Life Cycle Analysis of Electric Vehicles

Quantifying the Impact

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Acknowledgements

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Executive Summary

The City of Vancouver has an extensive fleet of vehicles. Due to the significant impact of transportation on total greenhouse gas emissions from a region, the City wants to reduce this impact by replacing more internal combustion engine vehicles (ICEVs) in its fleet with electric vehicles (EVs). This study uses life cycle analysis (LCA) to comparatively analyze two vehicle models of similar size of each type (ICEV and EV) currently used in the City's fleet. Ford Focus is chosen for the ICEV and Mitsubishi i-MiEV for the EV, both with a vehicle life of 150,000km. Carbon emissions and energy consumption are analyzed for each phase from cradle-to-grave for both vehicles: raw material production, vehicle manufacture, transportation, operation, and decommissioning. The analysis shows that the electric vehicle has notably lower carbon emissions and lower energy consumption per kilometer. After considering all phases, the Ford Focus emits 392.4gCO$_2$-eq/km and Mitsubishi i-MiEV emits 203.0gCO$_2$-eq/km over the vehicle life. Corresponding energy consumption is 4.2MJ/km for Ford Focus and 2.0MJ/km for Mitsubishi i-MiEV. Sensitivity analysis with a vehicle life of 100,000km and 250,000km is also conducted, with the longer vehicle life further shifting the efficiency balance toward the electric vehicle.

Introduction

Electric powertrains are a promising technology for the propulsion of vehicles with potential to improve air quality and reduce greenhouse gas emissions associated with road transport. Electric powertrains are more efficient than internal combustion engine vehicles (ICEVs) and have zero tailpipe emissions (Sadek, 2012). In addition, the technology can help to mitigate the transport sector's heavy reliance on fossil fuels.

On the flipside, large scale adoption of electric vehicles (EVs) may require additional electricity generation. Electric powertrains also require advanced components with a more diverse resource requirement that may have different environmental impacts to those of a conventional vehicle (Nordelöf & Messagie, 2014).

This study employs the cradle-to-grave approach of life cycle analysis to assess environmental impacts for similar sized gasoline and electric vehicles in the City of Vancouver fleet that have been in service for at least 5 years.

Why Life Cycle Analysis?

Life cycle analysis (LCA) can be utilized to analyze the advantages and disadvantages of a technology (ISO, 2006). In this study, this is done by assessing the environmental impacts, specifically energy use and CO_2-equivalent emissions, during each stage of the vehicle's life.

When a new vehicle is acquired, there are already significant inflows and outflows associated with it. The inflows to a system can include water use, natural resources and energy input, while the outflows can include emissions and waste products. While average mileage or tailpipe emissions allow us to compare the efficiency of different vehicles, it provides an incomplete picture as this is only comparing flows associated with operation of the vehicle; none of the flows associated with stages prior to vehicle operation have been considered.

This data is relevant to decision makers within the City of Vancouver and could be used for strategic planning within the Equipment Services division of the City for potential future electrification of vehicle fleets.

Goal

The goal of this study is to analyze environmental impacts, specifically energy use and CO_2-equivalent emissions, and quantify data based on a functional unit for two vehicle types of similar size: Ford Focus and Mitsubishi i-MiEV. This data is collected for the resource extraction, manufacturing, transportation, operation, and decommissioning stages of the vehicle. Options are also presented for future use of retired vehicle components such as the lithium-ion battery.

Scope

The scope of this study is to analyze 13 Ford Focus internal combustion engine vehicles put in service in 2006 or later and 27 Mitsubishi i-MiEV electric vehicles put in service in 2012 or later in the City of Vancouver fleet. These vehicles are comparatively analyzed due to their similar size. This analysis encompasses the equipment life cycle of the vehicles and is focused on scope 1 emissions, as shown in Figure 1. The well-to-wheels lifecycle of energy production (scopes 2 and 3) falls outside of the scope of this study and is considered under the BC Low Carbon Fuel Standard.
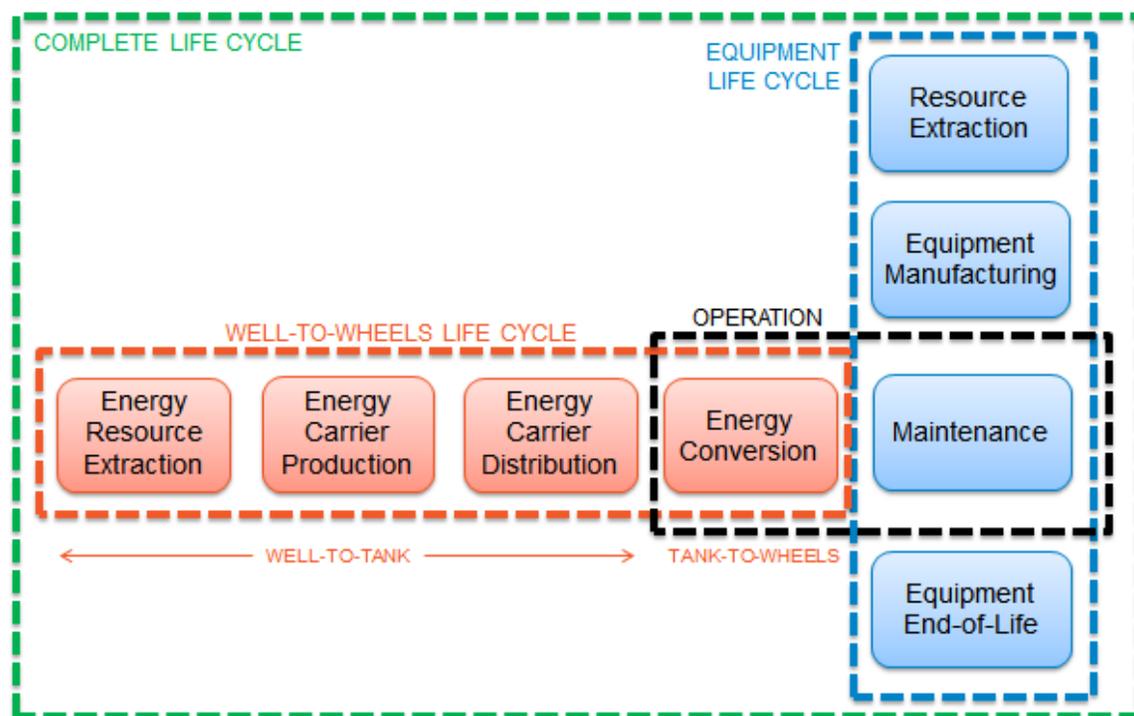

