Meeting our greenhouse gas emission targets: can electric vehicles meet the challenge?

– A probabilistic Life Cycle Assessment (LCA) for GHG emissions from Australian passenger vehicles

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Table of Contents

Executive Summary

All Australian and New Zealand jurisdictions have set net zero greenhouse gas (GHG) emission targets by 2045/2050. However, the Paris agreement has made clear that in order to limit the rise in global temperatures below 1.5 °C and reduce the risk of disastrous runaway climate change, the world needs to achieve at least a 50% GHG emission reduction **by 2030**, only ten years away.

Road transport makes up a substantial contribution to total national GHG emissions, and this contribution has been growing. Australia has experienced a sustained increase in total GHG emissions from road transport, as well as an increase in average GHG emissions per kilometre for new passenger vehicles since 2015. New Australian passenger vehicles are underperforming in relation to CO_2 emissions (and fuel economy) when compared to the USA, EU and Japan.

This study addresses the question: does electrification of the Australian passenger vehicle fleet, with its own unique characteristics, reduce GHG emissions, and if so, by how much and when? It provides a solid answer to this question by being comprehensive in scope (life cycle assessment), as well as being clear about the level of uncertainty associated with the answers (probabilistic statistical analysis). Life cycle assessment includes greenhouse gas emissions from **all aspects** of a vehicle's life ('cradle to grave'): vehicle production, fuel/electricity production and infrastructure, grid/charging losses, on-road use and vehicle disposal/scrappage.

This study shows that when compared to fossil-fuelled (petrol, diesel, LPG, CNG) vehicles, battery electric vehicles (BEVs) significantly reduce average life cycle GHG emission rates for passenger vehicles with a high level of confidence. This finding explicitly accounts for the variability and uncertainty in GHG emissions in all relevant life cycle aspects of fossil-fuelled vehicles and BEVs.

The weight of evidence suggests that electrification of the passenger fleet would reduce GHG emission rates (g/km) from between 16% to 40% for the current (2018) Australian electricity mix, which is still largely generated with fossil fuels. Even in a marginal electricity scenario (i.e. 100% fossil-fuelled electricity production), BEVs will still reduce GHG emission rates (g/km) between 5% to 29%. Importantly, in a renewable Australian electricity mix (i.e. 90% renewable, 10% fossil fuels), BEVs will produce **deep GHG emission reductions** of about 70% to 80%.

Rapid electrification of the Australian passenger vehicle fleet is a robust way to substantially reduce life-cycle GHG emissions from road transport. For each BEV sold, it would **immediately** provide significant reductions in GHG emissions per passenger vehicle kilometre travelled. It is therefore essential that BEV sales are promoted **now** to ensure that a significant level of electrification is achieved in 2030 in the Australian on-road fleet. The GHG emission benefits of electric vehicles will only increase further over time as the Australian electricity grid becomes decarbonised.

The study results can be further refined with a state/territory specific analysis and incorporation of new information on BEV sales (e.g. which BEV make/models replace which fossil-fuelled vehicle make/models?).

1. Introduction

All Australian (AUS) and New Zealand (NZ) jurisdictions have set net zero greenhouse gas (GHG) emission targets by 2045/2050. The Paris agreement has made clear that in order to limit the rise in global temperatures below 1.5 °C and reduce the risk of disastrous runaway climate change, the world needs to achieve at least a 50% GHG emission reduction by 2030, only ten years away.

More than 20% of total GHG emissions in AUS/NZ come from transport, which is in turn dominated by road transport. Moreover, total CO_2 emissions from Australian road transport have increased by 31% in the period 2000-2017.[1] So transport emissions are increasing rather than decreasing. To make matters worse, the average on-the-road CO_2 emission rates of newly sold passenger vehicles in Australia have been on the rise since 2015, increasing with a few percent each year, mainly due to ever increasing weight and a shift to 4WD/AWD vehicles (in particular large diesel SUVs).[1] A comparison with the EU, USA and Japan confirms that new Australian passenger vehicles are underperforming in relation to CO_2 emissions (and fuel economy).[2]

Australia is moving in the wrong direction regarding GHG emissions from road transport. So the question is: what to do? How can we change this? Battery electric vehicles (BEVs) are generally seen as the best solution to rapidly reduce GHG emissions from road transport.[e.g. 3-5] But does this hold true for the Australian on-road fleet with its own unique characteristics?

To inform decision making it is essential to develop a sound and evidence based understanding of the environmental impacts of road vehicles over their entire lifecycle. This study examines greenhouse gas (GHG) emissions performance of battery electric vehicles (BEVs) and fossil-fuelled (petrol, diesel, LPG, CNG) vehicles, referred to as internal combustion engine vehicles (ICEVs), focussing on the Australian market.

