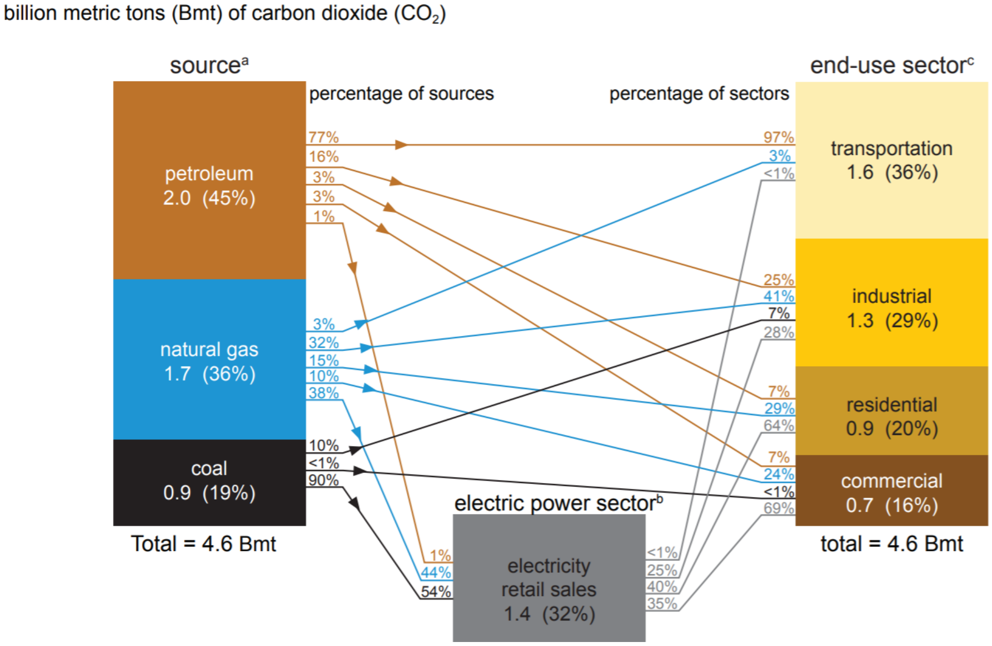
The US Average energy mix combines the following sources [3]:

- 33% of Natural Gas
- 23% of Nuclear Power
- 23% of Coal
- 8.2% of Wind Power
- 7% of Hydropower
- 2.3% of Solar PV
- 1.1% of Biomass Power
- 1% Petroleum
- 0.4% Geothermal Power

6. CO_2 Emissions by US End-Use-Sectors

Figure 12 shows the generated carbon dioxide emissions due to energy consumption by the fossil-based sources and for each of the end-use sectors including the electric power sector. As aforementioned, petroleum supplies about 35 percent of US energy needs. And, as seen above, it is responsible for 45 percent of the CO_2 emissions due to energy consumption. All these emissions are mostly produced by the transportation sector. This sector's main energy source is petroleum. This has to drastically change if emissions goals are to be met. Proportionally comparing the carbon dioxide emissions with the energy generated by each of the three fossil fuels, it is possible to conclude that the worst of the three is coal, followed by petroleum.

Figure 12 US emissions from energy consumption by source and sector, 2020 [3]



The latter statement is confirmed by the GHG Emissions Factors Hub by the US EPA [4]. This study from April 2021 states that the mixed coal and coke used for the electric power sector has a CO_2 factor of 95.52 kg CO_2 per mmBtu. As for solid petroleum coke, this factor rises to 102.41 kg CO_2 per mmBtu. However, as seen in Figure 12, the main use for petroleum is transportation. 77% of all petroleum is consumed by the transportation sector. Transportation does not use straight petroleum but gasoline. The motor gasoline factor is 70.22 kg CO_2 per mmBtu. A lower value of the one solid coal has.

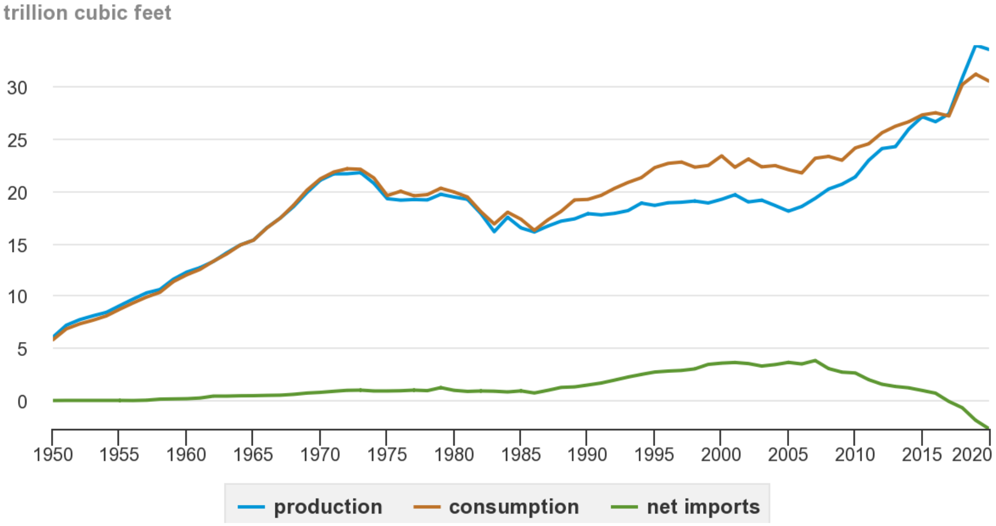
Motor gasoline is defined by the EIA as 'A complex mixture of relatively volatile hydrocarbons with or without small quantities of additives, blended to form a fuel suitable for use in spark-ignition engines […]. Motor Gasoline includes conventional gasoline; all types of oxygenated gasoline, including gasohol; and reformulated gasoline, but excludes aviation gasoline […]'.

That is the reason to compare mixed coal coke with motor gasoline and not petroleum coke. Lastly, as aforementioned, natural gas is the least emissions producer of the three presented in Figure 12. Natural gas has a CO_2 factor of 53.06 kg CO2 per mmBtu [4].

The aforementioned data explains why 'more than 100 coal-fired plants have been replaced or converted to natural gas since 2011' and 28% of the 240 operating US coal plants as of January 2022 are planned to be decommissioned by 2035 [5].

Having natural gas with a lower CO_2 factor than coal, causes its demand to rise, as Figure 13 shows. Furthermore, natural gas is expected to continue growing in demand. Nowadays, as seen below, the US produces all their consumed natural gas.

Figure 13 US natural gas consumption, dry production, and net imports 1950 – 2020 [6]



Renewable sources such as wind and solar are very volatile. The electric power sector requires energy generation sources that can provide flexibility. This means that in times when sources such as solar and wind are not producing electricity (i.e., intermittency due to weather conditions), the power sector requires technology capable of rapidly producing electricity to be wired into the grid to meet the demand in that specific moment. That is the reason for fossil fuel power plants having such a big share in the US Average mix. Natural gas is today's best alternative to petroleum-based and coal sources [7].

7. Energy Generation Mix for US States

The energy mixes for every US State are presented in this section. All of these mixes combined are the US average, presented in section 5 of this chapter. Getting to know how the electric power is generated at lower scales, helps conclude if electrification is convenient depending on where is planned. As Table 1 shows, there are States with high shares in carbon-based energy generation technologies, while others have greener processes. This is basically due to available land and resources in every location.

Table 1 (1) State electricity generation fuel shares (%) [8]

State	Nuclear	Coal	Natural Gas	Petroleum	Hydro	Geothermal	Solar PV	Wind	Biomass	CSP	Ocean
Alabama	32	16	33	1	7	0	2	8	1	0	0
Alaska	0	13	38	16	31	0	0	3	1	0	0
Arizona	29	13	46	0	6	0	6	1	0	0	0
Arkansas	29	29	32	0	8	0	1	0	2	0	0
California	8	0	48	0	11	6	16	7	3	0	0
Colorado	0	36	34	0	3	0	3	24	0	0	0
Connecticut	38	0	57	0	1	0	1	0	3	0	0
Delaware	0	2	95	0	0	0	1	0	1	0	0
District of Columbia	0	0	65	0	0	0	9	0	26	0	0
Florida	12	7	75	1	0	0	3	0	3	0	0
Georgia	28	12	49	0	3	0	3	0	5	0	0
Hawaii	0	13	0	66	1	2	6	6	6	0	0
Idaho	0	0	21	0	59	1	3	14	3	0	0
Illinois	58	18	14	0	0	0	0	10	0	0	0
Indiana	0	53	38	0	0	0	1	7	1	0	0
Iowa	5	24	12	0	2	0	0	58	0	0	0
Kansas	20	31	6	0	0	0	0	43	0	0	0
Kentucky	0	69	23	0	7	0	0	0	1	0	0
Louisiana	17	4	72	3	1	0	0	0	3	0	0
Maine	0	1	17	0	34	0	0	24	23	0	0
Maryland	42	9	39	0	5	0	2	2	2	0	0
Massachusetts	0	0	76	0	3	0	9	2	11	0	0
Michigan	29	27	34	1	1	0	0	6	2	0	0
Minnesota	26	25	20	0	2	0	3	22	3	0	0
Mississippi	10	7	80	0	0	0	1	0	2	0	0
Missouri	11	71	11	0	3	0	0	5	0	0	0

Table 1 (2) State electricity generation fuel shares (%) [8]