Figure 1 – System boundaries for a complete life cycle analysis of vehicles. This study focuses on the equipment life cycle and does not analyze the well-to-wheels life cycle. (Nordelöf & Messagie, 2014)

Methodology

A functional unit of one kilometer (1 km) travelled by a vehicle is used throughout the study. This functional unit is then adapted for the different analyses – energy consumption is presented as MJ/km and emissions as gCO_2-eq/km, assuming an average vehicle life of 150,000km for both vehicles. Data is gathered for inflows and outflows at each stage. The processes are linked from cradle-to-grave and an inventory is taken for the flows to show how they connect and affect each other. Finally, sensitivity analysis is completed for cases where vehicle lifetime is 100,000km and 250,000km.

Data Sourcing

Data for raw materials used in both electric and gasoline vehicles was obtained from Weiss et al. (2000), a study that breaks down total materials by element for both vehicle types. While the dataset is based on predictions made in the early 2000's, it is a robust study that is still relevant today. (Weiss & Heywood, 2000)

Data for vehicle manufacture was estimated as a linear function of material mass due to the highly complex supply chain in the automobile industry. The Ford Focus is assumed to be assembled in Wayne, Michigan and is transported by a combination of rail and truck with a gross vehicle weight of 1355kg (Ford Motor Company, 2018). The Mitsubishi i-MiEV is assumed to be assembled in Kurashiki, Japan and is transported by sea with a gross vehicle weight of 1450kg (Mitsubishi Motors, 2018).

Operational data for fuel consumption and maintenance is sourced from the City of Vancouver databases for gasoline vehicles. Electric vehicle charging stations are manufactured by ChargePoint and access to their online dashboard provides data on electricity consumed for EVs operated by the City.

Finally, the end of life procedures assume that a vehicle is dismantled and all parts except for the lithium-ion batteries are shredded. Options for future use of the lithium-ion batteries are presented later in the report.

Life Cycle Inventory

Energy requirements and emissions from vehicle material production are presented in the following sections. Figures 2 and 3 show the mass distribution by material for both ICEV and EV. Ferrous metals (mainly high-strength steel) are a large percentage of material used in ICEVs while both steel and aluminum are significant components of an EV.

Internal combustion engine vehicle mass distribution by material (kilograms)

Legend:
- Ferrous Metals
- Aluminum
- Nickel
- Others
- Plastics
- Wood, Felt, etc.
- Rubber
- Glass
- Magnesium
- Copper
- Paint, coatings
- Zinc
- Lead
- Fluids

Main pie values: 886, 81, 0, 9, 100, 64, 54, 35, 10, 85
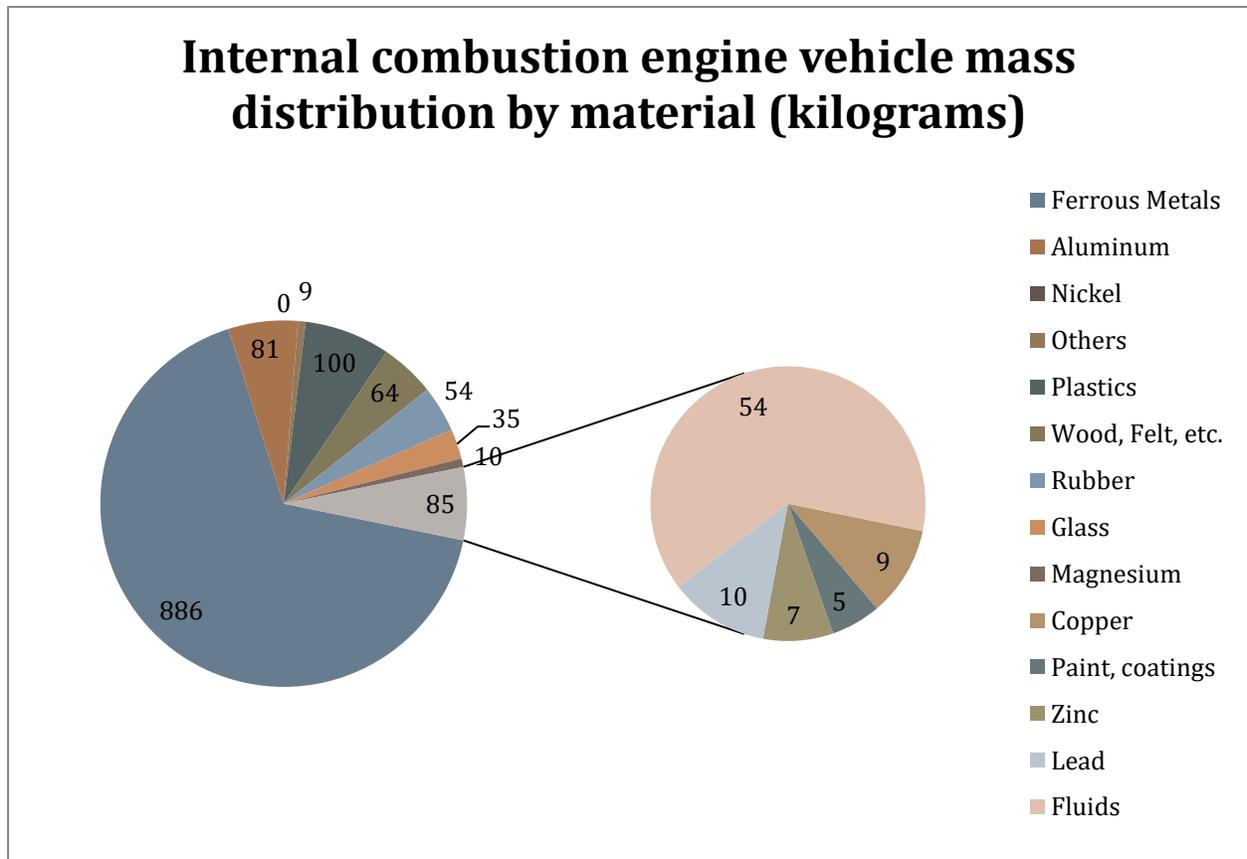Secondary pie values: 54, 9, 5, 7, 10

