Equipment Life Cycle Assessment of Diesel, Hybrid, and Electric Buses

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ABSTRACT – This paper applies a case study approach for Australia and calculates the equipment life cycle assessment of diesel, hybrid, and electric buses. This study prepared the assessment according to the procedures and methodologies outlined in the ISO 14040:2006 Environmental Management – Life Cycle Assessment. The authors have chosen three bus models currently in service in the Australian bus fleet to serve as a baseline model for comparison. The amount of greenhouse gas emissions were calculated from the production, assembly, transportation, maintenance, and disposal phases. The results in this study show that the electric bus has a higher total environmental impact than the diesel and hybrid bus, mainly due to the manufacturing of the lithium-ion battery. The results also show that the electric bus has a higher environmental impact than the diesel and hybrid bus (18.2% and 14.7% higher, respectively), albeit specific to the product life cycle and without including operation emissions. However, there are many opportunities to reduce product life cycle emissions, such as improvement in manufacturing efficiency, developing new battery technology, and production in regions with low carbon-intense grid-mixes.

Keywords: Life Cycle Assessment; Battery Electric Vehicles; Greenhouse Gas Emissions; Global Warming Potential; Electric Buses; Environmental Impact.

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1 INTRODUCTION

Public transportation by transit bus contributes significantly to the effective mitigation of traffic congestion in urban regions.[1] With such strong and urgent incentives to reduce emissions from transportation, electrified powertrain technologies have been under rapid development. Transitioning the transport sector to electrified powertrains have been perceived as the optimal solution to decarbonise the transport sector.[2,3,4] For Hybrid Electric Vehicle (HEV) buses there are a reduction in tailpipe Greenhouse Gas (GHG) and toxic gases emissions, whereas Battery Electric Vehicle (BEV) buses have no tailpipe emissions at all. In the public transport sector, the traffic conditions in urban and suburban bus routes allow HEV and BEV buses to operate at low speeds and with frequent stops which assists with the recuperation of energy from regenerative braking.

Electrified powertrains offer considerable advantages over the conventional Internal Combustion Engine Vehicle (ICEVs) powertrains. The most notable advantages include higher powertrain efficiency, lower need for maintenance, absence of tailpipe emissions, and reducing urban air pollution.[5] The growing awareness of the environmental impact of global GHG emissions has led to a general perception of phasing out diesel buses immediately. In the Australian transport sector, there are relatively few electrified powertrains in operation. There have been substantial development and impact evaluation results from the successful launch of electric powertrain systems in passenger vehicles, such as the Toyota Prius and Tesla Model 3. However, the extrapolation of the results into heavy commercial vehicles remains limited in terms of both research quantity and degree of success. Thus, there is a major research gap for developing a comprehensive understanding of the potential for and impact of powertrain electrification in the Australian public transport sector.

The environmental burden from the life cycle of diesel, hybrid, and electric buses is non-negligible and complex to analyse. Some studies have performed Life Cycle Assessment (LCA) evaluations on the environmental impact of the electrified powertrain technology at varying levels of detail, accuracy, and transparency. Pero, Delogu & Pierini (2018)[6] conducted a comparative LCA of ICEVs and BEVs. The production, operations, and disposal stages were considered in both vehicle's entire life cycle. However, transportation during production and vehicle maintenance have been excluded from the system boundaries. Lajunen & Lipman (2016)[3] assessed the GHG emissions of various types of transit buses and was based on the operating environment case scenarios for Finland and California (USA) Well-to-Tank (WTT) and operations phases. Tagliaferri et al. [7] presented a life cycle assessment of a BEV based on the lithium-ion technology in Europe and compared the results with an ICEV. The study applied a cradle-to-grave approach and included the manufacturing, operations, and disposal phases into the assessment. Mierlo, Messagie & Rangaraju[8] performed a comparative environmental assessment of alternative fuelled vehicles using LCA in Belgium. Hawkins et al.[2] developed a transparent life cycle inventory of ICEVs and BEVs and applied the inventory to assess the vehicles over a range of impact categories. Ellingsen et al.[9] provided a comprehensive inventory for a lithium-ion nickel-cobalt-manganese (NCM) traction battery based on primary data and report the battery's cradle-to-grave environmental impacts. Cooney, Hawkins & Marriott[10] compared the life cycle environmental impacts of diesel buses and electric buses operating in the USA. Their study included the production of the bus, battery, and use phase impacts from both diesel production/combustion and electricity generation.

This study builds upon existing literature and provides an appropriate comparison of ICEV, HEV, and BEV buses. The novelty of this paper is shown by applying a case study approach for Australia and addressing the research gap on the environmental impact of transitioning the Australian transport bus fleet to electrified powertrains. First, the methodology section defines the scope, system boundary, and functional unit adopted for this study. Next, an in-depth and comprehensive process-based equipment LCA of diesel, hybrid, and electric buses is conducted which includes the environmental impact resulting from the production, assembly, transportation, maintenance, and disposal phases. Then, the results present the detailed estimation of GHG emissions produced throughout the life cycle of transit buses and discuss the environmental sustainability of the three bus variants. Finally, a sensitivity analysis is conducted to address the technological developments uncertainties and assumptions made in this study.

2 METHODOLOGY

2.1 SCOPE DEFINITION

Generally speaking, LCA is an evaluation tool used to assess a product's environmental impact throughout the entire service life.[11] Applying a case study approach for Australia, this study performs an emissions LCA of diesel, hybrid, and BEV buses in the Australian bus fleet. The city of Sydney was chosen as it is the most populous city in Australia and several bus operators have begun trailing BEV buses in their bus routes. This study prepared the LCA according to the procedures and methodologies outlined in the ISO 14040:2006 Environmental Management – Life Cycle Assessment.[12] The objective of this study is to calculate the amount of life cycle Greenhouse Gas (GHG) emissions produced to investigate the environmental implications for when the Australian bus fleet eventually transitions to BEV buses.