State	Nuclear	Coal	Natural Gas	Petroleum	Hydro	Geothermal	Solar PV	Wind	Biomass	CSP	Ocean
Montana	0	36	2	2	47	0	0	13	1	0	0
Nebraska	17	51	4	0	4	0	0	24	0	0	0
Nevada	0	5	66	0	5	10	13	1	0	0	0
New Hampshire	59	1	22	0	9	0	0	3	6	0	0
New Jersey	44	2	50	0	0	0	3	0	2	0	0
New Mexico	0	37	36	1	1	0	5	21	0	0	0
New York	29	0	40	0	24	0	1	4	2	0	0
North Carolina	34	17	34	0	5	0	7	0	2	0	0
North Dakota	0	57	4	0	8	0	0	31	0	0	0
Ohio	15	37	44	1	0	0	0	2	1	0	0
Oklahoma	0	7	52	0	5	0	0	35	0	0	0
Oregon	0	3	29	0	52	0	2	13	2	0	0
Pennsylvania	33	10	52	0	1	0	0	2	1	0	0
Rhode Island	0	0	92	0	0	0	3	3	3	0	0
South Carolina	56	13	25	0	3	0	2	0	2	0	0
South Dakota	0	10	7	0	51	0	0	33	0	0	0
Tennessee	47	18	20	0	12	0	0	0	1	0	0
Texas	9	17	53	0	0	0	2	20	0	0	0
Utah	0	62	25	0	3	1	7	2	1	0	0
Vermont	0	0	0	0	58	0	8	16	18	0	0
Virginia	30	4	61	0	1	0	1	0	4	0	0
Washington	8	5	12	0	66	0	0	7	1	0	0
West Virginia	0	88	5	0	3	0	0	3	0	0	0
Wisconsin	16	39	35	0	5	0	0	3	2	0	0
Wyoming	0	80	4	0	3	0	0	12	0	0	0

8. Life cycle GHG emission factor from electricity generation technologies

Every energy generation technology has its own direct and indirect emissions. In order to account for the emissions throughout the whole energy generation process, the life cycle emission factor for every technology included in Table 1 is presented in Table 2.

As aforementioned, Table 2 shows the median values for four life cycle phases as well as the total life cycle GHG emission factor. The presented technologies are the most important energy generation technologies used in the US power sector to provide the demanded energy.
The mentioned phases take into account the following:

- One-Time Upstream: materials acquisition and plant construction
- Ongoing Combustion: where applicable, when combustion of the source takes place
- Ongoing Non-Combustion: operation and maintenance
- One-time Downstream: plant decommissioning and disposal/recycling

Table 2 Median life cycle emission factors for electricity generation technologies (g CO_2eq / kWh) [9]

Generation Technology		Phases				Total Life Cycle
		One-Time Upstream	Ongoing Combustion	Ongoing Non-Combustion	One-Time Downstream	
Renewable	Biomass	NR	—	NR	NR	52
	Photovoltaic	~28	—	~10	~5	43
	CSP	20	—	10	0.53	28
	Geothermal	15	—	6.9	0.12	37
	Hydropower	6.2	—	1.9	0.004	21
	Ocean	NR	—	NR	NR	8
	Wind	12	—	0.74	0.34	13
Storage	Pumped-storage hydropower	3	—	1.8	0.07	7.4
	Lithium-ion battery	32	—	NR	3.4	33
	Hydrogen fuel cell	27	—	2.5	1.9	38
Non renewables	Nuclear	2	—	12	0.7	13
	Natural Gas	0.8	389	71	0.02	486
	Oil	NR	NR	NR	NR	840
	Coal	<5	1010	10	<5	1001

CSP = Concentrating Solar Power ; NR = Not Reported

CHAPTER 3: US TRANSPORTATION SECTOR

1. Freight Transportation Sector

The transportation sector is divided into mainly four modes of transportation: air, water, railway, and road transportation. The purpose of this study is to focus on the freight transportation sector.

In 2018 the US transportation system moved about 51 million tons of goods worth $51.8 billion each day. This translates into moving more than 18.6 billion tons of goods valued at $18.9 trillion in 2018. The COVID-19 pandemic has affected the freight transportation sector. There has been an upswing in e-Commerce and home deliveries. Moreover, work from home hours has increased, translating into less commuting. Trucks transported 11.3 billion tons of the weight (60.8 percent) and $11.5 trillion of the value of all goods shipped (60.9 percent) in the United States in 2018 and continue to be the primary mode of transporting goods. Trucks carry the largest shares by value, tons, and ton-miles of all goods shipped in the United States and are the predominant mode for shipments under 1,000 miles. Rail leads in tonnage and ton-miles for goods shipped from 1,000 to 2,000 miles. Air and multiple modes accounted for 50 percent of the value of shipments moving over 2,000 miles [10].

Road freight transportation is the scope of this study. Road freight transportation is divided into mainly two types of vehicles: commercial light-duty vehicles (LDVs) and medium/heavy-duty vehicles (HDVs). In 2019, a total of 14,369,340 medium and heavy-duty trucks were registered in the US. This accounts for 5.2 percent out of all the on-road registered US vehicles. The total US fleet was 276,491,174 vehicles in 2019. Medium and heavy-duty trucks account for all trucks over 10,000 pounds gross vehicle weight rating. Gross vehicle weight rating accounts for the maximum capacity of a vehicle, including the weight of the vehicle’s base, all its components, the driver and possible passengers, and all the cargo. [11] For this study, the medium and heavy-duty vehicles are accounted together under the semi-truck vehicle type model.

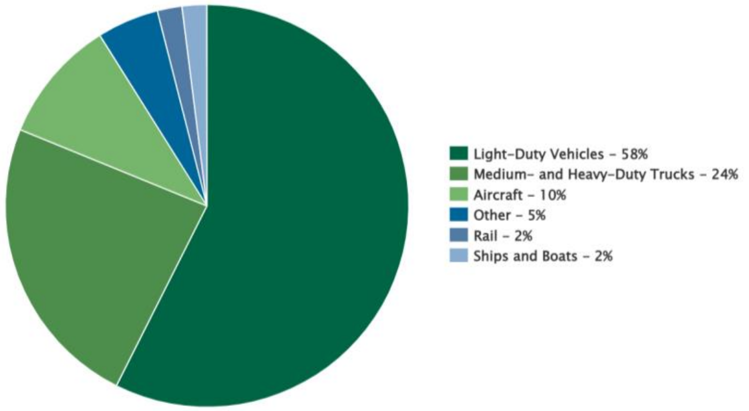
In 2019, HDVs had a total of 300,051 million vehicle-miles. The same amount of passenger-miles as well. Therefore, HDVs have one person in each vehicle, the driver. Vehicle-mile measures the total amount of travel for all considered vehicles in a geographic region (the US in this case) over a given time (2019). HDVs consumed 172.8 billion liters of fuel (such as gasoline, diesel, and other fuels, however, diesel is the predominant fuel among the freight vehicles). The combustion process of all the consumed fuel is responsible for emitting the majority of the GHGs into the atmosphere from transportation. In 2019, HDVs emitted 444.4 million metric tons of CO_2eq as direct emissions to the environment. [11]

For this study, commercial LDVs are represented by vans. In 2019, there were 15,077,377 van vehicles registered on US roads. Commercial vans account approximately for 6 percent of the total fleet of LDVs. Vans covered a total of 169,780 million vehicle-miles in 2019. Furthermore, to do so, a total of 36.5 billion liters of fuel were consumed. The combustion of all that amount of fuel accounted for 79.7 million metric tons of direct CO_2eq. In order to move and deliver all the goods around the whole US land, a total of approximately 30 million freight vehicles were used. [11]

2. GHG Emissions by Mode of Transportation

Figure 14 shows the emission percentages that every mode of transportation in the US is responsible for in the transportation sector. For the purpose of this study, the two areas of Figure 14 that apply are the light, medium, and heavy-duty vehicles. The majority of the medium and heavy-duty trucks are used for freight transportation. Moreover, as aforementioned, commercial vans accounted for 6 percent of the total fleet of LDVs. Therefore, road freight transportation accounts for approximately 30 percent of the emissions due to transportation. As aforementioned, the transportation sector is responsible for 36 percent of the total US emissions. Thus, road freight transport emits approximately 11 percent of the total US emissions.

Figure 14 2019 U.S. transportation sector GHG emissions by source [12]

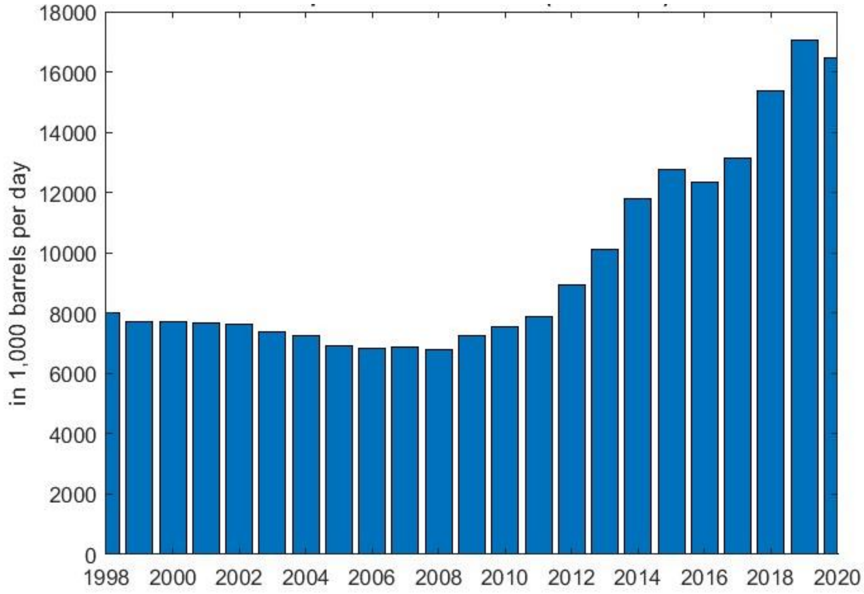


3. Fuel Production

Apart from the direct emissions due to fuel combustion, another important source of emissions is fuel production. Fuel production includes the activities for crude oil exploration, the production field operations, the crude oil transportation activities, and the refining operations to get the final fuel product, such as gasoline or diesel. In 2019, these activities emitted 2.4, 77.9, 0.2, and 5.9 million metric tons of CO_2eq, respectively, summing a total of 86.4 million metric tons for the entire fuel production process [13].