Figure 2 – Mass distribution of an internal combustion engine vehicle. Various alloys of steel account for two thirds (67%) of vehicle mass, with aluminum and plastics having the largest mass for non-steel materials (Weiss & Heywood, 2000).
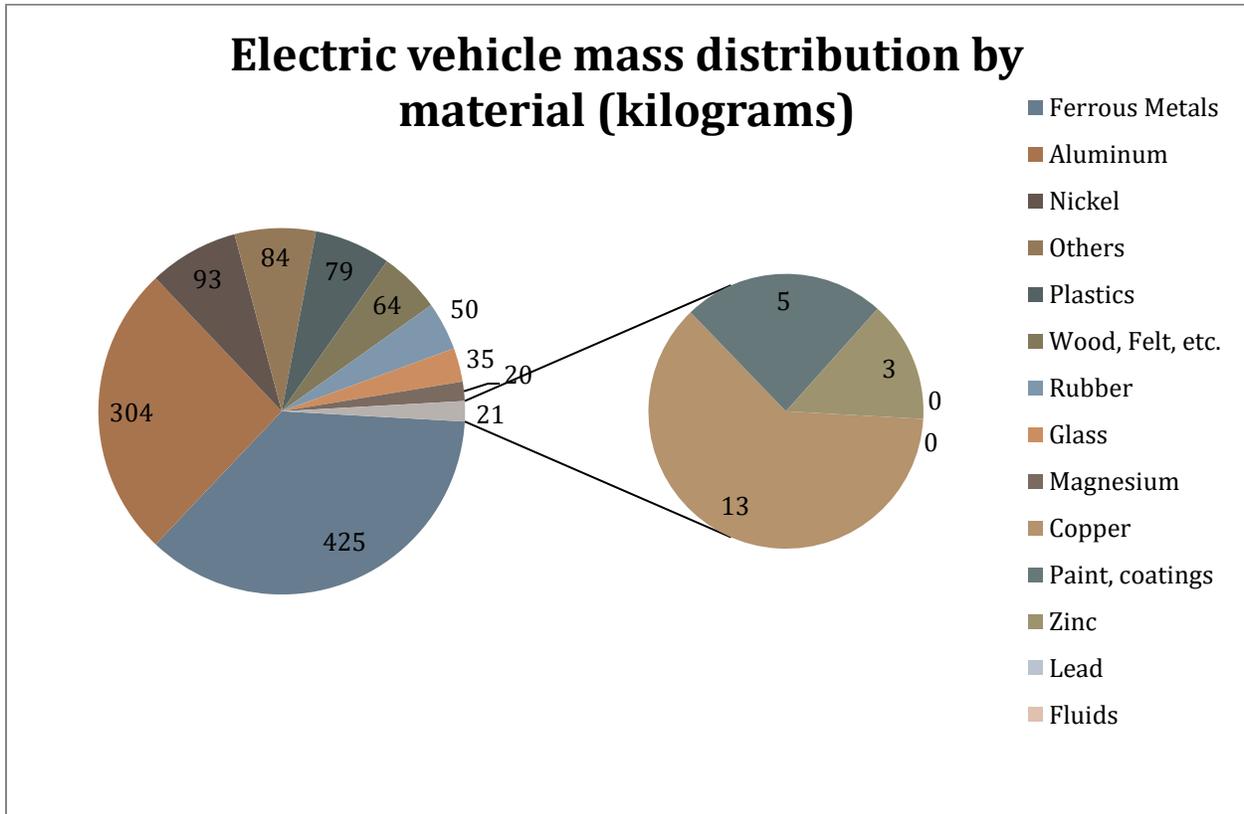
Figure 3 – The predicted mass distribution of an electric vehicle in 2020 shows a different picture, with aluminum and nickel having a much more significant role. Ferrous metals (mainly high-strength steel) are still the dominant material. **(Weiss & Heywood, 2000)**

Raw Material Production

The production to convert raw material to a virgin input for manufacturing is analyzed based on data from Sullivan et al. (2010) and is summarized in Figure 4. This energy intensity data was then applied to the data shown in Figure 2 and Figure 3. This gave total energy consumed in material production as 73.2GJ for the Ford Focus and 139.2GJ for the Mitsubishi i-MiEV, or **0.49MJ/km and 0.93MJ/km respectively**.[1]

Carbon intensity of this stage was calculated from emission factors at the respective manufacturing locations. The emission factor for the electricity grid in the United States is

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[1] These values, and all other values in this section that are given per km, are calculated assuming an average vehicle life of 150,000km.