2.2 SYSTEM BOUNDARY

A system boundary is set within which process data are collected to meet the objective of the study. Processes found to contribute negligibly to the end results are excluded. There is a complex interaction between vehicles and larger systems, such as infrastructure, emerging technologies, power generation, and transportation options specific to a region. A complete LCA can be divided into two studies: the Well-to-Wheel (WTW) life cycle and the equipment life cycle (or Cradle-to-Grave).[13] The former focuses on the life cycle of the energy carrier (fossil fuel or electricity) that propels the vehicle. The latter, and also the focus of this study, consists of processes specific to vehicle production.

Thus, this study performs an equipment LCA of diesel, hybrid, and electric buses through the investigation of the main GHG pollutants released during the five phases of production, assembly, transportation, maintenance, and disposal. Materials production is the first process that involves the extraction of raw materials and the manufacturing of vehicle components. It is followed by the assembly phase, which examines the energy consumed to assemble vehicle components together and build a functioning bus. Then, the transportation phase involves the GHG emissions produced from the process of shipping the fully built buses from their respective manufacturing plants to Sydney, Australia. The next phase relates to the aspects of the operations phase that relates solely to the equipment life cycle, namely the periodic replacement of components and servicing, which this study refers to as the maintenance phase. The remaining aspects of the operations phase relate to the WTW life cycle and are excluded from the study. Finally, the disposal phase involves vehicle components disassembly, materials segregation, recycling, and disposal. The scope of recycling is limited to the process prior to implementing the recycled materials into new products.

An ICEV, HEV, and BEV bus are selected that best represent the current bus fleet operating in Sydney NSW, Australia. It is sufficient to assume that many vehicle components do not differ significantly from each other, nonetheless, the technical specifications of the buses are standardised to provide a frame of reference. To clarify this further, this study standardises most of the components, such as vehicle chassis, interior, exterior, wheels, tyres, etc. The emissions produced from manufacturing components are specific to the bus variant, namely the powertrain and associated components.

2.3 FUNCTIONAL UNIT

McIntyre et al.[14] defines a functional unit of the environmental load as a unit mass of GHG – in Carbon Dioxide equivalent (CO_2e) – per unit of material production or assembly process: **kgCO_2e/kg**. The Carbon Dioxide Equivalent (**kgCO_2e**) of other greenhouse gases (CH_4 and N_2O) is calculated by multiplying the mass (in tonnes) by the gas's Global Warming Potential (GWP). GWP is defined as the measure of energy the emissions of a unit mass of gas will absorb over a given period of time (usually 100 years), relative to the emissions of a unit mass of reference gas CO_2 (1): CH_4 (28) and N_2O (265).[15,16,17] The assessment of the emission values will be within the time frame of the year 2018 – 2021. It is important to note that the emissions values presented in this study are only going to be current at the time it was authored and may be superseded at the time it is being read. It is therefore recommended to use this work as a guide and reflection. The assessment is designated to be within the time frame of the year 2018 – 2021.

2.4 LIFE CYCLE INVENTORY ANALYSIS

Manufacturing a diesel, hybrid, and BEV bus requires components, materials, and processes unique to the bus variant, insinuating that the life cycle emissions from constructing the buses differ at each life cycle phase.[18] Thus, this section calculates the total amount of emissions associated with the production, assembly, maintenance, and disposal of diesel, hybrid, and BEV buses in the Australian bus fleet. The focus, in particular, is on the GHG that contributes to global warming: Carbon Dioxide (CO_2), Methane (CH_4), and Nitrous Oxide (N_2O), with the functional unit **kgCO_2e** (see *Section 2.3 Functional Unit*). An appropriate comparison of the LCA requires the inclusion of all relevant differences and similarities across the three bus variants[2].

2.4.1 REFERENCE BUS SPECIFICATIONS

An ICEV, HEV, and BEV bus (Volvo B8R Low Entry[19], Volvo B5L Hybrid[20], and BYD K9[21], respectively) are chosen as a baseline model for comparison. The specifications of the chosen buses, such as passenger capacity and dimensions, are currently in service in the Australian bus fleet. Furthermore, the manufacturers have readily provided the necessary data the authors need to conduct an LCA. To ensure the comparability of the three bus variants, a common generic glider (a vehicle absent of its powertrain components) is established, hereinafter referred to as Reference Bus. Here, the bus specifications are standardised wherever possible to provide a frame of reference. Table 1 provides key specifications for the Reference Bus used in this study.

Table 1 - Key specifications of diesel, hybrid, BEV, and representative bus.

Specifications	Volvo B8RLE	Volvo B5L Hybrid	BYD K9	Reference Bus
Dimensions				
Wheelbase (m)	6.80 m	6.30 m	6.20 m	6.50 m
Length (m)	12.5 m	12.5 m	12 m	12.5 m
Width (m)	2.5 m	2.6 m	2.6 m	2.5 m
Height (m)	2.3 m	2.3 m	3.2 m	2.5 m
Kerb Weight (kg)	12,700 kg	12,400 kg	14,400 kg	-
Gross Weight (kg)	19,000 kg (GVM)	18,600 kg (GVM)	19,700 kg (GVM)	-
Passenger Capacity	35 seated, 27 standing			
Chassis				
Suspension	Air Suspension			
Brakes	Front & Rear Disc, Anti-Lock Braking System (ABS)			
Tyres	275/70R 22.5”			
Frame	Carbon Steel			
Powertrain				
Engine/Motor Type	8 L Inline 6-Cylinder	5.1 L Inline 4-Cylinder AC Permanent Magnet	AC Synchronous (in-wheel motors)	-
Max Power (kW)	246 kW	177 kW; 110 kW	2 x 150 kW	-
Torque (Nm)	1,200 Nm	918 Nm; 800 Nm	2 x 550 Nm	
Gearbox	6-Speed Automatic	12-Speed Automatic	-	-
Fuel Tank & AdBlue (L)	300 L; 50 L	220 L; 30 L	-	
Battery Capacity (kWh | Ah)	-	19 kWh	324 kWh | 600 Ah	-
Fuel Type	Diesel	Diesel	-	-

Battery Composition	-	$LiFePO_4$	$LiFePO_4$	
Fuel/Power Consumption (L/100km, kWh/km)	29.2 L/100km[22]	20.4 L/100km[22]	120 kWh/100 km[21]	-
Charging Capacity (kW)	-	-	80 kW	-
Charge Time (h)	-	-	4 h @ 80 kW (fast), 6 h @ 60 kW (normal)	-