In 2019, the US produced 261,000 million gallons of crude oil. Figure 15 shows the history of oil production. One oil barrel accounts for 42 US liquid gallons.

Figure 15 Oil production in the US in barrels 1998 – 2020 [14]



4. Proposed Electric Vehicle Models

In order to estimate the emissions of electrification of the freight transportation fleet, the electric models proposed to represent or substitute the already existing fuel-powered vehicles are the following. For commercial vans, the Mercedes Benz eSprinter was chosen, whereas, for semi-trucks, it is chosen the coming new model Tesla Semi. Table 3 shows the most important specification of these electric models used later on in the environmental assessment.

Table 3 Specification of the proposed electric vehicle models

Vehicle	**COMMERCIAL VAN** **Mercedes Benz eSprinter** [15]	**SEMI-TRUCK** **Tesla Semi** [16]
Battery size (kWh)	47	600
Range (miles)	95	300
GVWR (kg)	3,500	36,287
Price ($)	67,800	150,000

CHAPTER 4: ENVIRONMENTAL ASSESSMENT

This chapter covers the following aspects. First of all, the presented data previously of every US state energy generation mix and the life cycle emissions factor for every generation technology are mixed in this chapter. By combining these two data sets, the emission factors (kg CO2 emitted per every kWh generated) for every state in the US are known. Second of all, an user-friendly tool is presented for stakeholders to know the emission factor in a specific site. Third and last of all, the emissions of an internal combustion engine vehicle (ICEV) and a battery electric vehicle (BEV) throughout all the stages in the vehicle's life are presented. Later on, this ICEV and BEV data are used to estimate the emissions of freight vehicles (i.e., for light-duty and heavy-duty vehicles).

1. Emission factor for each US state

Table 2 shows the total life cycle emissions for every electricity generation technology. Moreover, Table 1 presents how electricity is being generated in every US state. Electricity may be generated via the following sources: nuclear power, coal, natural gas (NG), petroleum, hydroelectric power, geothermal, solar photovoltaic (PV), concentrated solar power (CSP), wind power, biomass, or ocean energy. The selected technologies from Table 2 to represent each of the previous sources are (as stated in the NREL source, i.e., Table 2):

- Biopower (All Technologies)
- Photovoltaic (All Technologies)
- Concentrating solar power (Trough and Tower)
- Geothermal (All Technologies)
- Hydropower (All Technologies)
- Ocean
- Wind (All Technologies)
- Nuclear Light Water Reactor (LWR)
- Natural Gas – Conventional Gas
- Oil
- Coal (All Technologies)

The 'Nuclear Light Water Reactor' was chosen to represent the nuclear power source because currently, it is the most common nuclear reactor used. LWR includes two types of reactors: pressurized and boiling water reactors. Moreover, the term 'All Technologies' is the average between the different methods to produce energy with the corresponding source. For example, PV has two main types, thin-film, and crystalline silicon. Therefore, the median value for 'All Technologies' shown in Table 2, is the average life cycle emissions between thin-film and crystalline Si. The same explanation applies to the rest of the technologies with this same characteristic.

The emissions factor is calculated with the summation of every energy generation technology share times the energy generation emissions factor. Therefore, by combining Table 1 and Table 2, the emission factors for every state are calculated. Table 4 shows the mentioned factors.

Table 4 Emissions factor for every US State (kg CO_2eq / kWh)

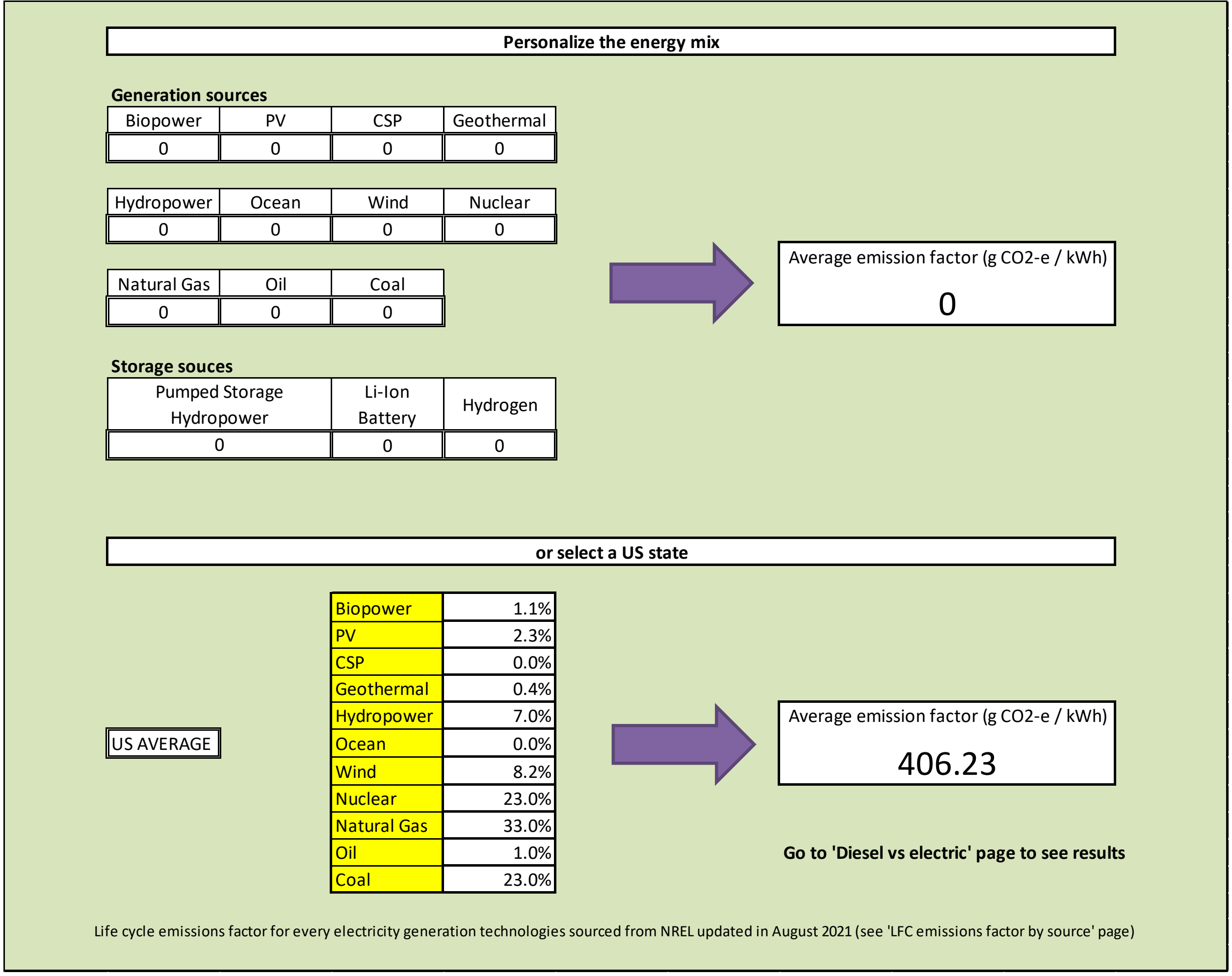
State	**Emission factor (kg CO_2eq/kWh)**	**State**	**Emission factor (kg CO_2eq/kWh)**
Alabama	0.3644	Montana	0.3964
Alaska	0.4502	Nebraska	0.5377
Arizona	0.3582	Nevada	0.3799
Arkansas	0.4532	New Hampshire	0.1287
California	0.2498	New Jersey	0.2682
Colorado	0.5298	New Mexico	0.5551
Connecticut	0.2842	New York	0.2082
Delaware	0.4864	North Carolina	0.3427
District of Columbia	0.3325	North Dakota	0.5976
Florida	0.4430	Ohio	0.5964
Georgia	0.3657	Oklahoma	0.3315
Hawaii	0.6879	Oregon	0.1795
Idaho	0.1184	Pennsylvania	0.3627
Illinois	0.2563	Rhode Island	0.4498
Indiana	0.7179	South Carolina	0.2583
Iowa	0.3054	South Dakota	0.1461
Kansas	0.3495	Tennessee	0.2926
Kentucky	0.8037	Texas	0.4270
Louisiana	0.4213	Utah	0.7443
Maine	0.1140	Vermont	0.0272
Maryland	0.2921	Virginia	0.3403
Massachusetts	0.3815	Washington	0.1216
Michigan	0.4451	West Virginia	0.9128
Minnesota	0.3552	Wisconsin	0.5658
Mississippi	0.4635	Wyoming	0.8249
Missouri	0.7623	US Average	0.4062

2. Emission factor user-tool

A practical tool was built using Microsoft Excel to let the user know the emission factor of a specific power generation mix. As aforementioned in section 1 (chapter 4), the emission factor is calculated using the share amount for each power generation technology in the specified site times the life cycle emission factor for each of those technologies presented in Table 2. Figure 16 shows a screenshot of this tool.

The tool is divided into two main parts. The first part lets the user customize the mix. In addition, it has three storage technologies as well, in case the studied area considers their implementation. By inserting the percentages of each of the technologies, the tool automatically shows the average emission factor value. For the second part, the tool shows the average emission factor for the selected US state. In the list is also included the average energy mix for the US, as it was presented in Chapter 2. These values correspond with the ones in Table 4.