744gCO$_2$-eq /kWh (EPAa, 2016) and that of Japan is 635gCO$_2$-eq/kWh (IEA, 2017). 73.2GJ of energy equates to 20.3MWh; thus, the Ford Focus emits 15.1tonsCO2-eq due to material production, which translates to 101gCO$_2$-eq /km from this segment. A similar calculation for Mitshubishi i-MiEV using Japanese grid intensity yields emissions of 164gCO$_2$-eq/km due to material production.[2]
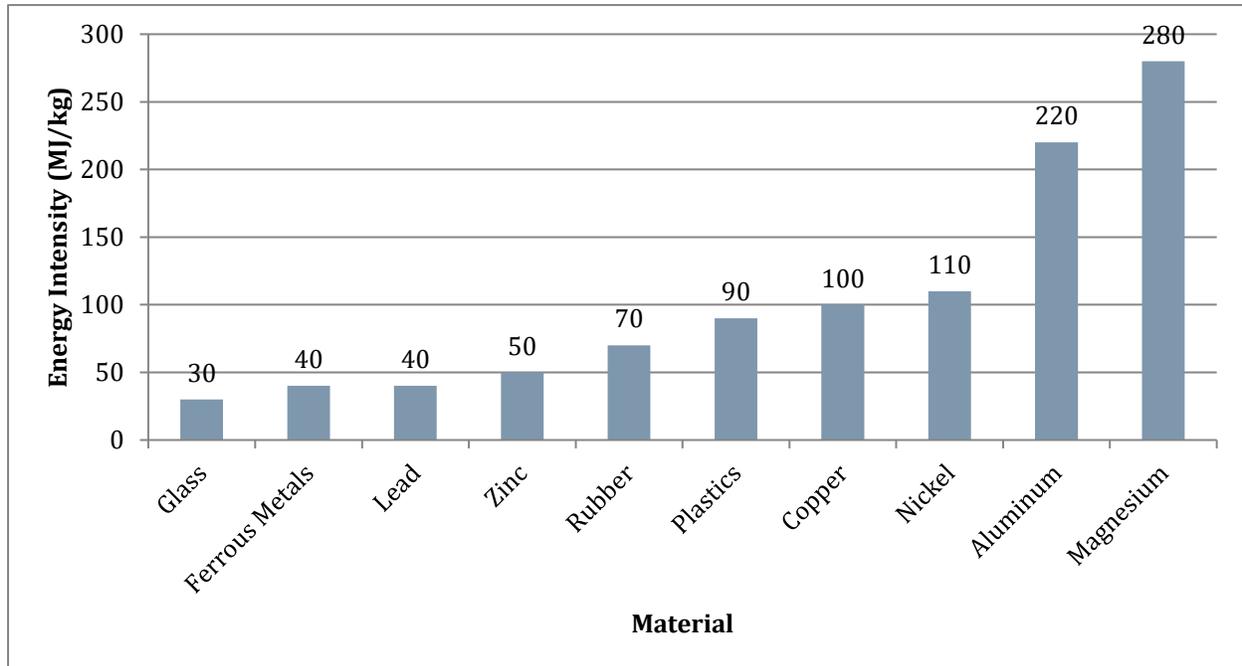

Figure 4 – Graph showing energy required per unit mass to convert various raw materials to usable virgin feedstock for a manufacturing process **(Sullivan & Burnham, 2010)**.

Manufacturing

The typical range of energy consumption for compact car manufacture is 17-22MJ/kg (Weiss & Heywood, 2000). Taking an average value of 20MJ/kg, the manufacturing process requires 27.1GJ for the Ford Focus and 29GJ for the Mitsubishi i-MiEV, or **0.18MJ/km and 0.19MJ/km respectively**.

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[2] While these calculations assume only electricity use at the production sites, actual energy use will likely be a mix of both electricity and oil-based products. However, to simplify the analysis and still yield meaningful data, the above calculation is an appropriate approximation.

Again, using emissions factors of 744gCO_2-eq /kWh for US and 635gCO_2-eq /kWh for Japan, this translates to 37gCO_2-eq/km for the Ford Focus and 34gCO_2-eq/km for Mitsubishi i-MiEV due to the manufacturing process.[3]

Transportation

Transportation of the vehicles was analyzed from the vehicle assembly plant to the point of use. The Ford Focus is assumed to be assembled in Wayne, Michigan, 3953km from Vancouver, BC. This route is serviced by a combination of rail and truck, and a 50-50 split is assumed for calculation purposes.

The energy intensity of rail transport is estimated at 0.5MJ/ton-km (Railway Association of Canada, 2014) while that for trucking is approximately 1.5MJ/ton-km (NRCAN, 2016). As such, an average energy intensity of 1MJ/ton-km is used, giving energy consumed as 5.3GJ to transport the Ford Focus the required distance. Amortizing this value over a 150,000km vehicle life gives **0.04MJ/km**. Using the same datasets from (Railway Association of Canada, 2014) and (Natural Resources Canada, 2016), the emission factors for transportation were calculated as 15.2gCO_2-eq/ton-km for rail and 63.8gCO_2-eq/ton-km for truck, which translates to an average value of 39.5gCO_2-eq/ton-km with a 50-50 split. Given the distance travelled and weight of the vehicle, this translates to **1.4gCO_2-eq/km** for the Ford Focus.

The Mitsubishi i-MiEV is assumed to be assembled in Kurashiki, Japan, 8005km from Vancouver, BC. This route is assumed to be covered entirely by sea, with negligible amounts of trucking. Energy intensity of sea transportation is approximately 0.8MJ/ton-km (European Energy Agency, 2016), giving energy consumed as 9.3GJ to transport the Mitsubishi i-MiEV the required distance. Amortizing this value over a 150,000km vehicle life gives **0.06MJ/km**. Using the same dataset from European Energy Agency, 2016, an emission factor of 34gCO_2-eq/ton-km was developed for marine freight transportation. Given the distance travelled and weight of the vehicle, this translates to **2.6gCO_2-eq/km** for the Mitsubishi i-MiEV.

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[3] See footnote 2 about energy use mix and oil-based products, which applies to these calculations as well.

Operation

City of Vancouver databases were used to determine an average fuel efficiency of 10.9litres/100km for the ICEV in service. Given an energy density of 44.4MJ/kg and a product density of 0.71kg/litre for gasoline (USDOE, 2000), this gives an energy consumption of **3.44MJ/km** for the Ford Focus. The fuel efficiency translates to **253gCO$_2$-eq/km** (EPAb, 2017).

Data from ChargePoint's infrastructure was used to determine an average energy efficiency of 0.21kWh/km for the Mitsubishi i-MiEV vehicles in service, equivalent to **0.76MJ/km**. Given an emission factor of 10.7tonCO$_2$-eq/GWh (BCHydro, 2015) for electricity generated in BC, the average energy efficiency translates to **2.2gCO$_2$-eq/km** in carbon emissions.