To properly assess GHG emissions performance of different vehicle technologies, a holistic and systematic method is required that considers and evaluates all aspects of a vehicle's life and its associated impacts (cradle to grave). The method used to quantify the environmental impacts of a product's manufacture, operational use, and end-of-life is referred to as life cycle assessment (LCA).[6] LCA can help clarify potential trade-offs between different environmental impacts and between different stages of the life cycle.[7] The comprehensive scope of LCA is useful in avoiding problem-shifting from one life cycle phase to another, from one region to another, or from one environmental problem to another.[8]

LCA studies can be set up in different ways, naturally with several underlying assumptions. LCA considers processes that are complex, location specific and vary in time, as well as over time (trends). It is therefore not surprising that LCA studies have caused diverging arguments about the environmental performance of the technology that is assessed.[5,9] For instance, significant differences in LCA results have been reported for similar electricity generation technologies, reflecting differences in local conditions as well as LCA methods and assumptions.[8]

There are many types of environmental impacts that can be assessed with LCA such as GHG emission impacts, toxicity, mineral resource depletion and land use.[9,10] Given the sheer amount of work associated with detailed consideration of the various aspects of a vehicle's life, LCA studies often incur restrictions in scope. For instance, LCA studies can focus on specific environmental impacts (e.g. greenhouse gas emissions only) or have a broader consideration of environmental impacts but focus on a few specific vehicle make/models.[10,11]

Given the complexity, localised and dynamic nature of life cycle impacts, it is important that the uncertainty in LCA results is quantified and that LCA results are regularly updated and improved. Although the majority of LCA studies have used deterministic approaches, a few recent studies have deployed a probabilistic approach to LCA.[11-13] A probabilistic LCA approach is useful to determine the robustness of study outcomes and to identify which aspects of the LCA are most uncertain and warrant further targeted examination.

This study will focus on GHG life cycle emission impacts of BEVs and ICEVs for the Australian on-road fleet, and will specifically quantify the uncertainty of the estimates. It is noted that the results of a probabilistic analysis rely on the assumptions regarding the probabilistic definitions of uncertain input parameters. These assumptions are affected by limitations on the availability and the quality of data sources. The probabilistic definition of input variables is as accurate as possible and based on statistical analysis of actual data and results from peer-reviewed scientific studies, wherever available.

2. Probabilistic life cycle assessment - BEVs versus ICEVs

This study will focus on life cycle GHG emissions.

The GHG emission factor is used as the assessment variable or 'functional unit'. This variable normalises the amount of GHG emissions per kilometre driven and is expressed as CO_2-e/vehicle km.

Carbon dioxide equivalent (CO_2-e) emissions are computed by multiplying emissions of a particular greenhouse gas with its Global Warming Potential (GWP) and taking the sum of these emissions.[1]

These GHG emission life cycle aspects are considered:

- Production of the vehicle:
    - Manufacturing of non-battery components
    - Manufacturing of the BEV battery
- Production of fuels (ICEV)
    - Fossil fuel extraction
    - Fossil fuel transport
    - Fossil fuel refining (infrastructure and fuel processing)
- Production of electricity (BEV):
    - Fossil fuel extraction
    - Fossil fuel transport
    - Electricity generation
    - Electricity distribution losses
    - Power generation infrastructure (fossil-fuelled and renewables)
- Operation or use of the vehicle, i.e. driving on the road
    - Fossil-fuel use (ICEV)
    - Energy use (BEV)
    - Battery charging losses
- Disposal/recycling of the vehicle at the end of its life

[1] GWP was developed to allow comparisons of the global warming impacts of different gases. GWP is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2), which has a GWP of 1. The larger the GWP, the more a given gas warms the Earth's atmosphere compared to CO_2 over that time period. For instance, methane (CH_4) is estimated to have a GWP of 28–36 over 100 years. Nitrous Oxide (N_2O) has a GWP 265–298 times that of CO_2 for a 100-year timescale. Chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), hydrochlorofluorocarbons (HCFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are sometimes called high-GWP gases because, for a given amount of mass, they trap substantially more heat than CO_2. The GWPs for these gases can be in the thousands or tens of thousands. The time period usually used for GWPs is 100 years.[1]

Comparing life cycle GHG emissions of BEVs and ICEVs in Australia requires consideration of the most likely (plausible) values for each of these aspects and their associated levels of uncertainty. Australian data are used as much as possible, supplemented with information from the available scientific literature. A plausible range is either quantified with statistical bootstrap resampling (95% confidence interval) or estimated from the literature and defined with a minimum and maximum plausible value.

Figure 1 shows an overview of the various sources of information used in this study. They are discussed in more detail in subsequent sections.