Figure 16 Designed tool for automatic emission factor calculation



Personalize the energy mix

Generation sources

Biopower	PV	CSP	Geothermal
0	0	0	0

Hydropower	Ocean	Wind	Nuclear
0	0	0	0

Natural Gas	Oil	Coal
0	0	0

Storage souces

Pumped Storage Hydropower	Li-Ion Battery	Hydrogen
0	0	0

Average emission factor (g CO2-e / kWh)
0

or select a US state

US AVERAGE

Biopower	1.1%
PV	2.3%
CSP	0.0%
Geothermal	0.4%
Hydropower	7.0%
Ocean	0.0%
Wind	8.2%
Nuclear	23.0%
Natural Gas	33.0%
Oil	1.0%
Coal	23.0%

Average emission factor (g CO2-e / kWh)
406.23

Go to 'Diesel vs electric' page to see results

Life cycle emissions factor for every electricity generation technologies sourced from NREL updated in August 2021 (see 'LFC emissions factor by source' page)

3. Life cycle emissions of ICEV and BEV

For this next part, the following article has been used as the main source of data: ‘Estimation of CO2 emissions of Internal Combustion Engine Vehicle and Battery Electric Vehicle using LCA’ by Kawamoto R, Mochizuki H, Moriguchi Y, Nakano T, Motohashi M, Sakai Y, Inaba A [17].

This article presents three systems to power compact vehicles: ICE with gasoline and diesel as fuels, and with an electric battery. Nowadays, the big majority of freight vehicles are powered by diesel. Therefore, this study focuses on the diesel and the electric battery models presented. The specifications for these types of vehicles are presented in Table 5. In the Case Study chapter, the emission values for the vehicles in this paper are used to proportionally estimate the corresponding values for the freight vehicle models (i.e., the Mercedes Benz eSprinter and the Tesla Semi Truck). Table 5 includes the weight, the output power for each vehicle, and the installed battery's size. However, the paper includes more specifications such as displacement (cc), and torque (Nm), among others. Nonetheless, to estimate proportionally the life cycle emissions for the freight vehicles, only the variables presented in Table 5 are needed. In Chapter 5, it is given a more detailed explanation of the previous statement.

Table 5 Presented compact vehicles specifications [17]

Vehicle	**Diesel Engine Vehicle (DE)**	**Battery Electric Vehicle (BEV)**
Weight (kg)	1360	1590
Output (kW)	77	100
Battery capacity (kWh)	-	35.8
Lifetime (miles)	200,000	

This study considers the entire life cycle of a vehicle. The life of a vehicle is divided into 5 phases, and emissions have been calculated separately for each of those phases.

Phase 1 corresponds to the vehicle production, i.e., includes the raw material extraction, the material production, the vehicle component production, and the vehicle assembly.

Phase 2 represents the generation of the energy used to power the vehicle. In the case of the DEs, this phase is the obtainment and production of the diesel fuel (i.e., exploration, production, crude oil transportation, and crude oil refining into diesel). Whereas for BEVs, electric power is the energy for the batteries. Therefore, this phase would represent the generation of the electric power by the different sources available in the mix, as aforementioned.

Phase 3 only applies to DEs because it represents the combustion of the fuel due to vehicle usage.

Phase 4 characterizes the required maintenance of a vehicle. Thus, this phase applies to both the DEs and the BEVs. However, there are some maintenances that DE vehicles need but BEVs do not, and vice versa. The proposed maintenances are for the tires, the lead-acid battery, the engine oil, the radiator coolant, and the Li-ion battery.

Phase 5 represents the processes needed for the end-of-life (EOL) of the vehicle, i.e., the shredding and sorting, the transport, and the required landfilling, while do not takes into consideration the possible recycling of the vehicle's parts nor the waste material disposal.

3.1 Vehicle production emissions (phase 1)

As aforementioned, phase 1 accounts for the emissions of the vehicle's production. The proposed paper divides the production into four main items: (1) chassis, (2) engine and transmission for DEs, (3) electric motor and inverter for BEVs, and (4) battery for BEVs. For the scope of this study, the CO_2 emissions for the chassis parts are assumed to be proportionate to the vehicle's weight. The chassis is responsible for 76.8 percent of the overall production emissions. The other 23.2 percent correspond to the engine and transmission for DEs or, the electric motor and the inverter for BEVs. Furthermore, the emissions related to the Li-ion electric battery production have been averaged out of six different LCA sources. The averaged CO_2 emissions factor is the following:

177 kg CO_2eq / kWh [17]

Therefore, for the proposed BEV with a 35.8 kWh battery installed, the life cycle emissions for its production are 6337 kg CO_2eq (= 35.8 kWh x 177 kg CO_2eq / kWh).

Table 6 Life cycle emissions due to vehicle production [17]

Part name		Referenced data of CO_2eq emission (kg CO_2eq)	Apply to
Chassis parts		4219	DE, BEV
Diesel engine and transmission		1539	DE
Electric drive unit parts	Li-ion battery	6337	BEV
	Motor	1070	BEV
	Inverter	641	BEV

3.2 Fuel production, fuel consumption and electric power generation emissions (phases 2 and 3)

On the one hand, the emissions for fuel production and fuel consumption are all accounted for together with the same factor. The emission factor of diesel is 2.62 kg CO_2eq per liter of fuel [17]. On the other hand, to take into account the emissions for power generation, the mix used to produce the energy has to be known. At this point is where the presented tool in Section 2 (chapter 4) comes in useful.

3.3 Maintenance emissions (phase 4)

For this phase, the paper presents the emissions for the maintained parts in each maintenance process. Table 7 shows these intervals. For the scope of this study, it is important to know the lifetime driving distance for each of the freight vehicle models. The considered lifetime for the van model is 300,000 miles, whereas for the truck model is 500,000 miles. Knowing the lifetime driving distance of these freight models, it is possible to get the number of required maintenances for the presented vehicle's parts.

Table 7 Life cycle emissions due to vehicle maintenance [17]

Part name	Maintenance interval (miles/Maintenance)	CO_2eq emission (kg CO_2eq/Maintenance)	Applied vehicles
Tire	25,000	108	DE, BEV
Lead-acid battery	31,000	19.5	DE, BEV
Engine oil	6,200	3.22	DE
Radiator coolant	17,000	7.03	DE
Li-ion battery	100,000	6337	BEV

3.4 End-of-life (EOL) emissions (phase 5)

The processes included in this phase are disassembly, shredding, sorting, transport, and landfilling. However, the energy consumed in the disassembly process is considered insignificant compared to the other four processes. The presented emissions in Table 8 apply for both the DE and BEV in the same amount.

For the purpose of this study, EOL emissions are also considered proportionate to the weight of the vehicle. This statement is used later to proportionally get the emissions for a van and a semi-truck. These types of vehicles weigh much more than the ones considered in the referenced paper. That is the reason for using the previous statement.

Table 8 Life cycle emissions due to vehicle EOL [17]

Process name	**CO_2eq emission (kg CO_2eq)**	**Apply to**
Disassembly	-	DE, BEV
Shredding and sorting	24	DE, BEV
Transport	4	DE, BEV
Landfilling	38	DE, BEV
Total	65	DE, BEV

CHAPTER 5: CASE STUDY - LIFE CYCLE EMISSIONS OF FREIGHT VEHICLES

The purpose of this chapter is to calculate the life cycle GHG emissions for a van and a semi-truck. These two types of vehicles are the most common vehicles for freight delivery. To estimate the life cycle emissions of them the following assumption have been made:

- The emissions due to chassis parts production are proportionate to the vehicle's weight.
- The emissions for the diesel engine and transmission, and the electric motor and inverter, are proportionate to the vehicle's output power.
- The diesel and electric models for the van and the semi-truck models are considered to have the same weight, output power, and lifetime driving distance characteristics.
- The commercial van model proposed in this study has a lifetime of 300,000 miles.
- The semi-truck model proposed in this study has a lifetime of 500,000 miles.
- The average curb weight of the van is 2470 kg.
- The average curb weight of a class 7 semi-truck is 16,000 kg (with an empty trailer).
- The power output of the proposed van is 120 kW (161 horsepower).
- The power output of the proposed semi-truck is 373 kW (500 horsepower).
- The emissions for the EOL phase of the vehicle are proportionate to the vehicle's weight, i.e., the heavier and bigger the vehicle, the more material has to be processed to get it landfilled.
- To account for the chassis parts and EOL emissions, an 'average vehicle' is calculated between the gasoline, the diesel, and the electric models presented in the mentioned article [17]. This 'average vehicle' has a curb weight of 1420 kg and an output power of 93 kW. The reason for this assumption is that the emissions presented in these phases are equal for the three models, hence by creating the 'average vehicle' it is possible to proportionally estimate the emissions for bigger and heavier vehicles.
- The energy mix considered for this case study is the US average, i.e., 406.2 grams of CO_2eq emitted for every kWh produced, as presented in Table 413.
- As stated in the article [17], the electric battery is replaced every 100,000 miles of service.
- As aforementioned, the emissions factor for battery production is 177 kg CO_2eq/kWh.
- It is assumed that all the chassis parts, the diesel engine, the transmission, the electric motor, and the inverter, do not have to be replaced throughout the lifetime of the vehicle, thus these are not included in the maintenance phase.
- The average fuel performance of a commercial van is 4.75 miles per fuel liter.
- The average fuel performance of a class 7 semi-truck is 1.72 miles per fuel liter.

Table 9 shows the emissions for the proposed van and semi-truck through every phase of their lifetime, taking into consideration all the previous assumptions.