Decommissioning

To decommission the vehicles, the ICEV and EV use similar processes of dismantling and shredding. All components of both vehicles are assumed to be disposed, except for the EV lithium-ion battery pack which is assumed to be recycled in this analysis. It is assumed the vehicles are transported by heavy truck to a shredding facility, many of which exist in the Lower Mainland with an average round-trip distance of 40km. As such, the energy required to transport the vehicle to the shredder is 1.5MJ/ton-km * 40km = 0.06MJ/kg. Average energy to operate the shredder is 0.37MJ/kg (Bakker, 2010), and as such the total energy to shred the vehicles is 0.43MJ/kg. Ford Focus shredding: 1355kg * 0.43MJ/kg = 583MJ, or **0.004MJ/km**. Using electricity in BC, this translates to **0.012gCO$_2$-eq/km** in carbon emissions.

Data from Ishihara et al. shows lithium-ion batteries require 469MJ/kWh to recycle (Ishihara & Kihira, 2002). Given a 16kWh battery (Mitsubishi Motors, 2018), this translates to 7.5GJ. The non-battery components of the Mitsubishi i-MiEV will require 1150kg * 0.43MJ/kg = 495MJ to be shredded. This gives a total energy consumption of 8.0GJ, or **0.053MJ/km**. Again, assuming the shredding and recycling takes place in BC, this translates to **0.2gCO$_2$-eq/km** in carbon emissions.
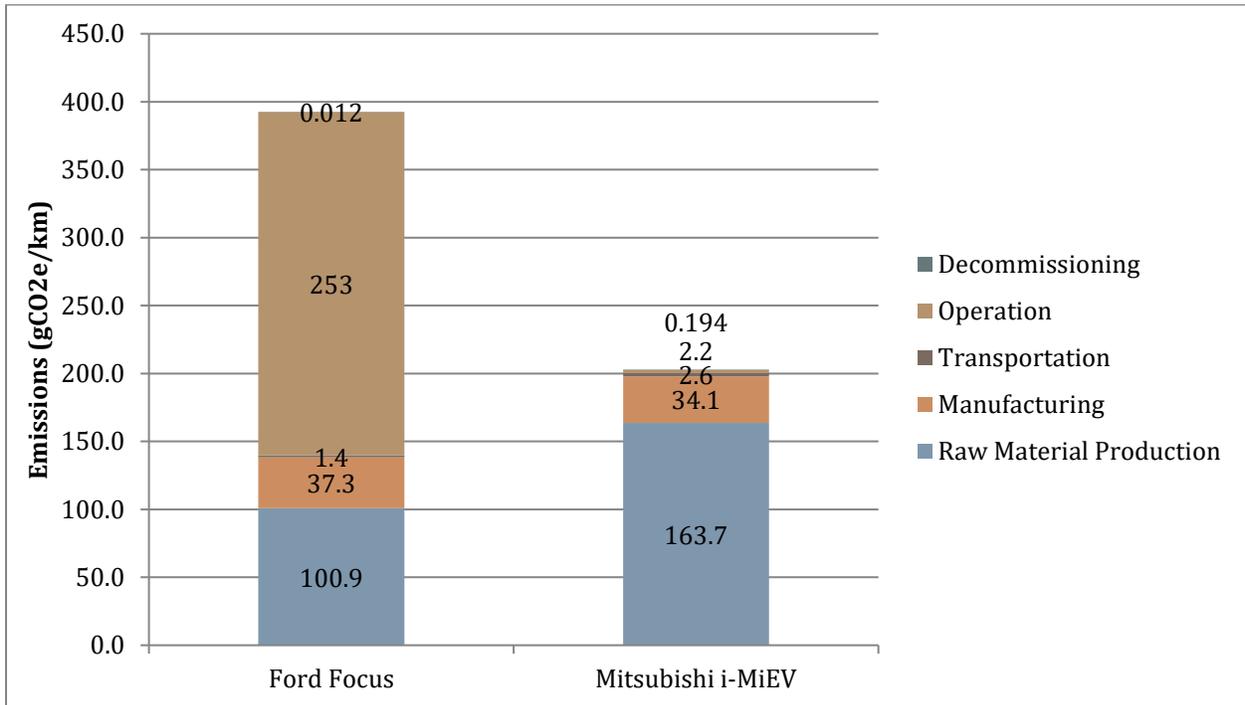
Summary

Figure 5 – Graph comparing CO_2-equivalent emissions with a vehicle life of 150,000km.

Total effective emissions shown in Figure 5 for the Ford Focus were 392.4gCO$_2$-eq/km, while those for the Mitsubishi i-MiEV were 48% lower and nearly half this value, at 203.0gCO$_2$-eq/km. Emissions due to operation represented 65% of the total for the Focus, and just 1.3% for the i-MiEV, highlighting the significant advantage EVs have in operational efficiency over ICEVs, especially in regions with predominantly clean power sources, such as British Columbia.