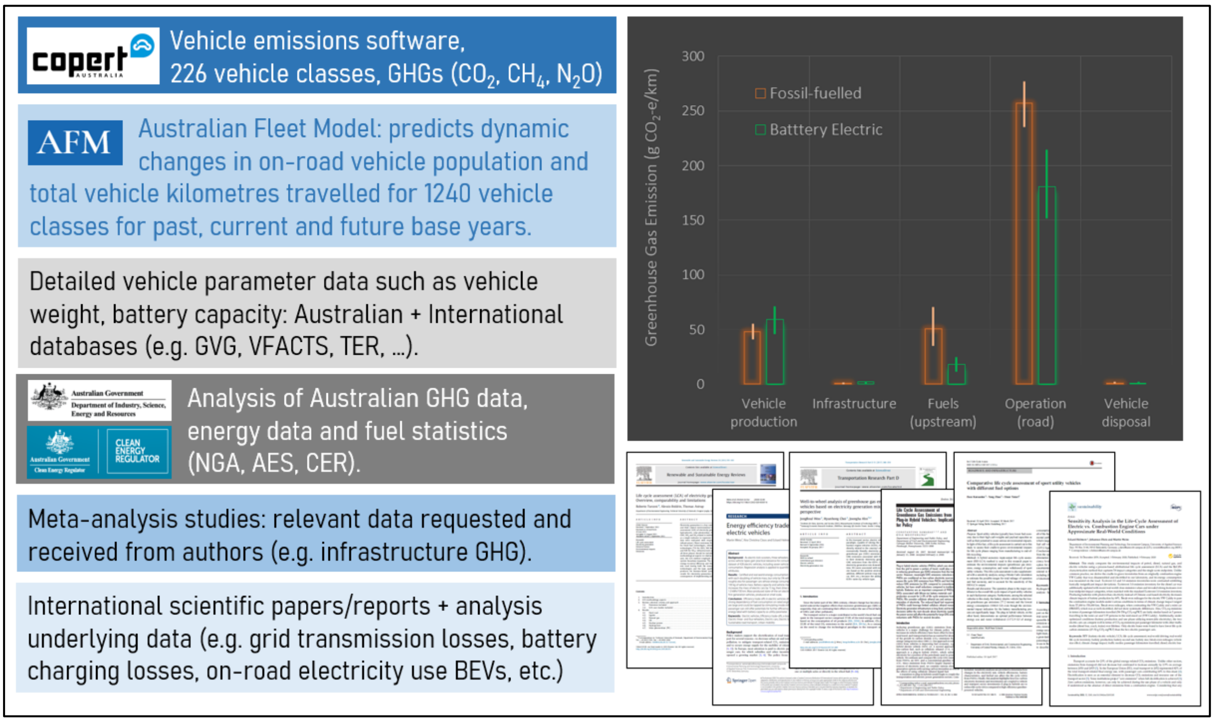

Figure 1 – The wide range of input data sources used in this project.

The life cycle GHG emission factors e_{ICEV} and e_{BEV} are computed with two additive models and sub-models (if applicable). In equations 1 and 2, $e_{i,j}$ is used to represent a GHG emission factor (CO_2-e/km) for life cycle aspect *i* (vehicle production, infrastructure, fuel/electricity production, on-road driving, disposal) and vehicle type *j*.

$$e_{ICEV} = e_{vehicle,ICEV} + e_{infra,ICEV} + e_{fuels,ICEV} + e_{road,ICEV} + e_{disposal,ICEV} \quad (1)$$

$$e_{BEV} = e_{vehicle,BEV} + e_{infra,ICEV} + e_{fuels,BEV} + e_{road,BEV} + e_{disposal,BEV} \quad (2)$$

$$e_{vehicle,ICEV} = w_{ICEV}\ \varphi_v$$
$$e_{vehicle,BEV} = (w_{BEV} - w_{BAT})\ \varphi_v + (\theta_b \times \varphi_b)$$
$$e_{infra,BEV} = (\sigma / (\eta_g\ \eta_b))\ \varepsilon$$
$$e_{fuels,BEV} = (\phi / \eta_b)\ \varepsilon$$
$$e_{road,BEV} = (\omega / (\eta_g\ \eta_b))\ \varepsilon$$

W_{ICEV} = ICEV vehicle weight (kg)
W_{BEV} = BEV vehicle weight (kg)
W_{BAT} = BEV battery weight (kg)
φ_v = carbon intensity vehicle production (kg CO_2-e/kg vehicle)
φ_b = carbon intensity battery production (kg CO_2-e/kWh battery capacity)
θ_b = battery capacity (kWh)
σ = GHG emission intensity electricity infrastructure (g CO_2-e/kWh generated)
ϕ = GHG emission intensity upstream fuels for electricity generation (g CO_2-e/kWh consumed)
ω = GHG emission intensity electricity generation (g CO_2-e/kWh generated)
η_g = grid transmission efficiency (-)
η_b = battery recharging efficiency (-)
ε = real-world electricity use BEV (kWh/km)

It is important to note that this study investigates **fleet average** impacts. As a consequence, the LCA models require fleet averaged input data, such as mean vehicle weight and the associated uncertainty in this *mean* value. It is noted that the method can be readily applied to specific vehicles. This would require the use of vehicle specific input data (e.g. Tesla Model 3 battery capacity and weight), rather than fleet averaged input information.