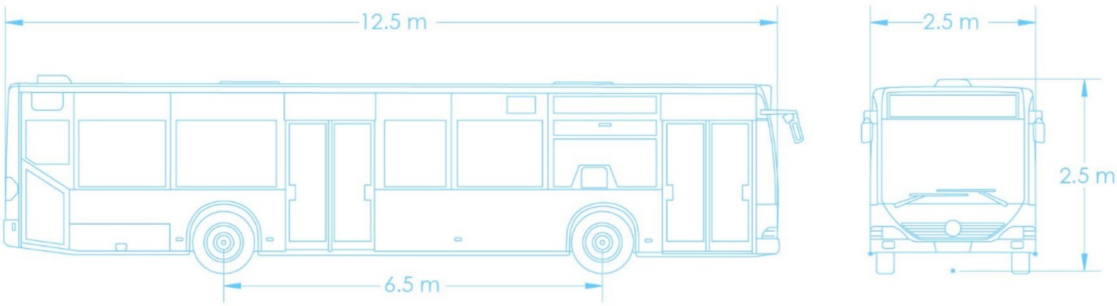


Figure 1 - Reference bus technical drawing.[23]

2.4.2 GREET© MODEL

This study utilises the GREET model:[24] Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation to estimate the GHG emissions rate per unit of material weight, as limited data is available in the public domain relating to materials processing emissions. The GREET model is sponsored by the U.S. Department of Energy's (DOE) Office of Energy, Efficiency, and Renewable Energy, and is an analytical tool that simulates the emissions output and energy consumption of a diverse range of vehicles and fuel combinations. The GREET model examines the life cycle environmental impacts of automotive technologies, fuels, energy systems, and products. For any given vehicle and energy system, the GREET model can calculate the total energy consumption, air pollutants emissions, GHG emissions, and water consumption. Furthermore, the GREET model is continuously updated by the Argonne National Laboratory and can therefore provide up-to-date calculations of transportation emissions and energy consumption. Thus, the model is suitable for equipment life cycle assessments and meets the demands of this study.

2.4.3 PRODUCTION PHASE

The production phase covers the entire manufacturing process of the buses. This includes the stages from raw materials extraction to the manufacturing of various bus components. For this phase, the data collection involves determining the components' typology, weight, and quantity of materials, as well as the components' manufacturing processes. Before analysing the emissions produced in this phase, it is necessary to apply a breakdown approach and divide the reference bus into assemblies, components, and structures. Industry inventories and reports regarding component masses, manufacturing processes, and materials were utilised whenever the information and data were available in the public domain. The total production emissions can be found in *Supplementary Materials: Table S3*. There are uncertainties regarding materials production, as the emissions vary depending on the assumptions made, such as the degree of virgin and recycled materials used. Additionally, the carbon intensity of a region's grid-mix influences energy consumption, which in turn induces uncertainty in the raw material manufacturing emissions. For example, if a bus is produced in a certain region, it is still necessary to assume that numerous sub-components and raw materials may originate from various parts of the world, where the manufacturing and assembly processes will then vary in their degrees of carbon intensity.

2.4.3.1 MATERIALS BREAKDOWN

An input-output approach is applied to estimate the emissions of the three buses in the production phase. First, the weight of each essential components (input) is determined. Next, the GHG emissions rate per unit of material weight (output) (e.g. $kgCO_2e/kgAl$ for aluminium) is estimated. Lastly, the total emissions of each component are calculated by multiplying the GHG emissions rate with the weight of each component. The environmental load from the production phase is designated as $\boldsymbol{E_{production}}$ **($kgCO_2e$)** hereinafter. The emissions produced from these materials are calculated using the cradle-to-grave emissions data extracted from the GREET® 2019 model. This section estimates the proportional weight of each material type that contributes to the total weight of each unit given in the product specifications.

Consumable components such as various fluids (transmission fluids, brake fluids, engine oil, and coolant), brake pads, and tyres have been included in the materials analysis. Furthermore, these consumable components require periodic replacement during the lifetime of the buses. It is, therefore, necessary to incorporate the emissions produced from the consumable components' initial installations and replacements. The GHG emissions intensity per unit of material weight produced can be found in the *Supplementary Materials: Table S1*.

2.4.3.2 BATTERY MANUFACTURING

The battery pack is an essential component to the HEV and BEV bus, comprising of a cooling system, battery cells, packaging, and Battery Management System (BMS). The modelled battery pack is split into three smaller packs, installed on the roof of the bus.[7] The battery thermal management is done by the cooling system and is made up of the radiator, manifolds, clamps, pipe fittings, thermal gap pads, and coolant. Battery performance is achieved by the BMS, which includes the Battery Management Board (BMB), Integrated Battery Interface System (IBIS), fixings, and high and low voltage systems. The battery cells are made up of five subcomponents: anode, cathode, electrolyte, separator, and cell container. The packaging is divided into three subcomponents: battery retention, battery tray, and module packaging. In their study, Ellingsen et al.[9] report that the battery assembly process requires little energy, as it is mainly performed using manual labour. The only direct energy requirement is for the welding process, which itself only amounts to 3.89×10^{-3} kWh per kWh of battery capacity. There is a lack of access to industry data for the GHG emission of battery packaging and BMS production. The production of lithium-ion batteries requires extracting and refining rare earth metals. It is a carbon-intense process involving high heat and sterile conditions during manufacturing. The GHG emissions from energy use are highly sensitive to a region's electricity grid mix.