Also notable is the 62% higher emissions due to raw material production in an EV, which can be attributed to the complex supply chain of components and significant use of uncommon metals such as nickel and other metals in the lithium-ion battery. The remaining stages of manufacturing, vehicle transportation and decommissioning did not represent a significant part of total emissions.
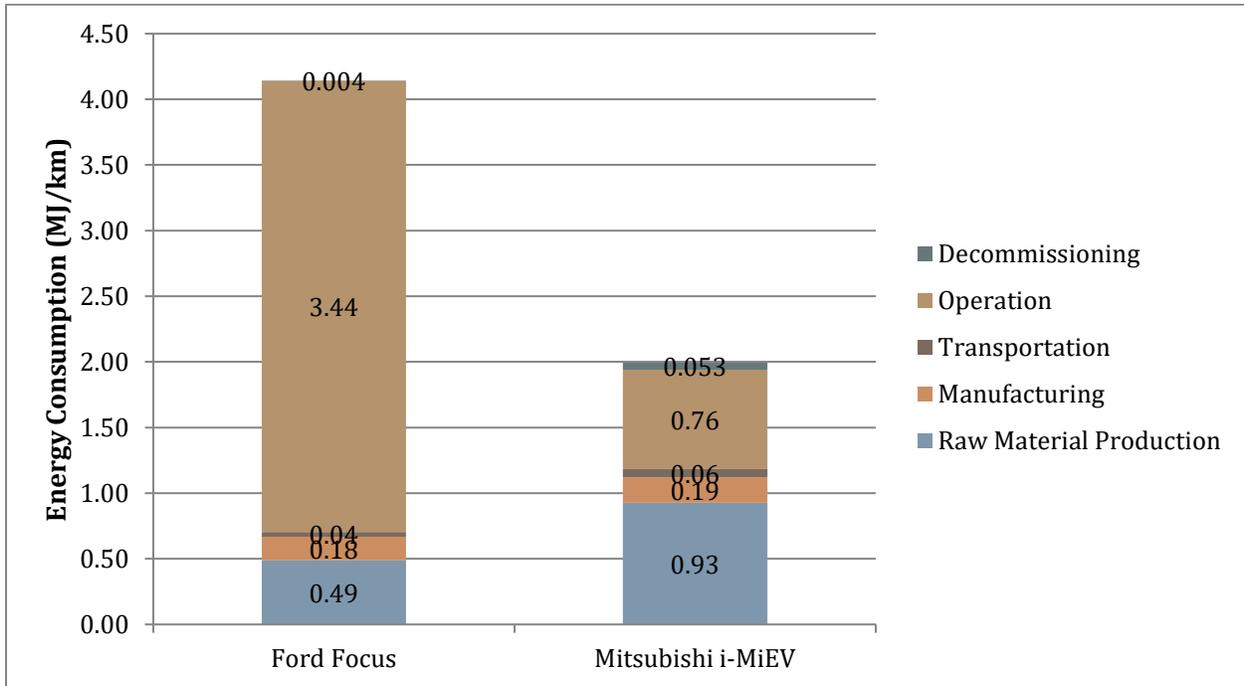
Figure 6 – Graph comparing energy consumption with a vehicle life of 150,000km.

The total values for energy consumption in Figure 6 followed a similar pattern to carbon emissions, with total energy consumption per kilometer for the Ford Focus being 4.2MJ/km, more than double that for the Mitsubishi i-MiEV, which came in at 2MJ/km, 52% lower.

The most significant energy consumption for the Ford Focus was in the operation stage, while that for Mitsubishi i-MiEV having a much smaller amount. Again, the raw material production energy use had a higher value for the i-MiEV than the Focus, possibly explained by similar reasons as discussed in the carbon emissions section. Other phases of the life cycle did not contribute significantly in either of the two categories.

Comparison of Results with Similar Analysis

Poovanna et al. (2018) performed a similar analysis of an ICEV vs. EV in British Columbia with a product life of 150,000km. Lifetime emissions calculated were 38.4tonsCO$_2$-eq for the ICEV and 12.2tonsCO$_2$-eq for the EV. Energy consumed was 480.8GJ for the ICEV and 228.8GJ for the EV.

In this analysis, the corresponding lifetime emissions are 58.9tonsCO$_2$-eq for the ICEV and 30.5tonsCO$_2$-eq for the EV. Lifetime energy consumed was 630GJ for the ICEV and 300GJ for the EV.

These discrepancies for carbon emissions and energy consumed could be attributed to the methodology of both reports. The most significant difference was noted in the production segments of the LCA, where (Poovanna & Davis, 2018) consider manufacturing while this analysis accounts for both raw material production and manufacturing.

Sensitivity Analysis

The calculations were repeated using a vehicle life of 100,00km and 250,000km for both cases to illustrate the effect of a vehicle life on the final numbers.
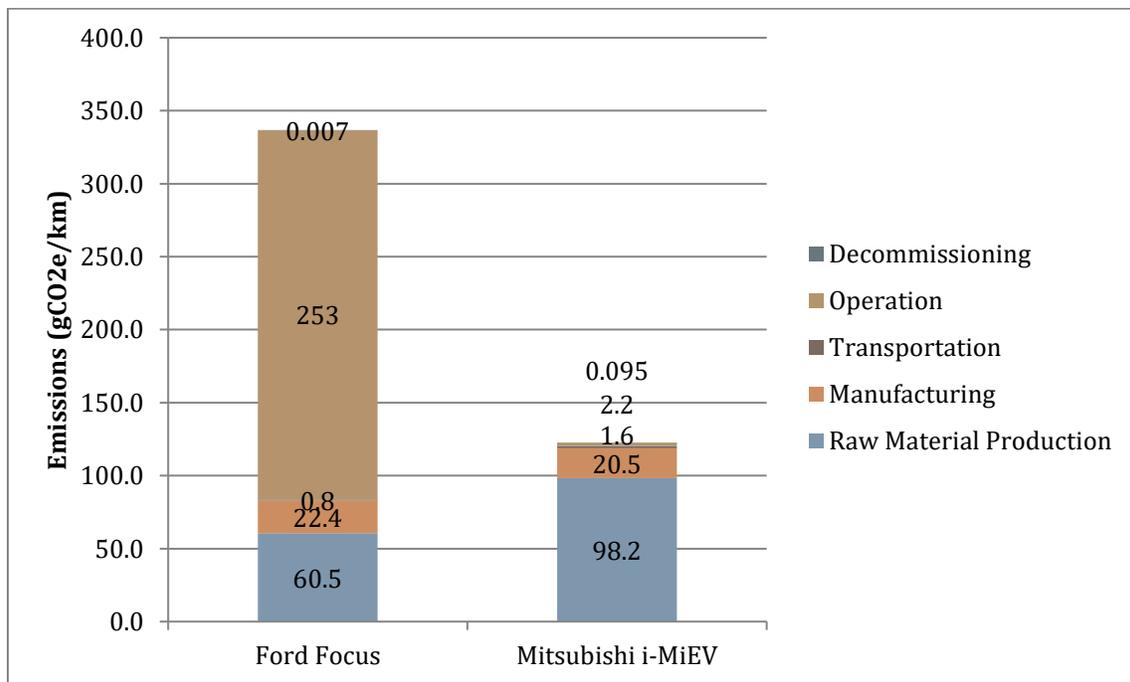

Figure 7 – Graph comparing CO$_2$-equivalent emissions with a vehicle life of 250,000km.