A probabilistic analysis is used to estimate the life cycle GHG emission factor probability distribution for (fossil-fuelled) ICEV vehicles (e_{ICEV}) and BEVs (e_{BEV}). The model inputs $e_{i,j}$ are specified as emission factor distributions. Uncertainty is represented with a probability distribution, with the uniform and triangular distribution considered here.

- The uniform distribution is a continuous probability distribution, which is defined by a lower limit (minimum plausible value) and an upper limit (maximum plausible value).[14] A uniform distribution represents equal probability between two end points. This distribution is appropriate if only an upper limit value and a lower limit value are available.
- The triangular probability distribution is a continuous probability distribution, which is defined by a lower limit (minimum plausible value), an upper limit (maximum plausible value) and the most plausible estimate (e.g. sample mean, median or mode). The triangular distribution is appropriate for situations in which the exact form of the distributions are not precisely known but in which values toward the middle of the range of possible values are considered more likely to occur than values near either extreme.[15] The triangular probability distribution can be asymmetrical.

A Monte Carlo simulation is used to propagate the uncertainty reflected in the input distributions to the model outputs e_{ICEV} and e_{BEV}.[16] Random samples are taken from the input distributions, propagated through the models, and this is repeated many times (100,000), to create a probability distribution for e_{ICEV} and e_{BEV}. This way not only expected life cycle GHG values are estimated, but also the associated uncertainty. The process is a mathematical analogue of an experiment, which is repeated many times to provide an accurate description of the variability in the output estimate.

Table 1 and 2 present an overview of the inputs used in the probabilistic assessment. Table 1 shows 'level 1' input for each LCA aspect expressed in the functional unit used in this study. Table 2 shows 'level 2' input, which has been used to compute some of the results presented in Table 1. A detailed discussion on the input values presented and used in Tables 1 and 2 is provided in Section 3 for the interested reader.

Table 1 – Level 1 input to the probabilistic life cycle GHG emission assessment (Australian PV fleet).

Vehicle type	Life cycle aspect	Unit	(Most) Plausible	Plausible minimum	Plausible maximum	Distribution
ICEV	Vehicle production	g CO_2-e/km	48	42	56	See Table 2
	Infrastructure	g CO_2-e/km	1.1	0.3	1.9	Uniform
	Fuels (upstream)	g CO_2-e/km	51	37	72	Uniform
	Operation (road)	g CO_2-e/km	257	238	279	Triangular
	Vehicle disposal	g CO_2-e/km	0.5	0.1	1.0	Uniform
BEV	Vehicle production	g CO_2-e/km	59	47	72	See Table 2
	Infrastructure	g CO_2-e/km	2.0	1.5	2.6	See Table 2
	Fuels (upstream)	g CO_2-e/km	18	12	25	See Table 2
	Operation (road)	g CO_2-e/km	181	152	214	See Table 2
	Vehicle disposal	g CO_2-e/km	0.5	0.1	1.0	Uniform

Some of the variables in Table 1 will have some level of inter-dependence (e.g. infrastructure and upstream fuel). These dependencies are accounted for in scenario definitions, as will be discussed shortly.

Table 2 – Level 2 input to the probabilistic life cycle GHG emission assessment (Australian PV fleet).

Vehicle type	Life cycle aspect	Unit	(Most) Plausible	Plausible minimum	Plausible maximum	Distribution
ICEV	Vehicle production					
	Carbon intensity vehicle	kg CO_2-e/kg	5.0	4.0	6.5	Triangular
	Mean vehicle weight	kg	1,800	1,783	1,817	Uniform
	Lifetime mileage	km	200,000	-	-	Constant
BEV	Vehicle production					
	Carbon intensity vehicle	kg CO_2-e/kg	5.0	4.0	6.5	Triangular
	Carbon intensity battery	kg CO_2-e/kWh	100	41	156	Triangular
	Mean vehicle weight	kg	1,700	1,625	1,753	Triangular
	Mean battery weight	kg	335	265	413	Uniform
	Mean battery capacity	kWh	46	42	50	Uniform
	Lifetime mileage	km	200,000	-	-	Constant
	Infrastructure					
	Infrastructure	g CO_2-e/kWh	8	6	10	Uniform
	Grid transmission loss**	%	6%	5%	10%	Triangular
	Battery charging loss**	%	15%	5%	27%	Triangular
	Energy consumption	kWh/km	0.19	0.18	0.21	Triangular
	Fuels (upstream)					
	Fuels (upstream)	g CO_2-e/kWh*	90	53	104	Uniform
	Battery charging loss**	%	15%	5%	27%	Triangular
	Energy consumption	kWh/km	0.19	0.18	0.21	Triangular
	Operation (road)					
	Electricity	g CO_2-e/kWh	738	623	831	Triangular
	Grid transmission loss**	%	6%	5%	10%	Triangular
	Battery charging loss**	%	15%	5%	27%	Triangular
	Energy consumption	kWh/km	0.19	0.18	0.21	Triangular

* kWh consumed at the power point, ** Efficiency is computed as 100% minus loss (%).