Literature (*Supplementary Materials: Table S2*) have suggested that most early BEV battery LCAs relied on only a few primary sources for emissions inventories, rendering high degrees of uncertainty and may not accurately represent the multiple BEV battery production facilities operating around the globe. Many of these studies have indicated that a large share of GHG emissions is produced from the electricity used in manufacturing. Different battery types also influence the final LCA results, as some battery chemistries hold higher concentrations of energy-intense metals. Furthermore, these studies also typically do not incorporate the disposal (including recycling) phase into the end results, therefore there is significant uncertainty regarding a battery's end-of-life environmental load.[4] The studies listed in *Supplementary Materials: Table S2* reported battery production emissions from the combination of several different types of lithium-ion batteries. As the specific emissions values for a $LiFePO_4$ battery is needed, it is therefore decided to determine the battery production emissions from the GREET model. The $LiFePO_4$ battery energy density is assumed to be 0.12 kWh/kg.[25,26,27,28,29,30,31,32,33]

2.4.3.3 BILL OF MATERIALS

This section establishes the Bill of Materials (BoM) of the generic glider, without including any components relating specifically to ICEVs, HEVs, or BEVs. Next, the ICEV, HEV, and BEV bus respective powertrains are included. An investigation is conducted on the additional electronics components (the $LiFePO_4$ battery, BMS, and controller) specific to the HEV and BEV bus. Table 2 provides an estimated BoM of vehicle components, and Table 3 provides an estimated BoM of the $LiFePO_4$ battery.

Table 2 – ICEV, HEV, and BEV bus bill of materials.[34, 35, 36, 37, 38]

Material	Material Weight (kg)		
	ICEV	HEV	BEV
Aluminium	635	565	650

Battery Management System	-	50	50
Cast Iron	1,540	1,050	125
Fiberglass Composites	965	965	965
Copper	65	565	975
Nylon 66	45	45	45
Fluids & Lubricants	385	420	415
Glass	475	475	475
Polyurethane Flexible Foam	75	75	75
Lead	25	-	-
Lithium Battery	-	115 (7.7 kWh)	2,700 (324 kWh)
Magnesium	75	75	75
Paint	45	45	45
Plastics	445	445	445
Rare Earth	15	35	90
Rubber	645	645	645
Stainless Steel	545	475	520
Steel	6,655	6,290	6,040
Zinc	65	65	65
Total	12,700	12,400	14,400

Table 3 - $LiFePO_4$ battery bill of materials.[24,39]

Components (%)	HEV	BEV
Active Material	15.5%	23.8%
Graphite/Carbon	9.1%	13.8%
Binder	1.3%	2.0%
Copper	24.3%	10.4%
Wrought Aluminium	20.1%	23.1%
Electrolyte ($LiPF_6$)	1.9%	2.5%
Electrolyte (Ethylene Carbonate)	5.4%	6.8%
Electrolyte (Dimethyl Carbonate)	5.4%	6.8%
Plastic (Polypropylene)	2.0%	1.0%
Plastic (Polyethylene)	0.5%	0.3%
Plastic (Polyethylene Terephthalate)	0.3%	0.2%
Steel	1.4%	0.7%
Thermal Insulation	0.7%	0.5%

Coolant (Glycol)	5.7%	5.1%
Electronic Parts	6.4%	3.0%

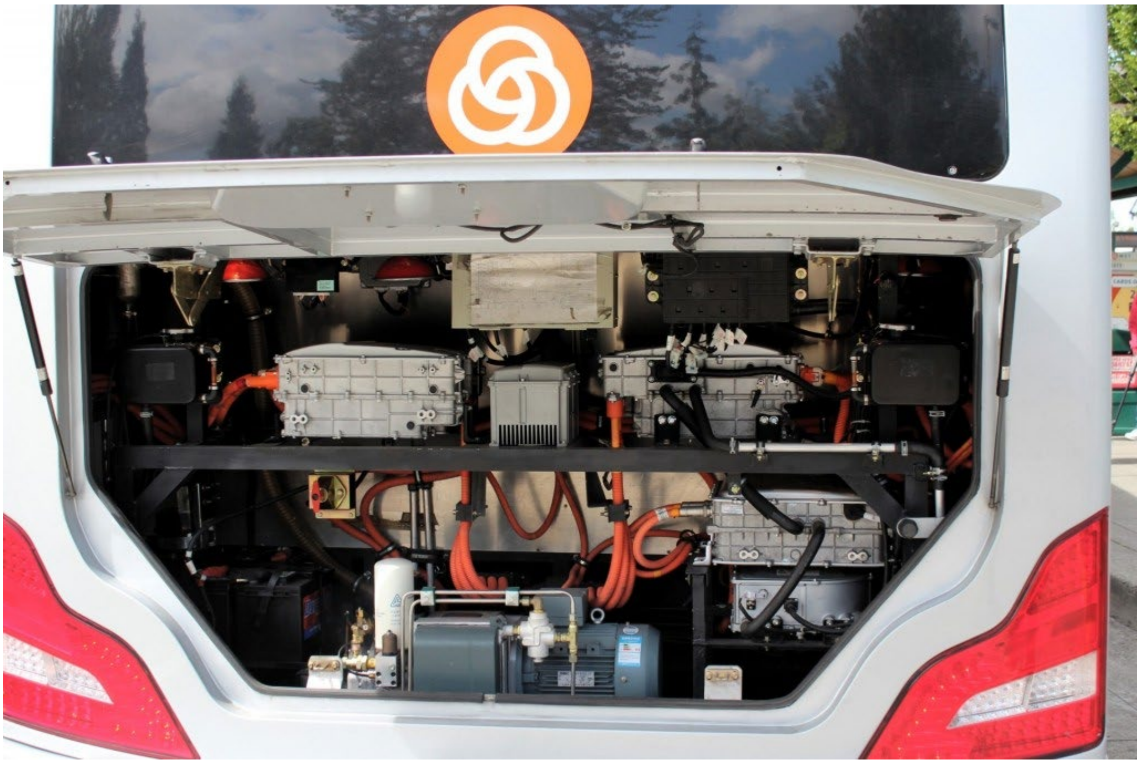


Figure 2 - BYD K9 battery modules.[40]

2.4.4 ASSEMBLY PHASE

Accordingly, this section calculates the GHG emissions produced during the assembly of the buses. The environmental load from the assembly phase is designated as $E_{assembly}$ **(kgCO_2e)** hereinafter. There is very limited data available in Australia in the public domain relating to automotive assembly emissions. Therefore the GREET model is utilised to estimate the GHG emissions rate per unit of material weight. The assembly emissions are subject to the assumptions incorporated by the GREET model. Here, an input-output approach is applied to simulate the vehicle assembly line. The per-ton vehicle output is used to connect the vehicle assembly processes together. Table 4 provides the GHG emissions intensity per ton of vehicle assembled. The overall emissions from assembly can be found in *Supplementary Materials: Table S4*.