Table 9 Life cycle emissions for freight transport vehicles (kg CO_2eq)

Life Vehicle's Phase \ Vehicle		**Van**		**Semi-Truck**	
		Diesel	**Electric**	**Diesel**	**Electric**
Phase 1	Chassis parts	7,339		47,538	
	Diesel engine and transmission	2,398	-	7,455	-
	Li-ion battery	-	8,319	-	106,200
	Electric motor	-	1,284	-	3,991
	Inverter	-	769	-	2,391
Phases 2 and 3	Fuel production and consumption[1]	165,474	-	761,628	-
	Electric power generation[2]	-	60,293	-	406,230
Phase 4[3]	Tires	1,188		2,052	
	Lead-acid battery	175.5		312	
	Engine oil	155	-	258	-
	Radiator coolant	120	-	204	-
	Li-ion battery	-	16,638	-	424,800
Phase 5	Shredding and sorting	42		270	
	Transport	7		45	
	Landfilling	66		428	
TOTAL		176,965	96,121	820,190	994,257
Per mile		0.59	0.32	1.64	1.99

[1] Lifetime of the vehicle divided by fuel performance equal to the fuel consumption (emission factor of diesel 2.62 kg CO_2eq / liter)

[2] Lifetime of the vehicle divided by the electric range equals the number of recharges
The number of recharges times the battery size equals the energy required to be produced
These values vary depending on the selected energy mix (in this case, the US average mix emits 406.2 g of CO2eq / kWh)

[3] Lifetime of the vehicle divided by the maintenance interval from Table 433 equal to the no. of recommended maintenances

The results shown in Table 9 have been plotted in a bar graph form as shown in Figure 17 and Figure 18. These graphs help with the visualization of the differences between the DE and the BEV life cycle emissions.

(As a reminder: Phase 1 represents the vehicle production; Phase 2 represents the diesel production and electric power generation; Phase 3 corresponds to the combustion of the fuel; Phase 4 accounts for the emissions due to vehicle maintenance; and Phase 5 represents the EOL of the vehicle. The 'TOTAL' phase is the sum of all the previous phases).

Figure 17 Van life cycle emissions

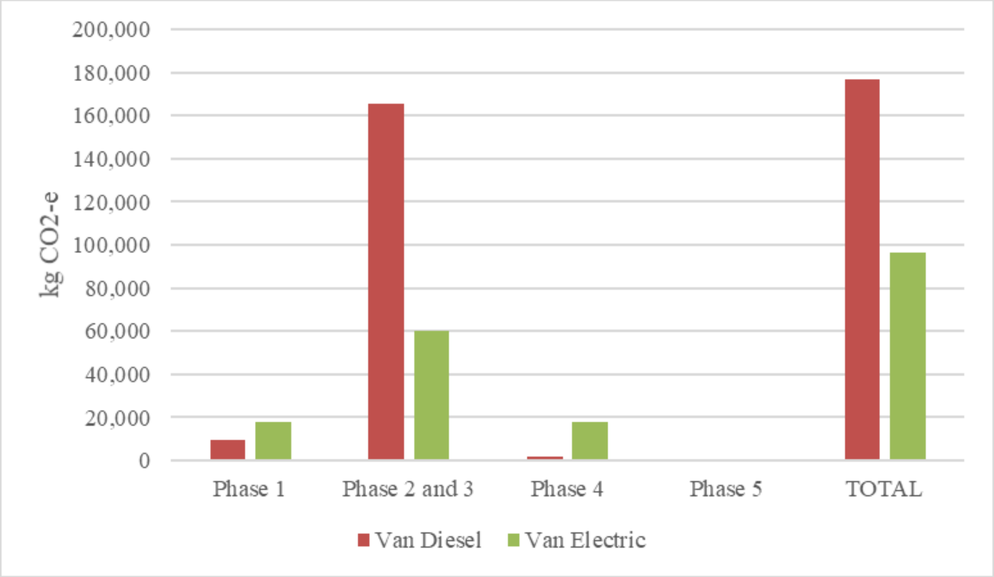
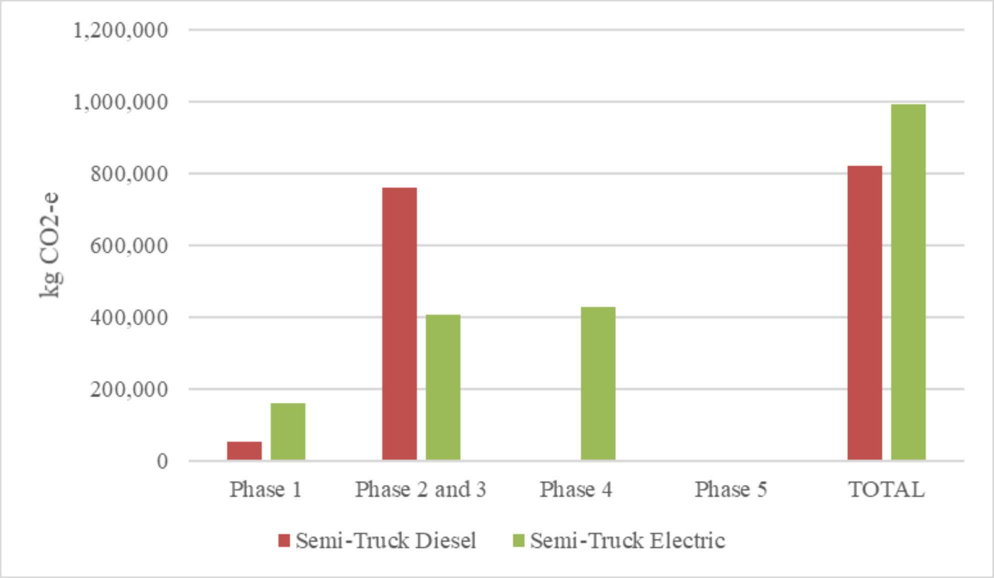


Figure 18 Semi-Truck life cycle emissions



CHAPTER 6: CONCLUSIONS

This chapter covers the conclusions of comparing the DE and BEV models for the freight vehicles using the US average energy mix. Furthermore, it covers other energy mixes to understand that a more renewable mix makes a great difference between the DE and the BEV models. Moreover, a sensitivity analysis is carried out comparing how the lifespan storage performance of an electric battery affects the vehicle's life cycle emissions. This point is discussed in more detail in section 1 of this chapter to get a better understanding of the reason to carry out this analysis. Finally, a summary of all the previous conclusions is presented.

1. Case study (chapter 5) conclusions

As aforementioned, the Case Study estimates the life cycle emissions of a diesel powered and an electric battery-powered both for a van and a semi-truck.

1.1 Commercial van life cycle emissions

For the van model the most energy-consuming phase, and thus the phase where the emissions are highest, is the power generation required throughout its lifetime.

Phase 1, the difference between the DE model and the BEV model is mostly due to the battery production.

Phases 2 and 3 are responsible for the highest impact on the overall emissions for the DE model. This is due mostly to the direct emissions in the combustion process of the ICE. Additionally, for the BEV model, these phases have also a big impact on the total emissions. As aforementioned, it is in these phases that the energy needed to recharge the battery is produced. Furthermore, the manufacturing of the chassis is also a high-consuming energy process.

Phase 4, the maintenance for DE has very low emissions. However, in the BEV model, due to the assumption of replacing the battery every 100,000 miles, two new batteries would have to be produced and installed throughout the van's lifetime. These battery replacements are assumed to be brand new models. This explains the difference between the DE and the BEV models.

In phase 5, compared to the other phases, the emissions to process and landfill the vehicle at the EOL are minimum.

The proposed BEV van model has installed a 47 kWh and a lifetime driving distance of 300,000 miles. Therefore, the energy required to be produced by the power sector and the battery replacement emissions do have not as a high impact as in the semi-truck, as it is discussed in the next section. In conclusion, due to mainly the fuel production and consumption, under the US Average energy mix, the emissions of the DE model are close to doubling the BEV model's emissions. The DE van would emit 80 tons of CO_2eq emissions more than the BEV model by the

EOL. From another point of view, the total emission factor of a DE model is 0.59 kg CO_2eq per mile traveled, whereas the BEV version does 0.32 kg CO_2eq per mile. In this situation, it is worth it to electrify the van vehicle's fleet in terms of the life cycle emissions of the vehicle.

1.2 Semi-truck life cycle emissions

As it happened for the commercial van, most of the total emissions in the DE model are due to fuel production and combustion. However, the BEV model's total emissions come mainly from the power sector's energy produced and the maintenance phase.

In phase 1, it can be seen a big difference between the DE and the BEV models due to the battery production. In this case, the semi-truck has installed a 600 kWh. Therefore, the process of manufacturing this battery is very energy-consuming, hence the emissions are high.

In phases 2 and 3, the DE model emissions almost double the BEV model emissions. Semi-trucks have a lower fuel performance than vans (i.e., semi-trucks average fuel performance is 1.72 miles per liter, compared to the commercial van doing 4.75 miles per liter), thus the amount of fuel required to power the vehicle through its lifetime is higher.

Phase 4 is the main problem in the life cycle emissions of a battery-electric semi-truck. Having 500,000 miles lifetime, the battery is recommended to be replaced 4 times (every 100,000 miles). As aforementioned, the battery installed in these BEVs has 600 kWh. Therefore, the 4 times production of these batteries is very energy consuming, and the emissions have a big impact on the total emissions. The maintenance emissions for the BEV model are 20 tons CO_2eq higher than the emissions due to power generation (phase 2).

Phase 5 emissions are minimal compared to the rest of the phases.

In conclusion, under the US Average energy mix, due to the battery production, recommended battery replacements, and a 500,000 miles lifetime driving distance (the higher lifetime, the higher the total energy needed for all the recharges throughout the vehicle's lifetime), the BEV model ends up having higher life cycle emissions than the DE model. The difference is approximately 170 tons of CO_2eq. From another point of view, the total emission factor of the DE model is 1.64 kg CO_2eq per mile traveled, whereas the BEV version emits 1.99 kg CO_2eq per mile. Therefore, in this situation, it is not worth it to electrify the semi-truck vehicle's fleet in terms of the life cycle emissions of the vehicle.