The results of the Monte Carlo uncertainty analysis are shown in Table 3 and Figure 2 and 3 (boxplots) for base year 2018.

Table 3 – LCA GHG emission factors for Australian ICEVs and BEVs (Monte Carlo).

Technology	Average g CO_2-e/km	Lower 95% confidence limit g CO_2-e/km	Upper 95% confidence limit g CO_2-e/km
ICEV	362	336	389
BEV	260	227	297
Difference (BEV-ICEV)	-102	-144	-57

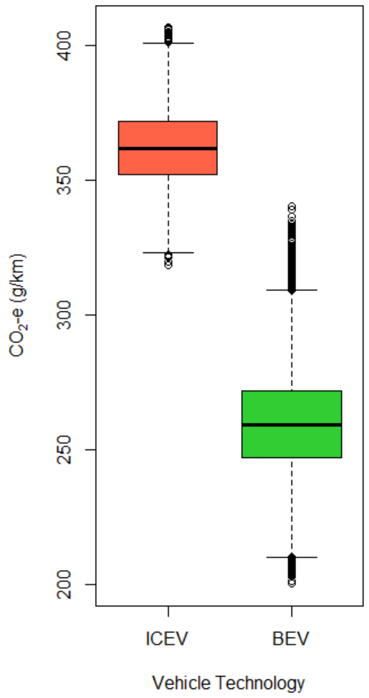

Figure 2 – Box-plot showing Monte Carlo simulation results for GHG emission rate distributions by technology class.

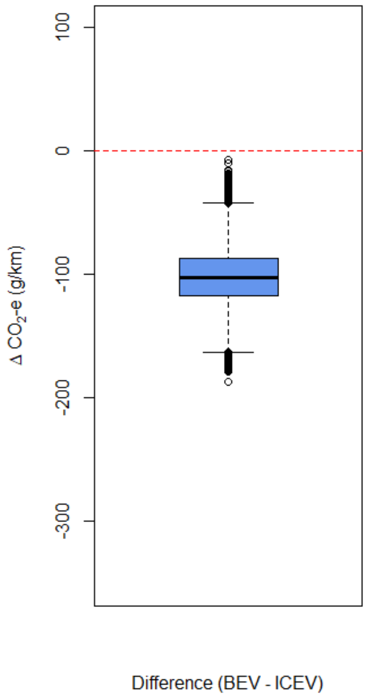

Figure 3 – Box-plot showing Monte Carlo simulation results for the difference in GHG emission rate distributions of BEVs and ICEVs.

Accounting for variability in GHG emission factors in all relevant life cycle aspects of ICEVs and BEVs, electric passenger vehicles are expected to significantly reduce average life cycle GHG emission rates for passenger vehicles with 95% confidence. In fact, none of the 100,000 uncertainty simulations generated a higher emission rate for BEVs as compared with ICEVs. The weight of evidence suggests that BEVs will reduce GHG emission rates with 16% to 40% (28% on average) for the current (2018) Australian electricity mix, which is still largely fossil fuels based.

The uncertainty analysis was repeated for different scenarios by changing the input distributions. Two alternative scenarios are assumed in this study:

- A worst-case 'marginal electricity' (ME) scenario, which is relevant for short term impact assessment. The ME scenario is 100% fossil-fuelled and assumes an Australian electricity mix of 73% coal, 24% gas and 3% oil.
- A longer term Australian renewable energy (RE) scenario. The RE scenario assumes an Australian electricity mix of 5% coal, 5% gas, 30% hydro, 25% wind, 5% biomass and 30% solar.

A worst-case ME Scenario (short term)

It has been argued that using average GHG emissions from electricity generation can produce somewhat misleading results, and that it would be more accurate to use marginal emissions from electricity generation.[4,6,17,18] Marginal electricity production reflects emissions from fossil-fuelled power plants, which are turned on to meet new demand from EV charging. Renewable energy sources are generally fully utilised and will not change their generation output in the short term when BEV penetration increases. In the short term, primarily coal and natural gas plants will increase generation in response to new loads.

The marginal grid mix typically has a higher emissions intensity than the average grid mix. A 'fossil fuels only' (coal, gas, oil) marginal GHG emissions intensity for the Australian electricity grid is estimated to be 878 g CO_2-e/kWh, with a 95% confidence interval of 797 to 956 g CO_2-e/kWh generated (Section 3.6). The marginal emission intensity is 18% higher than the average emission intensity, which is not a huge difference, mainly due to the already largely fossil-fuelled Australian electricity mix in 2018. In addition, plausible ranges for infrastructure (Section 3.2) and upstream fuel GHG emissions (Section 3.4) were modified for the marginal fuel mix scenario.