Table 4 - Emissions intensity per ton of vehicle assembled.

Process	Emissions (kg/ton)					
	CO_2	CO	NO_x	SO_x	CH_4	N_2O
Painting	211.5	0.2	0.3	0.1	0.6	5.94E-03
HVAC & Lighting	131.8	0.1	0.1	0.2	0.3	2.06E-03
Heating	195.1	0.2	0.2	0.04	0.7	6.46E-03
Material Handling	27.3	0.01	0.02	0.04	0.05	4.30E-04
Welding	36.3	0.02	0.02	0.07	0.07	5.70E-04
Compressed Air	54.4	0.02	0.04	0.09	0.1	8.50E-04

2.4.5 TRANSPORTATION PHASE

This section estimates the amount of emissions produced from transporting the buses from their respective manufacturing plants into Sydney, Australia. The ICEV and HEV bus (Volvo B8RLE and Volvo B5L Hybrid) are produced in Borås, Sweden, and the BEV bus (BYD K9) is produced in Shenzhen, China. To simplify the assessment, it is assumed that the buses are fully built before being loaded onto a cargo ship (Port of Gothenburg and Port of Shenzhen, respectively) bound for Australia. The environmental impact of transportation is estimated with an activity-based calculation method[41]:

Environmental Impact (kgCO_2e) = Transport Mass (kg) by Transport Mode x Transport Distance (km) x CO_2e Emissions Factor per kg/km.

The environmental load from the transportation phase is designated as $\boldsymbol{E_{transportation}}$ **(kgCO_2e)** hereinafter. The emissions intensity from transportation can be found in *Supplementary Materials: Table S5*.

2.4.6 MAINTENANCE PHASE

Moving on to the maintenance phase, this section accounts for the regular preventive maintenance for the studied buses. The GHG emissions produced during the maintenance phase buses is calculated by determining the emissions produced from manufacturing the replacement components. The environmental load from the maintenance phase is designated as $E_{maintenance}$ **(kgCO_2e)** hereinafter. There is very limited data available in the Australian public domain relating to automotive maintenance emissions, therefore the power consumption emissions are excluded from this study.

Multiple studies have also set the service life expectancy of electric buses to 10 ~ 12 years and 500,000 ~ 800,000 km.[42,43,44,45] To simplify the assessment, the service life expectancy of the studied buses is set to 12 years and 650,000 km. The lead-acid batteries in the ICEV bus are set to be replaced every 5 years.[3] According to literature, the lithium-ion batteries for heavy-duty vehicles such as the HEV and BEV bus are assumed to have an average life expectancy of approximately six to eight years.[26,27,28,30,46,47,48,49,50,51,52,53] Thus, with the lack of industrial data on real-world battery performance of heavy-duty vehicles, this study assumes that the HEV and BEV bus requires approximately one battery replacement for the set service life expectancy.

Consumable components have been accounted for in this study. The periodic replacement of the components is based on the first-hand data available in the international public domain.[54,55,56] To simplify the assessment, the replacement components are set to be produced from virgin materials. The tyre service life is set to 50,000 km, thus a total of 13 full sets of new tyres are replaced per bus. Brake pads are set to be replaced every 50,000 km. Components specific to the ICEV, HEV, and BEV bus powertrains have also been accounted for. Notably, since damage caused by accidents often occur unexpectedly, replacement components caused by accidents are therefore excluded from this study. The overall emissions from maintenance can be found in *Supplementary Materials: Table S6*.

2.4.7 RECYCLING AND DISPOSAL PHASE

Lastly, this section decommissions the buses at their end-of-life. A critical analysis shows that recycling lithium-ion battery materials, such as cobalt and nickel in the cathode, will result in a 51% reduction in natural resource consumption.[57] A scenario analysis was performed, where the three buses are assumed to be recycled and disposed of within the Australian border. The scenario analysis also applies a high recycling approach, where the buses are reverted back into their original state of raw materials. The spent materials are separated into individual modules, to the point where they have their lowest value. The recyclable materials are set to include, but not limited to: electronics, glass, metals, plastics, and rubber. Recyclable materials are sorted, cleaned, and then reprocessed into fresh materials in their respective recycling plants. The implementation process of the fresh materials into new products is excluded. The remaining non-recyclable materials are then disposed of in landfills. In addition, the high recycling approach includes recycling waste oil from the BEV and HEV bus.

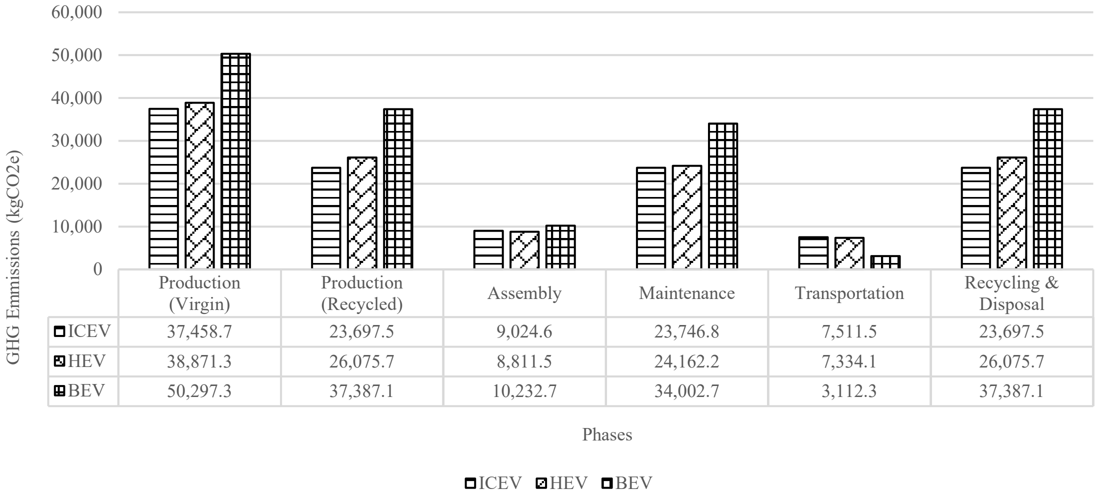
Most modern equipment is intricately integrated with plastics, electronics, metals, and other materials, making the recycling process challenging but not impossible. In the high recycling approach, most of the metals are stripped and recovered, the remaining waste materials will ultimately end up in landfills. Australia is one of the only countries part of the Organisation for Economic Co-operation and Development (OECD) that does not have a deliberate plan for handling automotive component recycling.[58] Presently, the Australian government is working with the Victoria Automotive Chamber of Commerce (VACC) and the Motor Trades Association of Australia (MTAA) to develop a vehicle End-of-Life (EoL) recycling strategy.