Later on, in section 3 of this chapter, a sensitivity analysis is carried out. This analysis studies the necessary improvement of the electric battery's lifespan (i.e., longer total distance traveled before energy storage performance decay, hence lower recommended replacements) in order to have a good emissions impact by electrifying the fleet.

2. Other studied cases

2.1 Illinois energy mix

The energy mix in the State of Illinois (IL) has a similar emission factor to the US Average mix. That is the reason for having a similar outcome in the emissions throughout the vehicles' lifetime, as shown in Figure 19 and Figure 20. IL produces 58 percent of its energy from Nuclear Power, 18 percent from Coal, 14 percent from Natural Gas, and 10 percent from Wind Power. Under the IL situation, the electrification of commercial vans would have a good impact on the environment (approximately 100 tons of CO_2eq less emitted to the environment). However, as it occurred under the US Average mix, semi-trucks should not be electrified yet.

Figure 19 Van life cycle emissions in IL State

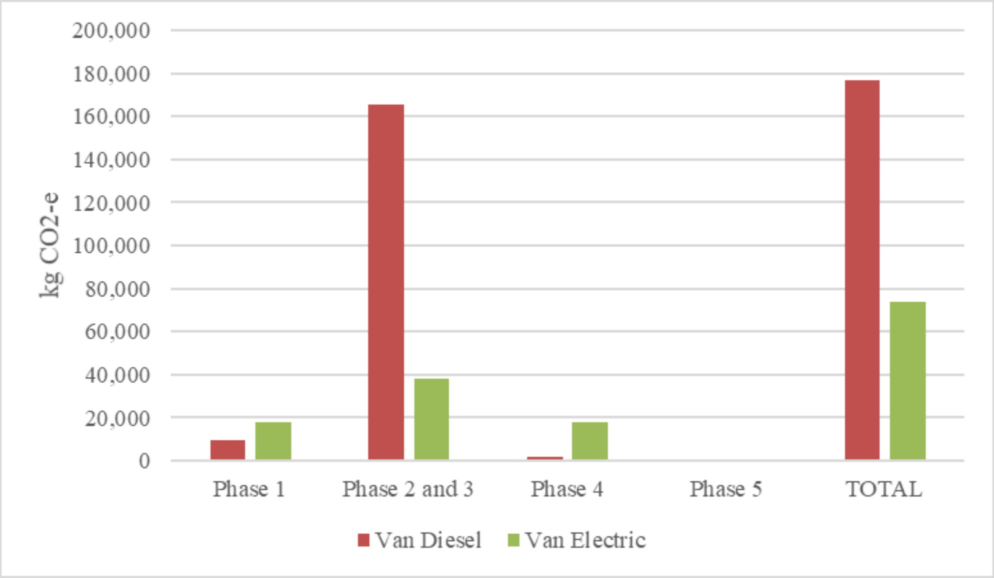
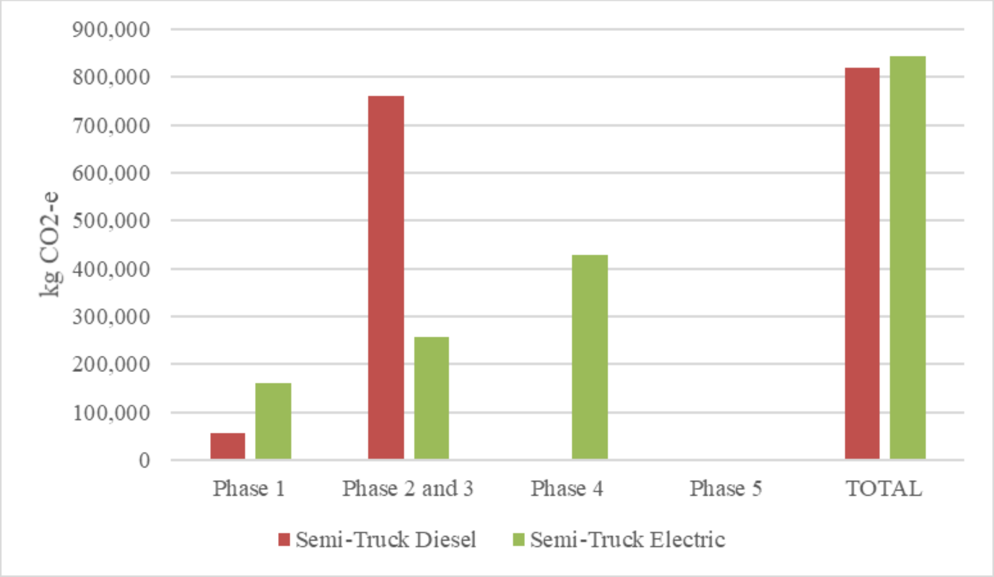


Figure 20 Semi-Truck life cycle emissions in IL State



2.2 Idaho energy mix

The State of Idaho (ID) has the lowest emission factor of all the US States, i.e., 118.4 g CO_2eq per kWh produced. As seen in Figure 21 and Figure 22, having a greener energy mix is important to lower the emissions in BEVs. ID produces 59 percent of its energy with Hydropower, 21 percent with Natural Gas, 14 percent with Wind Power, 3 percent with Solar PV, and 1 percent with Geothermal sources. Not using coal as an energy source makes a difference. Under the ID situation, both electrifications of vans and semi-trucks would have a good impact on the environment (approximately 120 tons and 110 tons of CO_2eq, respectively, less emitted than the DE models).

Figure 21 Van life cycle emissions in ID State

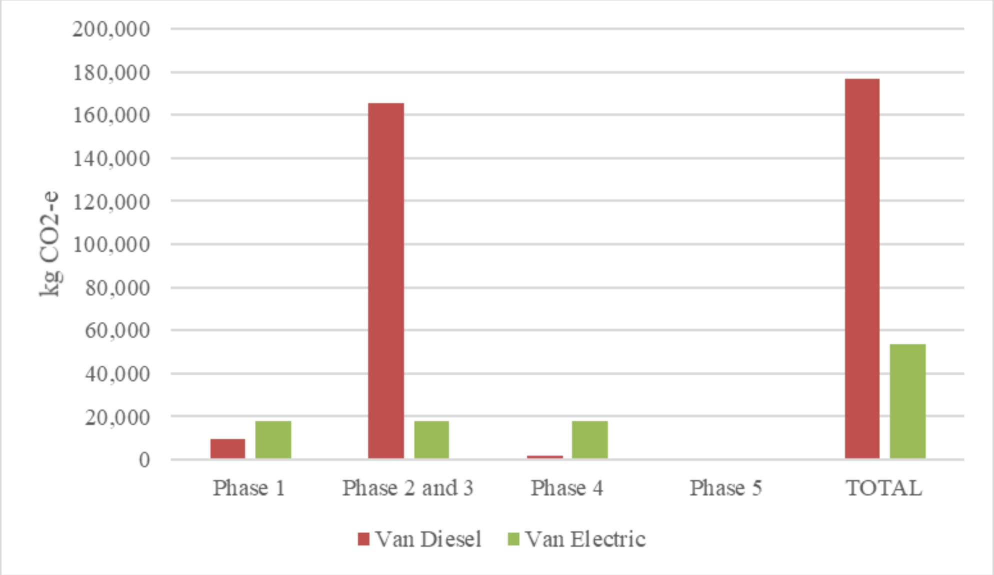
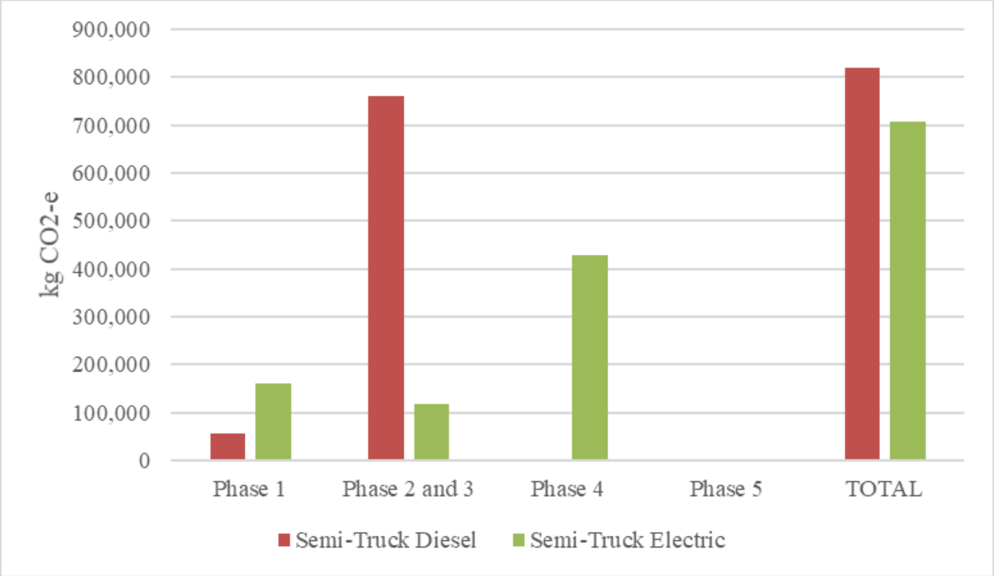


Figure 22 Semi-Truck life cycle emissions in ID State



2.3 West Virginia energy mix

On the contrary, the State of West Virginia (WV) has the highest emission factor of all the US States, i.e., 912.8 g CO_2eq per kWh produced. WV produces 88 percent of its energy with Coal, 5 percent with Natural Gas, 3 percent with Hydropower, and 3 percent with Wind Power. Having a high carbon-based energy mix has a bad outcome for semi-trucks electrification. Moreover, in Figure 24 it is possible to notice how the emissions to generate all the electric energy required for the BEV model are 150 tons higher than the fuel production and combustion for the DE model. By only considering direct emissions, it is not recommended to electrify the semi-trucks vehicle fleet. In addition, total emissions for the battery-electric van are approximately 5 tons lower than the diesel model, hence studying the life cycle costs is recommended to justify or not their electrification.