The Monte Carlo based uncertainty analysis for the ME scenario shows that electric passenger vehicles are still expected to significantly reduce average GHG emission rates for passenger vehicles with 95% confidence. The weight of evidence (95% confidence interval of the mean impact) suggests that BEVs will reduce GHG emission rates between 5% and 29% (17% on average) for a 100% fossil-fuelled marginal electricity mix.

A renewable energy RE Scenario (longer term)

Australia uses more fossil fuels than many other countries like the EU, USA, Canada, Japan, India, China, South Korea, Russia and Brazil.[19] This is despite the huge potential for renewables in Australia and associated economic and security benefits. Australia could become a renewable superpower with the required political will and support.[20] At the other end of the spectrum, Norway currently uses mainly renewable energy (98%), and is an example of what Australia could be like after the transformation to a sustainable energy system is completed.

A more renewable Australian electricity grid mix has a substantially lower emissions intensity than the current largely fossil fuel-based grid mix. A renewable GHG emissions intensity for the Australian electricity grid is estimated to be 90 g CO_2-e/kWh, with a plausible range of 80 to 110 g CO_2-e/kWh produced (Section 3.6). This renewable energy mix reduces GHG emissions by almost 90%. Plausible ranges for infrastructure (Section 3.2) and upstream fuel GHG emissions (Section 3.4) were also modified for the renewable energy scenario.

The Monte Carlo based uncertainty analysis for the RE scenario shows that electric passenger vehicles are expected to provide deep reductions in average LCA GHG emission rates for passenger vehicles with 95% confidence. The weight of evidence (95% confidence interval of the mean impact) suggests that BEVs will reduce GHG emission rates with 67% to 82% (74% on average) for a more renewable Australian electricity mix.

3. Input for the probabilistic life cycle GHG emission assessment

3.1 Vehicle manufacturing

GHG emissions associated with vehicle production requires estimation and division of two variables:

- total GHG emissions per vehicle (g CO_2-e/vehicle), and
- fleet average lifetime mileage (km).

For the first variable, GHG emissions per vehicle produced depends essentially on make/model and manufacturing location, and more generally on type of materials used, vehicle size and weight and emission intensity of the energy used in vehicle production. For electric vehicles, an important aspect is battery production, which produces significant amounts of GHG emissions.

ICEV production

For ICEV production, a plausible range for GHG emission intensity is taken from the literature: 4.0 to 6.5 kg CO_2-e/kg of passenger vehicle, with a typical value of 5 kg CO_2-e/kg.[21] A previous TER study estimated average ICEV PV weight to be around 1,800 kg, with an estimated uncertainty of 1%, i.e. a 95% confidence interval of 1,783 – 1,817 kg.[1] Assuming a triangular distribution for GHG emission intensity and a (conservative) uniform distribution for average weight, Monte Carlo simulation estimates that production of an average Australian passenger vehicle is expected to produce between 8.0 and 11.8 tonne of CO_2-e per ICEV produced, with a mean value of 9.6 tonne of CO_2-e per ICEV. The 95% confidence interval of the mean is 8.4 – 11.2 tonne of CO_2-e per ICEV.

BEV production

For BEV production, another TER study estimated a fleet average weight for Australian BEVs of about 1,600 kg, which is 200 kg lighter than the average ICEV PV weight.[22] A recent study into world-wide BEV characteristics (n = 218) computed an average BEV vehicle mass 1,689 kg with an uncertainty of 4% (95% CI is 1,625 – 1,753 kg).[23] To be conservative the fleet average weight for Australian BEVs was assumed to be 1,700 kg.

GHG emissions for battery production need to be estimated separately and added. For battery production, about half of the GHG emissions reportedly relates to the electricity used for production, the other half relates to off-site material production. Consequently, location of production is important. For instance, a battery produced in Asia (e.g. Nissan Leaf) generates relatively high emissions since a large portion of electricity is generated from coal. However, lifecycle emissions estimates for batteries produced in the US tend to be notably lower than those produced in Asia.[17]

A review of recent studies suggest that battery manufacturing emissions are likely between 41 and 156 kg CO_2-e per kWh of battery capacity, with a current average of about 100 kg CO_2-e per kWh.[10, 17] Average world-wide BEV battery capacity is estimated to be 46 kWh with an uncertainty of 8% (95% CI is 42 – 50 kWh).[23]

The BEV weight is corrected for the weight of the battery. A plausible range for battery energy density is assumed to be 0.12 to 0.16 kWh per kg of battery.[4,24,25,26] Using the plausible range in BEV battery capacity of 42 – 50 kWh, average battery weight is estimated to be 335 kg (plausible range is 265 – 413 kg), which is 20% of total BEV vehicle weight.

Assuming a triangular distribution for vehicle production and battery production GHG emission intensity, a triangular distribution for BEV weight and a conservative uniform distribution for BEV battery capacity and battery weight, Monte Carlo simulation estimates that production of an average Australian BEV is expected to produce between 7.8 and 16.5 tonne of CO_2-e per BEV produced, with a mean value of 11.8 tonne of CO_2-e per BEV. The 95% confidence interval of the mean is 9.4 – 14.3 tonne of CO_2-e per BEV.