The primary objective of the disposal phase is to maximise resource efficiency and reduce GHG emissions simultaneously.[59] Numerous international studies have unanimously shown that waste material recycling can result in a reduction of GHG emissions.[13,60,61,62] Similar to the virgin materials GHG emissions production, the calculation of waste material GHG emissions observe the same functional unit of a unit mass of GHG (or equivalent) per unit of energy/material production: **$kgCO_2e/kg$** (kg of CO_2 equivalent per kg of material reprocessed/recycled). The environmental load from the disposal phase is designated as $E_{disposal}$ **($kgCO_2e$)** hereinafter. With the limited literature investigating the GHG emissions produced from recycling and reusing materials, the GHG emissions from disposal are assumed to the same as virgin material production emissions, with the exception of aluminium and steel. According to the UE 2000/53/EC directive[63], requirements have been introduced to obtain the minimum recovery and recycling rates of EoL vehicles. Thus, in harmony with the directive, the reuse and recycling rate of a minimum of 85% by an average weight per vehicle was assumed.

2.4.7.1 BATTERY DISPOSAL OPTIONS

It is assumed that most components of the HEV and BEV bus are recycled similarly to the ICEV bus. The major difference then lies in the disposal of lithium-ion batteries. At present, there are three disposal options available: repurpose, recycle, or landfill. Repurposing is a relatively new concept, however, there are opportunities for reusing these batteries in stationary storage applications at the vehicle's end-of-life. This allows for a more thorough use of the batteries, as they are likely to retain approximately 75% to 80% of their original capacity at their vehicle end-of-life.[4] The repurposed batteries can then be applied in other applications, for example, stationary electricity storage from renewable energy sources (such as solar PV) used in households. The advantage of this application could potentially displace fossil-fuel electricity generation to some extent and offset the GHG emissions produced.[17] This study has deemed repurposing BEV bus batteries as out of the study's scope and therefore excluded from this analysis, however, it is a rich area to be considered for future work. In terms of recycling, the majority of lithium-ion battery components can be reverted back into raw materials and then recycled for use in producing new batteries. The degree of how much of the battery can be recycled depends on battery design and a given region's economic and technical abilities. This study considers battery recycling, therefore the GHG emissions produced from the battery recycling process is supplemented into the disposal phase environmental load calculations.

3 RESULTS AND DISCUSSION



	Production (Virgin)	Production (Recycled)	Assembly	Maintenance	Transportation	Recycling & Disposal
ICEV	37,458.7	23,697.5	9,024.6	23,746.8	7,511.5	23,697.5
HEV	38,871.3	26,075.7	8,811.5	24,162.2	7,334.1	26,075.7
BEV	50,297.3	37,387.1	10,232.7	34,002.7	3,112.3	37,387.1

Figure 3 - Life cycle GHG emissions results.

Figure 3 shows the life cycle GHG emissions, with the total environmental impact separated into production, assembly, maintenance, transportation, and disposal phases. The results from the production, assembly, maintenance, and disposal phases are based on the functional unit reported in the GREET model. The total life cycle environmental loads are calculated from the sum of GHG emissions produced by production, assembly, maintenance, and recycling & disposal phases.

Given the results obtained by this study, the main findings are as follows:

Producing a BEV bus has a higher environmental load than its ICEV and HEV counterparts, much of which is due to the manufacturing of lithium-ion batteries. Indeed, manufacturing the 324 kWh (weighing approximately 2,700 kg) $LiFePO_4$ battery contributes 11,038.8 $kgCO_2e$ of GHG emissions in its production phase. However, several studies have shown that the electricity used in the battery manufacturing process accounts for approximately 50% of GHG emissions.[4,7,9] Therefore an effort in grid decarbonisation, such as increasing the use of renewable energy and more efficient power plants will lead to reduced emissions in battery manufacturing. Furthermore, the results show that producing the buses from recycled materials yielded significant GHG emissions savings of 13.6, 12.2%, and 9.6%, respectively.

Assembling the three bus variants produces similar amounts of GHG emissions and contributed very little to the total life cycle environmental loads. It is still worth mentioning that the BEV bus has higher emissions from assembly due to its additional mass. The environmental impact of transportation is heavily dependent on the transport distance. For this case study where the buses are shipped to Sydney, Australia, the results show that both the ICEV and HEV buses reported higher GHG emissions, as both buses have to be transported for more than double the distance of the BEV bus. Here, the transportation phase contributed the least to the total life cycle environmental loads.

The emissions from maintenance are highest for the BEV bus, followed by the HEV, and then the ICEV bus. The maintenance needs for the ICEV and HEV buses are similar given that both buses have an ICEV powertrain. As per the assumption made previously, over their service lives the HEV and BEV bus requires one battery replacement every six to eight years. Thus, an additional 940.3 kgCO_2e and 11,038.8 kgCO_2e are included. The largest contribution to maintenance emissions comes from the replacement of tyres. A pessimistic approach is applied and has assumed that tyres are to be replaced every 50,000 km over the buses' 650,000 km service life. The amount of GHG emissions from producing tyres amount to 16,808.5 kgCO_2e. Replacement components caused by accidents have also been excluded, as such incidences often occur unexpectedly and are impractical to predict.

Very few literature investigated the GHG emissions produced from recycling and reusing materials, and there is limited data available in the public domain relating to materials processing emissions. The GHG emissions from virgin material productions for the materials processing in the disposal phase are therefore assumed, with the exception of some recycled materials data reported by the GREET model.