Figure 23 Van life cycle emissions in WV State

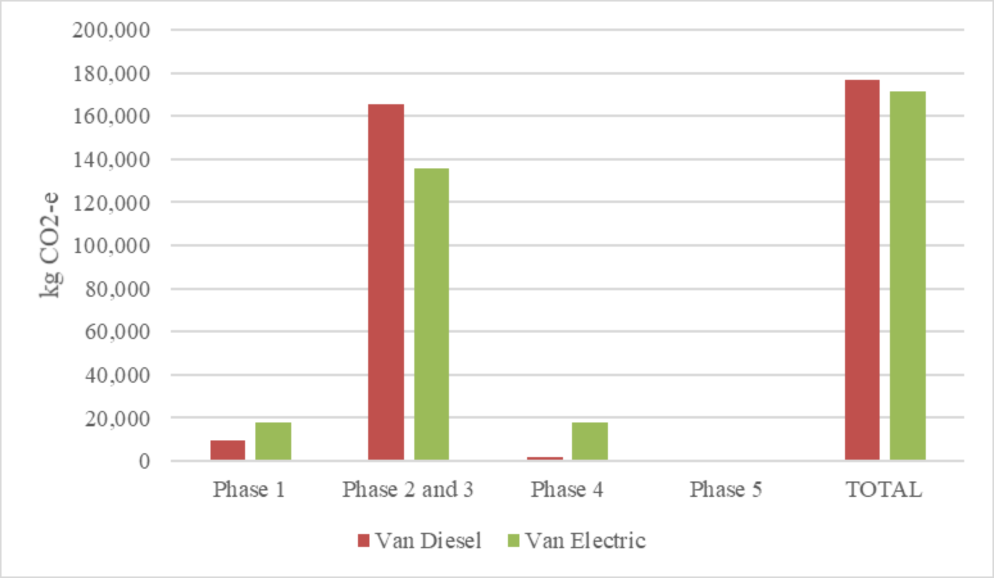
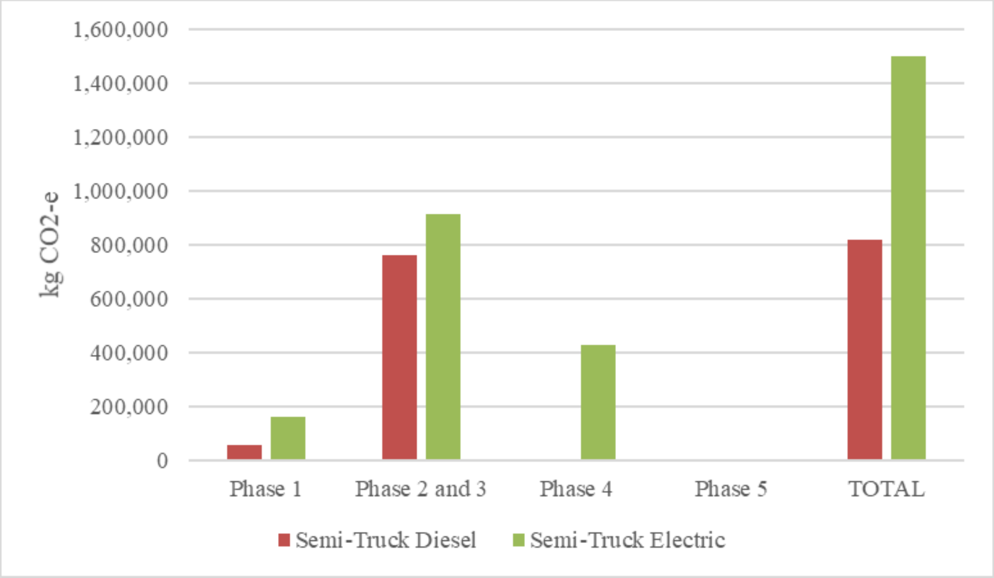


Figure 24 Semi-Truck life cycle emissions in WV State



3. Sensitivity analysis

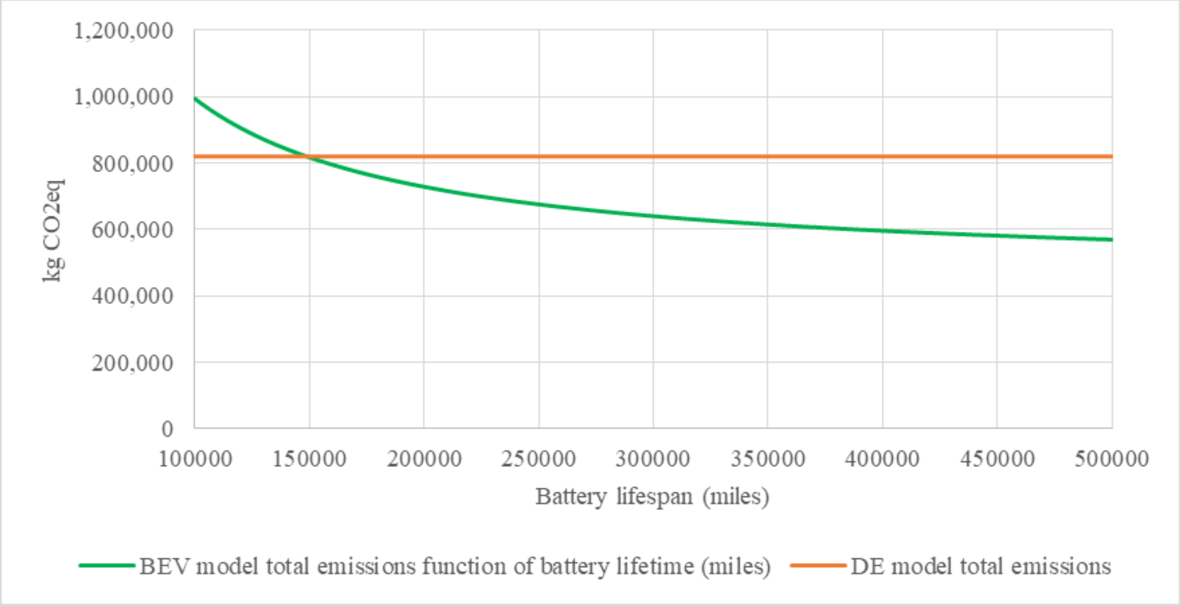
3.1 Lifespan of the electric battery

A first sensitivity analysis to understand how the lifespan of the electric battery affects the life cycle emissions was conducted. The analysis is made for the situation presented in the Case Study, i.e., under the US average energy mix. As presented in the Case Study, commercial vans would have a good impact on the environment, while semi-trucks do not. This is mainly due to the assumption of the battery replacement every 100,000 miles, as aforementioned. Therefore, the analysis is made just for the semi-truck, in which the BEV model ends up having higher emissions than the DE model.

Figure 25 shows two data sets. The DE model data set (orange line) represents its life cycle emissions. These emissions are a constant value (approx. 820 tons of CO_2eq) because none of its parameters are modified for this analysis. However, the BEV model data set (green line) has an exponential decay. The x-axis represents the number of miles that the BEV's battery can travel without having a lower storage performance. The minimum value is the proposed lifespan (i.e., 100,000 miles), while the maximum value is the lifetime of the vehicle (i.e., 500,000 miles). Therefore, the data point in the green line for a lifespan of 500,000 miles, represents the total emissions of the vehicle without any battery replacements.

In conclusion, Figure 25 shows that approximately at a lifespan of 150,000 miles (i.e., the battery should be replaced every 150,000 miles) the life cycle emissions become equal to the DE model. As the lifespan increases, the total emissions are lower, thus having a better impact on the environment than powering the vehicle with diesel.

Figure 25 Sensitivity analysis semi-truck life cycle emissions depending on the electric battery lifespan for the US Average energy mix

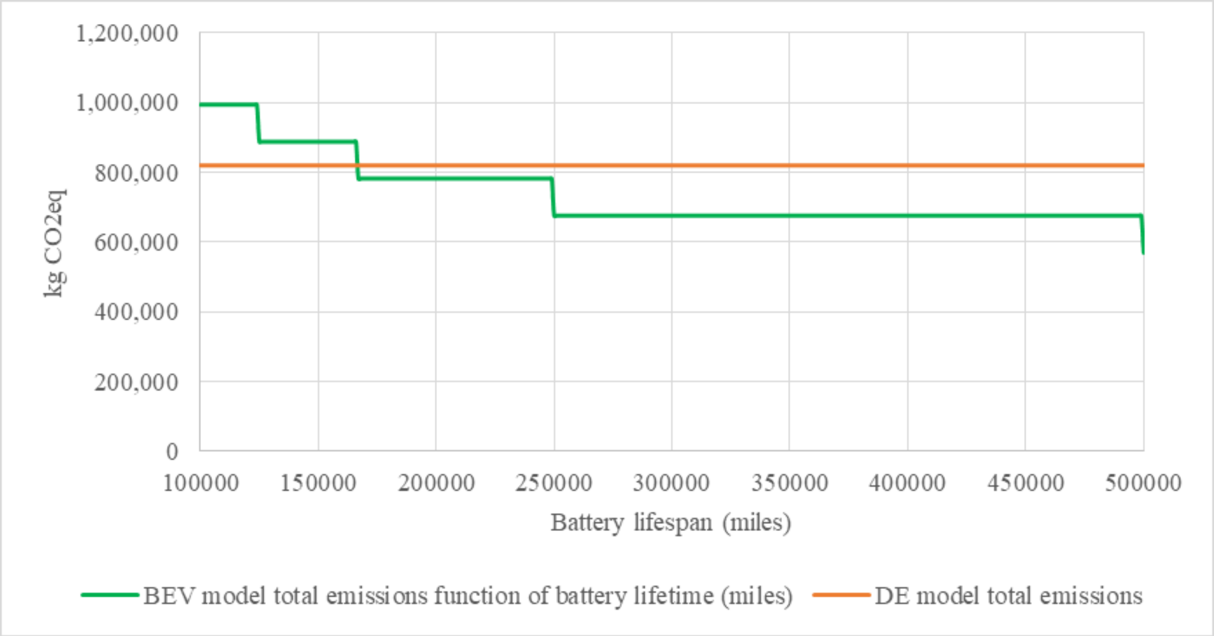


However, Figure 25 is not entirely correct. Replacing the battery every 150,000 miles means 2.33333 replacements. It is not possible to replace just one third of the battery. Therefore, the total number of replacements is 3. This statement increases the total life cycle emissions, hence with a 150,000 miles lifespan, it is not enough yet to subceed the DE model total emissions.