Normalised GHG emission rates for vehicle manufacture

LCA studies have typically used lifetime PV mileage between 150,000 and 200,000 km, and even up to 320,000 km.[13] Although there were initial doubts about the durability of BEV batteries, it is clear today that batteries retain more than 90% of the original capacity even at 200,000 km.[10] Therefore 200,000 km appears to be a reasonable estimate of fleet average lifetime mileage for both BEVs and ICEVs. Combining a lifetime mileage of 200,000 km with GHG emission estimates for ICEVs and BEVs gives the following results:

- Manufacture of an Australian ICEV produces on average 48 g CO_2-e/km (95% CI is 42 – 56 g CO_2-e/km).
- Manufacture of an Australian BEV produces on average 59 g CO_2-e/km (95% CI is 47 – 72 g CO_2-e/km).

For the Australian market, BEV production is expected to produce about 20% more GHG emissions as compared with conventional fossil-fuelled passenger vehicles, adding about 10 g CO_2-e per km to total life cycle emissions for BEVs. Previous studies have used 35 to 46 g CO_2-e/km for ICEVs and 37 to 79 g CO_2-e/km for BEVs.[9,17] This study estimates a higher carbon footprint for Australian PVs, which is caused by the large proportion of large and heavy fossil-fuelled passenger vehicles, as compared to for instance the EU market. The estimate for BEVs is within the reported ranges in other studies.

One other study estimated 36 g CO_2-e/km for ICEVs and 46 g CO_2-e/km for BEVs reflecting emissions for vehicle production, but also included vehicle maintenance and disposal.[18] These lifecycle emission rates are significantly lower than the estimates in this study, suggesting that the estimates in this study are conservative. The average difference between ICEVs and BEVs is 10 g CO_2-e/km, which is similar to this study's estimate.

3.2 Infrastructure for electricity generation

Commissioning and decommissioning of fossil-fuelled power plants, fossil fuel processing facilities (refineries, fuel storage) and renewable energy sources (wind farms, solar plants, hydro power, etc.) cost energy and generate GHG emissions. Infrastructure GHG emissions are particularly relevant for renewable energy sources.

One meta study reviewed 33 LCA studies, a number of which quantified GHG emissions due to electricity generating infrastructure.[8] The underlying data were kindly provided by the authors of the meta study and used in a bootstrap analysis (n = 89) to estimate the following plausible ranges for mean infrastructure related GHG emission rates per kWh generated:

- Coal 3.7 g CO_2-e/kWh (95% CI = 0.3 – 10.0)
- Gas 0.7 g CO_2-e/kWh (95% CI = 0.2 – 1.3)
- Oil 2.2 g CO_2-e/kWh (95% CI = 0.7 – 3.9)
- Hydro 7.3 g CO_2-e/kWh (95% CI = 4.2 – 11.9)
- Wind 19.0 g CO_2-e/kWh (95% CI = 13.0 – 25.3)
- Biomass 0.3 g CO_2-e/kWh (95% CI = 0.02 – 0.8)
- Solar 67.8 g CO_2-e/kWh (95% CI = 48.5 – 90.3)

Assuming triangular distributions for these (mean) infrastructure related GHG emission rates and using fuel mix data from the Australian Energy Statistics (AES) presented in Table 4 (refer to section 3.6), Monte Carlo simulation estimates that the average infrastructure GHG emission factor for the current Australian grid lies between 4 and 12 g CO_2-e/kWh (generated), with a mean value of 8 g CO_2-e/kWh. The 95% confidence interval of the mean is 6 – 10 g CO_2-e/kWh.

A different fuel/energy mix is assumed for the marginal electricity (ME) and renewable electricity (RE) scenarios, leading to the following adjustments for 95% confidence intervals of the mean:

- ME range: 1 – 7 g CO_2-e/kWh electricity generated (mean = 4 g CO_2-e/kWh),
- RE range: 23 – 33 g CO_2-e/kWh electricity generated (mean = 28 g CO_2-e/kWh).

As mentioned before, the ME scenario assumes an Australian electricity mix of 73% coal, 24% gas and 3% oil. The RE scenario assumes an Australian electricity mix of 5% coal, 5% gas, 30% hydro, 25% wind, 5% biomass and 30% solar.

Three other variables need to be estimated to quantify operational infrastructure GHG emissions for BEVs per km of driving:

- grid transmission losses (%),
- battery recharging losses (%)[2], and
- real-world electricity use per km (kWh/km).

[2] 'Battery charging losses' are broadly defined and include losses due to building electrical components (charging station or EVSE – Electric Vehicle Supply Equipment, breaker panels, transformers) and electric vehicle components (battery, PEU – Power Electronics Unit).