3.1 CONTRIBUTION ANALYSIS

The total life cycle environmental load is designated as $\boldsymbol{E_{total}}$ **(kgCO_2e)**. Here, E_{total} is obtained by the summation of environmental loads from all life cycle phases.

$$E_{total} = \sum(E_{production} + E_{assembly} + E_{maintenance} + E_{transportation} + E_{disposal}) \quad (1)$$

Therefore, when using virgin materials in the production phase, the total life cycle environmental loads of an ICEV, HEV, and BEV bus are $\boldsymbol{E_{total}}$ **= 101,439.1 kgCO_2e**, **105,254.8 kgCO_2e**, and **135,032.1 kgCO_2e**, respectively. Alternatively, when accounting for the scenario of using recycling materials in the production phase, the total life cycle environmental loads are $\boldsymbol{E_{total}}$ **= 87,677.9 kgCO_2e**, **92,459.1 kgCO_2e**, and **122,122.0 kgCO_2e**, respectively.

3.2 SENSITIVITY ANALYSIS AND UNCERTAINTY

The ICEV, HEV and BEV bus life cycle emissions calculated in this study are influenced by several factors, assumptions, and uncertainties. This is especially the case for the BEV bus, as the chosen BYD K9 BEV bus only entered mass production in 2010. It is rather difficult fixing specific values to some parameters the influences the life cycle environmental loading of bus production. The production phase emissions vary with the degree of virgin and recycled materials used. In addition, factors such as energy consumption in all phases are heavily influenced by the carbon intensity of a region's grid-mix and induce uncertainty in the raw material manufacturing emissions. If this study was to set the bus production to a certain region, it is still necessary to assume that numerous sub-components and raw materials may originate from various parts of the world. The manufacturing and assembly processes may vary in their degrees of carbon intensity, making it difficult to determine an accurate environmental load for imported sub-components and raw materials.

Supplementary Materials: Figure S1 demonstrates that variations in key parameters regarding materials production methods, maintenance frequency, service lifetime, and transportation distances can all influence the life cycle phases and consequently the total life cycle GHG emissions. A series of 19 scenarios (A-R) for each bus variant is illustrated through the vertical bars, which in turn demonstrate the potential range of life cycle GHG emissions under the influence of parameter changes. First, the variation of emissions in the production phase is due to the mixed manufacturing with virgin and recycled materials. Next, transportation emissions vary by the travel distance of transporting the buses from their respective manufacturing plants into Sydney, Australia. Then, GHG emissions from the maintenance phase are heavily influenced by unpredictable factors, such as traffic conditions, drive pattern, drive style, weather conditions, and road conditions. For instance, this study had applied a pessimistic approach and have set the replacement of brake pads to every 50,000 km. However, the HEV and BEV bus have regenerative braking abilities that will greatly extend the intervals of replacing brake pads. Last, at the discretion of bus operators, the predetermined service life (ranging from 500,000 ~ 800,000 km) contributes to additional maintenance requirements, which then exasperates the GHG emissions from the maintenance phase. For example, the assumed battery service life of this study is six to eight years. The real-world driving conditions may impact battery performance for the HEV and BEV buses, thus increasing the service life will require an additional battery replacement.

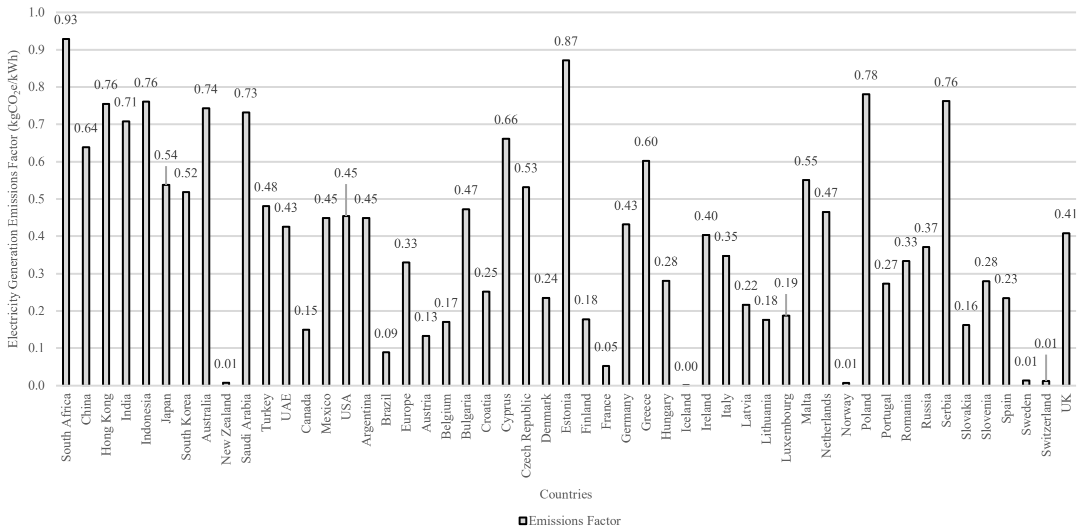


Figure 4 - Electricity generation carbon intensity of 49 countries.[20,64,65]

Figure 4 compares the recent carbon intensity of the grid-mixes of 49 countries, with the calculated average emissions factor of approximately 0.39 $kgCO_2e/kWh$. The results show that 25 countries reported under average carbon-intense grid-mixes, signifying cleaner electricity production. It is worth noting that the low emissions factor of Europe (0.33 $kgCO_2e/kWh$) should be interpreted as an average value only, as a few selected European countries such as Estonia, Poland, and Serbia have relatively high shares of fossil fuel in their grid-mixes. Australia is among the rest of the countries with significant carbon-intense grid-mixes. This signifies that any raw material and sub-component manufacturing and production processes in these countries that consume high electric power (for example, electric arc furnaces and machining processes) will yield high environmental loads. This corresponds with the study of Cooney, Hawkins & Marriott,[10] where the authors stated that there will be strong preferences for BEVs over ICEVs in regions where the grid is powered predominately by renewable energy or nuclear.