Figure 26 shows the corrected version of Figure 25. In Figure 26 the number of replacements has been rounded up, that is why the BEV model data set (green line) is no longer an exponential decay but a stairstep graph. The number of replacements ranges from 4 to 0 (when the battery's lifespan meets the vehicle's lifetime at 500,000 miles). Under the previous statements, the corrected lifespan that makes BEV total emissions subcedd the DE model's, is at 167,000 miles. As the lifespan is increased, the life cycle emissions will continue lowering, hence the environmental impact lowers as well. However, as long as the battery storage technology does not increase the battery charging cycles without losing performance, a diesel semi-truck has a better impact on the environment than the BEV model, under the US Average energy mix.

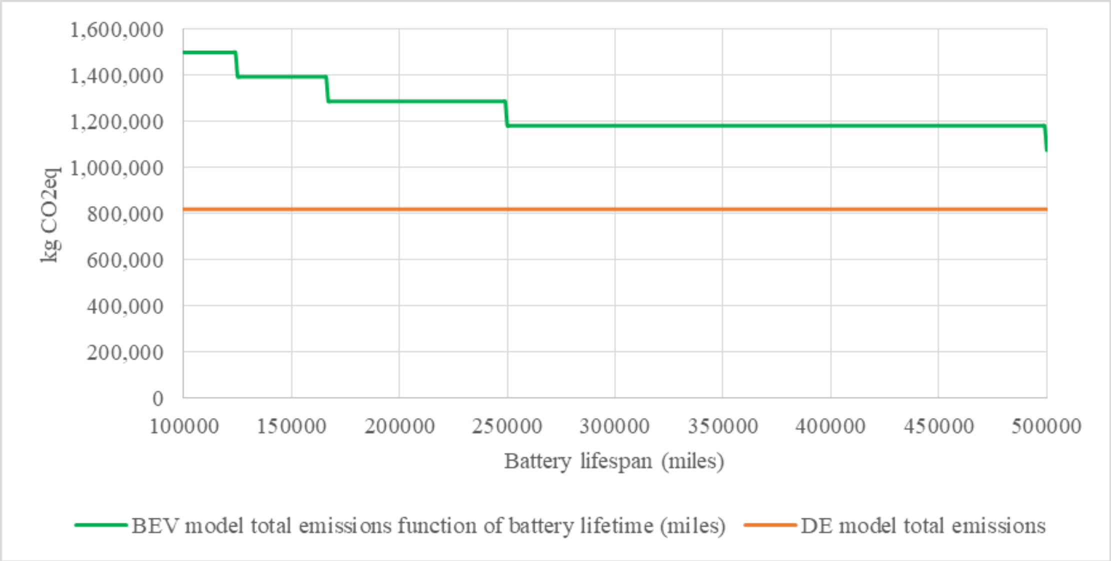
Furthermore, by making use of the presented tool in Chapter 4, it is possible to get the previous statements under a different type of energy generation mix, i.e., from a US State or a customized mix. For example, using the energy mix in West Virginia, even with a battery's lifespan equal to the semi-truck's lifetime, the life cycle emissions of the BEV model would continue to be higher than the DE model, as Figure 27 shows. As for the van, the BEV model emissions were already lower than the DE model.

Figure 26 Sensitivity analysis semi-truck life cycle emissions depending on the electric battery lifespan for the US Average energy mix (corrected version)



(Explanation of how the number of recommended battery replacements is calculated: an electric battery with a lifespan of 150,000 miles installed in a vehicle with a 500,000 miles lifetime, mathematically, means a total of 3.33333 batteries. However, the first battery installed in the vehicle has already been accounted for in the manufacturing process. Therefore, one entire unit is subtracted, leaving a total of 2.33333 recommended replacements).

Figure 27 Sensitivity analysis semi-truck life cycle emissions depending on the electric battery lifespan in WV State



3.2 Energy mix emission factor

A second sensitivity analysis was conducted to understand how the emissions factor of an energy generation mix affects the life cycle emissions. Once more, this analysis is focused on the semi-truck's life cycle emissions because the BEV commercial van already has lower emissions than the DE model, as it was shown in Figure 19, Figure 21, and Figure 23.

Figure 28 Sensitivity analysis semi-truck life cycle emissions depending on the energy mix emission factor

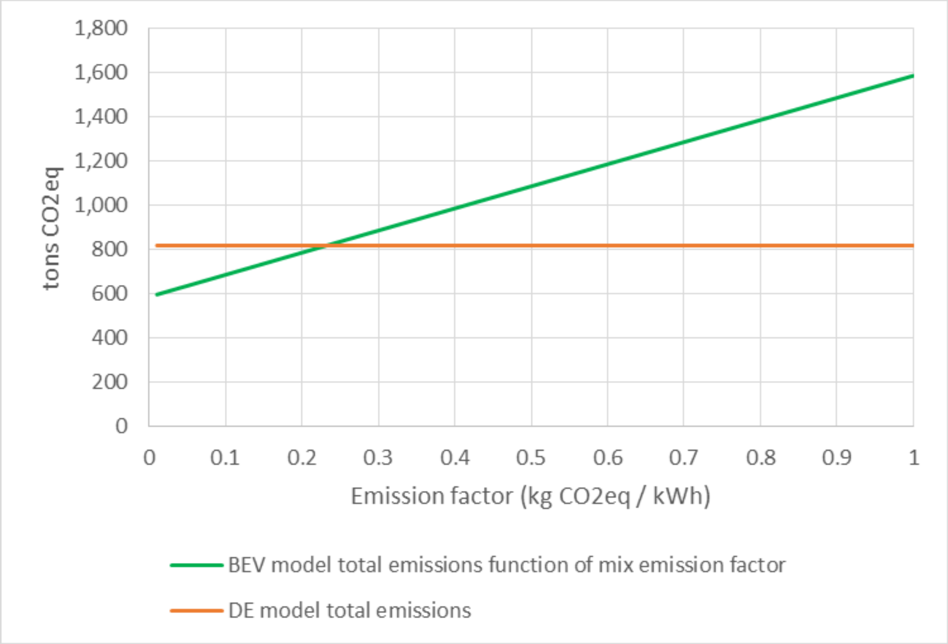


Figure 28 shows the difference in the life cycle emissions between a BEV and a DE semi-truck. The DE model data set values (orange line) are constant because varying the energy mix emission factor does not alterate these emissions. However, in Figure 28, a linear increment is seen for the BEV model. This is because as the emission factor increases, the life cycle emissions proportionally increase as well. Therefore, depending on the emission factor that the studied area has, it is recommended to electrify semi-trucks or not. For emission factors higher than 0.24 kg CO_2eq / kWh, semi-trucks would have a worse overall impact than the diesel version. Assuming the rest of the phases (i.e., manufacturing, maintenance, and EOL) in the vehicle's lifetime do not change.

For example, the US Average emissions factor, as aforementioned, is 406.23 g CO_2eq per kWh produced. This value exceeds the crossing point of the two data sets seen in Figure 28. Therefore, a BEV semi-truck would have higher emissions than a DE semi-truck, as seen in Figure 20. The electrification of their fleet would have a worse impact on the environment.

4. Summary

Commercial vans seem to be a good option to be electrified all over the US, i.e., the emissions of the BEV model are lower than the DE model for every State's energy mix emission factor. However, it has been seen that for semi-trucks, it is more complicated to conclude as fast as for vans. By carrying out the two previous sensitivity analyses, it has been concluded that the two ways to improve the semi-truck's life cycle emissions are by:

1. An improvement in the electric battery storage technology, hence lower replacements would have to be done throughout the vehicle's lifetime.
2. A greener (more renewable) energy generation mix. It has been shown that certain energy mixes around the US (such as ID State) achieve lower life cycle emissions. Nevertheless, many other States are highly dependent on fossil fuels, hence causing high CO_2eq emissions. Therefore, the supposed benefits of an electric vehicle are disrupted because the energy used to recharge their electric batteries comes from dirty sources.

FUTURE WORK

In addition to the presented environmental assessment, it is also important to carry out a cost assessment. There are some cases when the life cycle emissions of an electric vehicle are slightly better than the fuel-powered version. It would be key to know the cost of implementing those vehicles to make a final decision. Furthermore, additionally to all the phases already considered throughout the vehicle’s lifetime (i.e., vehicle manufacturing, fuel production, fuel consumption, electric power generation, vehicle maintenance, and EOL), it is important to consider the possibilities and the emissions behind the electric battery recycling process. Over and above that, alternative models could be added to the assessment to be compared to the presented DE and BEV models. The newly added model could be a vehicle powered by Hydrogen. It seems that HDVs are a big contender to use hydrogen as fuel. The less time a HDV is stopped (a HDV needs a big size electric battery to travel longer routes, but means longer periods of charging), the less money is lost by the delivery company. Therefore, hydrogen acts as diesel but is a green source with zero direct emissions. Another model could consider different materials for the manufacturing of the electric battery, such as the nickel-metal hydride battery.

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