With vehicle life of 250,000km, the Ford Focus now has emissions of 336.7gCO$_2$-eq/km and the Mitsubishi i-MiEV at 122.6gCO$_2$-eq/km, meaning the EV had 64% lower carbon emissions. As expected, the numbers for the operation stage were unchanged compared to the previous analysis. This is because the operational emissions do not depend on the vehicle lifetime and are

a function of the powertrain efficiency. The other stages all have lower emissions per km due to having a fixed amount of emissions that are now amortized over a longer vehicle life.
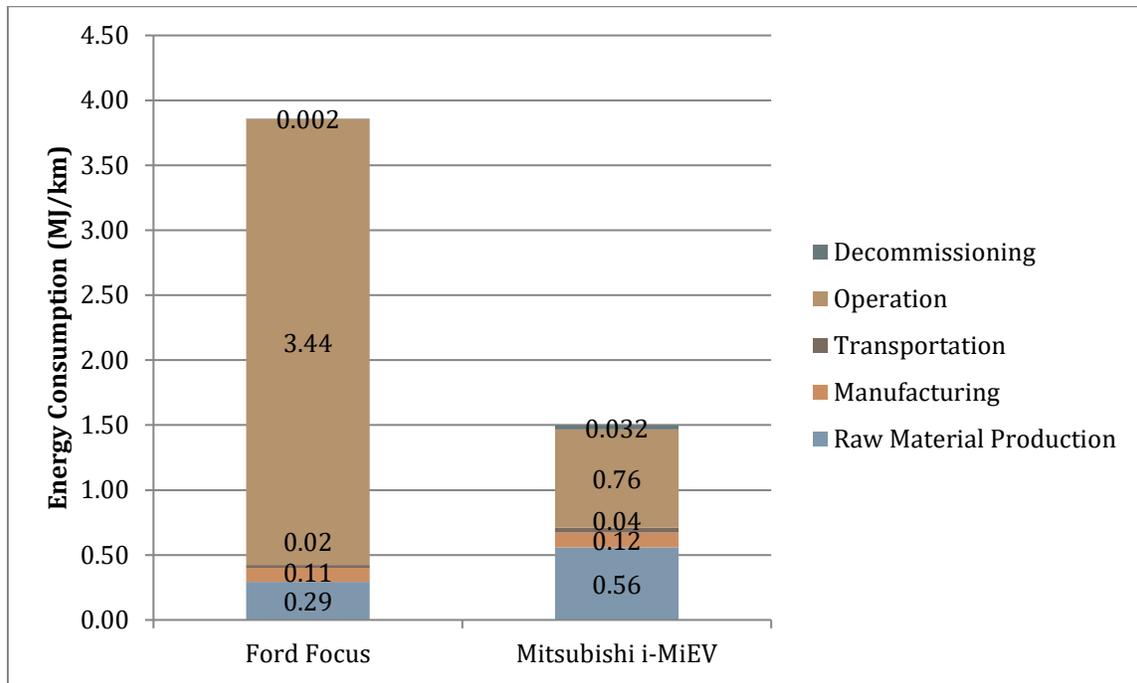

Figure 8 – Graph comparing energy consumption with a vehicle life of 250,000km.

Similar results were obtained for energy consumption – 3.86MJ/km for Ford Focus and 1.50MJ/km for the Mitsubishi i-MiEV, 61% lower. The operational numbers were unchanged while the other four stages had lower numbers.