Regarding vehicle emissions, Hall & Lutsey[4] reported that incorporating BEV life cycle manufacturing emissions into vehicle regulations would be misguided. Many governments pioneering the decarbonisation of the transport sector have been investigating the environmental impact of BEVs, especially the manufacturing emissions of BEV batteries. However, the regulations on vehicle emissions and energy efficiencies should also incorporate manufacturing emissions for all conventional vehicle components, in addition to vehicle batteries, so that BEVs would not be unfairly penalised.

The slow deterioration of the $LiFePO_4$ battery may influence the final environmental load of the HEV and BEV bus. Currently, there are opportunities to repurpose the batteries after the buses' end-of-life, thus allowing a more thorough and efficient operations phase. This study finds a significant variety in environmental load reported across the literature studied based on life cycle methodologies and battery chemistries. Earlier literature reported higher production emissions whereas the emissions gradually reduce in more recent literature. The improvement of battery technology allows for longer vehicle service life, which offers fewer replacements in the vehicles and an increase in secondary use for stationary storage applications. With the increase in HEV and BEV bus implementation into the transport sector, battery manufacturers will also scale their production to suit the demand. The energy intensity of manufacturing batteries relies heavily on the composition of battery chemistries. Eventually, batteries may be manufactured with less carbon-intense materials. As promising as the proposed technological improvements may be, these technologies are still undergoing development and the time to commercialisation is still unknown. Consequently, this study does not attempt to quantify the GHG savings from future battery technology improvements and breakthroughs.

At the buses' end-of-life, there will be opportunities for reusing the BEV batteries, such as repurposing them for stationary storage applications which allows for a more thorough use of the batteries. This study has assumed the recycling of the batteries, and with the lack of available data, it is assumed that the recycling process will have the same emissions as virgin material production. However, in the scenario where the batteries are repurposed, there will be considerable disposal emissions savings, consequently reducing the total environmental impact.

This study has clearly compared the life cycle emissions of the three bus variants, and the results show that the BEV bus has a higher environmental impact than the ICEV and HEV bus. Yet the authors strongly recommend for life cycle studies to be conducted and re-conducted in correspondence with the ever-innovating and developing BEV technologies. Although the data assumptions of materials and manufacturing emissions specific to the electric powertrain and BEV battery are current at the time this study authored and may be superseded at the time it is being read, savings from these emissions are likely to increase in the future.

4 CONCLUSION

The innovation and contribution of this study have been presented through an appropriate comparison of diesel, hybrid-diesel, and electric buses by applying a case study approach for Australia and addressing the research gap on the environmental impact of transitioning the transport bus fleet to electrified powertrains. This study has targeted a Volvo B8R Low Entry diesel bus, a Volvo B5L Hybrid bus, and a BYD K9 electric bus as baseline models for comparison. The buses were chosen as they are currently in service in the Australian bus fleet and manufacturers have readily provided the necessary data with the authors needed to conduct an LCA. Then, an in-depth and comprehensive LCA of the three bus variants was conducted which included the environmental impact resulting from the production, assembly, maintenance, and disposal phases. The detailed estimation of GHG emissions produced throughout the life cycle of transit buses assists in the accurate evaluation of the environmental sustainability between ICEV, HEV, and BEV buses. The uncertainty and assumptions made from the technological developments were addressed with a sensitivity analysis with respect to the parameters presented.

Based on the results obtained by this study, the authors make the following conclusions:

On average, in Australia, the BEV bus has a higher environmental impact in its product life cycle than the ICEV and HEV bus, much of which is due to the manufacturing of lithium-ion batteries.

The manufacturing of the 324 kWh (weighing approximately 2,700 kg) $LiFePO_4$ battery contributes 11,038.8 kgCO_2e of GHG emissions. Furthermore, the results show that producing the buses with recycled steel and aluminium instead yielded significant GHG emissions savings of 13.6%, 12.2%, and 9.6%, respectively. Additionally, these values will vary depending on the buses' country of origin. This study's sensitivity analysis shows that countries with high carbon-intense grid-mixes will yield higher environmental loads from raw material and sub-component manufacturing and production processes.

Lithium-ion battery, copper, and rare earth metals production accounts for the most significant difference between the buses but represents only a small percentage of the BEV bus's total equipment life cycle GHG emissions. Although the BEV bus's 2,700 kg lithium-ion battery is significant in weight, it represents only 21.9% of the production phase emissions and 8.2% of the total GHG emissions. Similarly, copper and rare earth metals account for 5.3% and 2.8% of the production phase emissions and only 2.1% and 1.2% of the total GHG emissions. In contrast, the sheer size of the buses dictate the large amounts of steel are used (6.1 ~ 6.7 tons), such as the chassis frame and suspension system, contributes the highest to the GHG emissions and represents 12.3% ~ 18.1% (16.6 ~ 18.3 tonCO_2e) of the total GHG emissions. In comparison, an average passenger vehicle only has approximately 900 ~ 1,000 kg worth of steel. Thus, it would not be accurate to simply extrapolate the known emissions data from BEV passenger vehicles and extend the application to BEV buses by assuming that the existing results will continue to be applicable.

Repurposing and recycling BEV batteries will reduce product life cycle GHG emissions. Currently, there are opportunities to repurpose the batteries after the BEV bus's end-of-life, thus allowing a more thorough and efficient operations phase. Additionally, as the energy intensity of manufacturing batteries rely heavily on the composition of battery chemistries, the improvement of battery technology may eventually lead to manufacturing batteries with less carbon-intense materials. This study's sensitivity analysis shows that the slow deterioration of the $LiFePO_4$ battery may influence the final environmental load of the BEV bus. There is significant variation in the environmental load reported across the literature studied based on life cycle methodologies and battery chemistries. The authors found that earlier literature reported higher production emissions and gradually reduces with recent literature.

Thus, the environmental burden from the life cycle of ICEV, HEV, and BEV buses is non-negligible and complex to analyse. Some studies have performed LCA evaluations on the environmental impact of the electrified powertrain technology at varying levels of detail, accuracy, and transparency. There are many opportunities to reduce product life cycle emissions, such as improvement in manufacturing efficiency, developing new battery technology, and production in regions with less carbon-intense grid-mixes. It is a rich area to be considered for future work.

5 SUPPLEMENTARY MATERIALS

The data supporting the findings of this study are available within the article's supplementary materials.

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