Figures 9 and 10 show similar data with a vehicle life of 100,000km. Ford Focus is at 462.3gCO$_2$-eq/km and 4.5MJ/km; Mitsubishi i-MiEV is at 303.2gCO$_2$-eq/km and 2.6MJ/km.
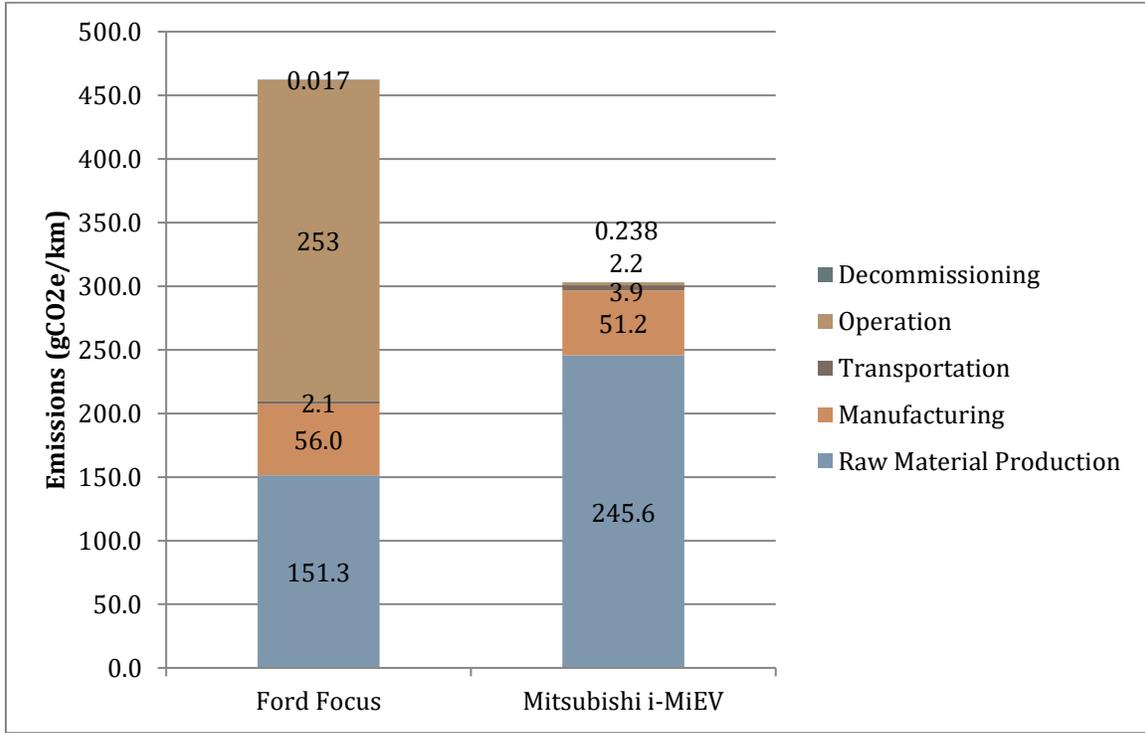
Figure 9 – Graph comparing CO_2-equivalent emissions with a vehicle life of 100,000km.
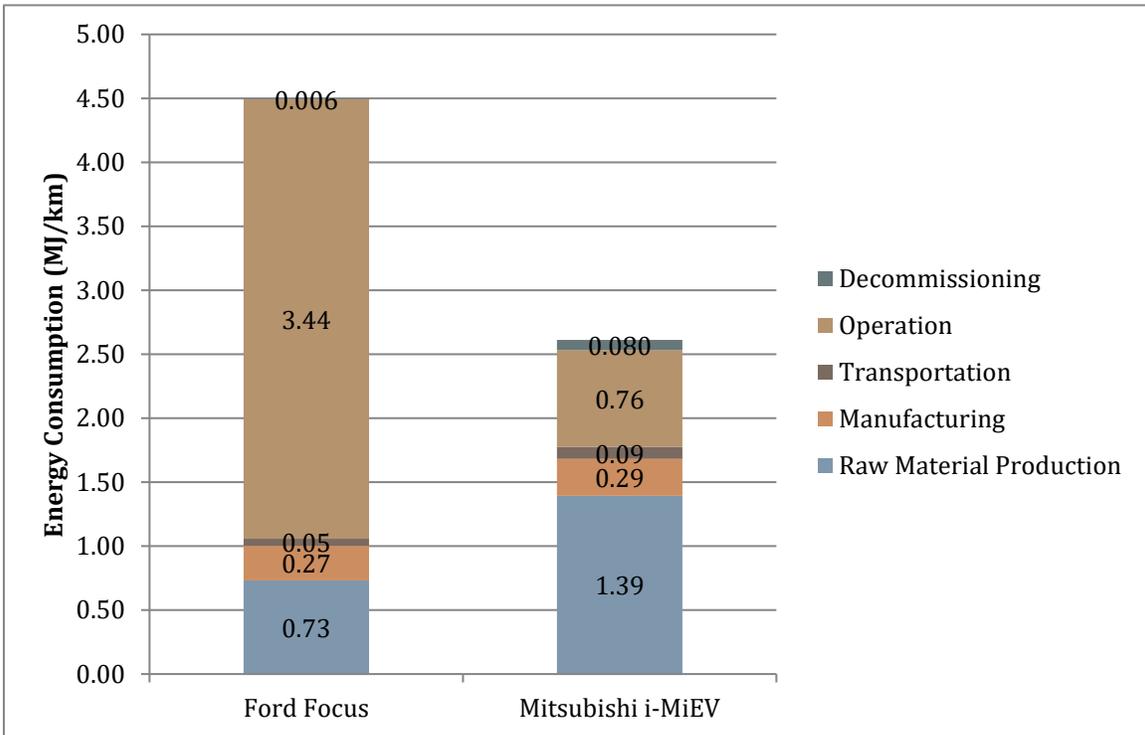

Figure 10 – Graph comparing energy consumption with a vehicle life of 100,000km.

Future Use of Lithium-Ion Batteries

Once an electric vehicle reaches end-of-life, the battery can still have further uses. Old EV batteries can undergo a recycling process where metals in the battery are recovered and reprocessed to make new batteries. Currently, two processes are most common for EV battery recycling – hydrometallurgical and pyrometallurgical recycling (Hendrickson & Kavvada, 2015). These processes are economically feasible due to the relatively high value of metals like nickel, cobalt, lithium, manganese, and aluminum, all of which can be recovered from the batteries. Companies such as American Manganese Inc., based in Surrey, BC, have developed a process that can extract 92% of lithium from the battery with costs as low as $0.25 to $0.30 per pound (JWN Energy, 2017). However, due to electric vehicles becoming more common only recently, a substantial amount of old lithium-ion batteries is not yet readily available. This will obviously change in the future as electric vehicle adoption increases and a critical mass of used batteries becomes available to recycle.

Other methods of using old EV batteries are for energy storage, where old EV battery cells still provide adequate capacity for terrestrial electricity storage. The lithium-ion cells are tested and assembled into scalable energy storage packs (Box of Energy, 2017). The intermittent nature of renewable power generation like wind and solar means that if the energy produced is not used immediately or stored, it is wasted. Currently, the vast majority of energy storage globally is done with pumped hydroelectric energy storage. Lithium-ion batteries offer energy storage where water supplies may not be readily available. The battery packs are also especially useful in grid stabilization due to their near-instantaneous operation (Electrek, 2018).

In other regions, car companies like Nissan are realizing the economic opportunity of creating a second revenue stream from end-of-life Leaf batteries (Nissan, 2018). The company has working prototypes of solar-powered lighting systems with integrated batteries that operate independently of the electrical grid. This is especially important in seismically active regions like Japan and the west-coast of North America.

Figure 11 – Nissan project "The Reborn Light", which creates solar-powered streetlights that operate independent of the grid with integrated Nissan Leaf batteries and have reached end-of-life in the vehicle.

Conclusion

The life cycle of electric vehicles and internal combustion engine vehicles was comparatively analyzed by dividing into five categories: raw material production, vehicle manufacture, transportation, operation, and decommissioning. The analysis of environmental impacts on energy use and carbon emissions revealed that electric vehicles have a markedly lower impact in both categories, especially in regions with clean power sources like British Columbia. This conclusion is reached after consideration of the higher environmental burdens of raw material production and decommissioning inherent to electric vehicles. The significantly lower impacts from the operation stage had the strongest effect on the results. Sensitivity analysis showed that a longer lifespan shifted the efficiency balance further toward the electric vehicle.

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