Used electricity (at the power point) is different from *generated* electricity. Used or consumed electricity needs to account for additional energy losses due to transmission and conversion of electricity (grid losses). A plausible range for transmission/conversion losses appears to be 5 to 10%, with a typical value of 6%.[4,27,28] Used electricity also needs to account for additional energy losses due to due to battery recharging. A plausible range for battery charging losses appears to be 5 to 27%, with a typical value of about 15%.[10,28-32,42] Note that in the LCA model equations (Section 2), grid transmission and battery charging *efficiency* are used rather than losses. Efficiency is computed as 100% minus loss (%).

It is important to estimate real-world electricity use of BEVs. It has been common practice to use type approval laboratory (NEDC, New European Drive Cycle) based measurements of BEV electricity usage reported by vehicle manufacturers. However, NEDC based data are known to underestimate on-road electricity usage of BEVs by about 25 to 35%, and its use will lead to misleading and inaccurate results.[10] A 2018 study estimated fleet average energy consumption of 0.19 kWh/km for Australian BEVs in real-world driving conditions.[3] This value is in line with other studies, which have reported real-world electricity consumption of 0.15-0.21 kWh/km for BEVs of different weights and sizes.[4,23,24] For this study, a plausible range for BEV real-world energy consumption in Australian conditions is considered to be 0.18 to 0.21 kWh/km, with a typical value of 0.19 kWh/km.

Assuming a uniform distribution for infrastructure GHG emissions and triangular distributions for grid losses, battery recharging losses and BEV on-road energy consumption, Monte Carlo simulation estimates that infrastructure GHG emissions per km of driving for BEVs, using electricity from the current Australian electricity grid, lies between 1.2 and 3.0 g CO_2-e/km, with a mean value of 2.0 g CO_2-e/km. The 95% confidence interval of the mean is 1.5 – 2.6 g CO_2-e/km.

3.3 Infrastructure for fossil transport fuels

For oil refineries an initial average infrastructure GHG emission factor is estimated as follows. First a plausible range for ‘oil’ is assumed to be between 0.7 and 3.9 g CO_2-e/kWh electricity generated (see previous section). These values are converted to 0.1 to 0.5 g CO_2-e per MJ of fuel assuming a power plant efficiency between 38 and 48% and a conversion factor of 3.6 MJ/kWh. The energy content of crude oil is taken as 45.3 MJ/kg fuel.[33] This then converts to a 3 to 24 g CO_2-e per kg of fuel.

Using the average on-road fuel consumption of 80 g per km for PVs (refer to Section 3.7) then computes an average infrastructure GHG emission factor range for refineries of approximately 0.3 to 1.9 g CO_2-e per km. It is noted that this value is quite uncertain, and that the plausible range may in fact be inaccurate. It effectively assumes that GHG emissions due to commissioning and decommissioning of a refinery are approximately similar to an oil-fuelled power generation facility. Nevertheless, the error of omission (i.e. assuming zero emissions for refinery commissioning and decommissioning) is considered larger than the error in the estimated range.

3.4 Electricity generation – Upstream

Upstream emissions resulting from the mining and transport of the power plant feedstock needs to be accounted for in the LCA. These are GHG emissions due to upstream extraction, transport, production and distribution of fossil fuels used in electricity generation.

The National Greenhouse Accounts (NGA) provide 'Scope 3' GHG emission factors for electricity production in Australia. Scope 3 accounts for extraction and production of purchased materials and transport of purchased fuels. These emission factors are provided for Australia as well as for individual states and territories. For Australia, the average upstream GHG emission factor for *consumed* electricity is 90 g CO_2-e/kWh for the 2017-2018 financial year, which is 10% of the total GHG emission factor. Emission rates vary greatly among jurisdictions, i.e. a minimum of 20 g CO_2-e/kWh (Tasmania) and a maximum of 120 g CO_2-e/kWh (Queensland).[33]

A similar range has been reported in other studies. For instance upstream emissions for different subregion grids in the USA vary between 27 and 140 g CO_2-e/kWh.[4] A bootstrap analysis using the USA data (n = 27) suggests that the uncertainty in the average national emission factor of 90 g CO_2-e/kWh is about ±15%. The resulting plausible range for the average upstream GHG emission factor for consumed electricity in Australia is 77 to 104 g CO_2-e/kWh.

An alternative calculation uses data from the meta study which reviewed 33 LCA studies.[8] As mentioned before, the underlying data were kindly provided by the authors of the meta study and used in a Monte Carlo simulation. Using fuel mix data from the Australian Energy Statistics (AES) presented in Table 4 (refer to Section 3.6) and assuming a triangular distributions for upstream fuel GHG emissions (by fuel type) and grid losses (refer to Section 3.2), Monte Carlo simulation estimates that average upstream GHG emissions for consumed electricity in Australia lies between 44 and 88 g CO_2-e/kWh (consumed), with a mean value of 65 g CO_2-e/kWh. The 95% confidence interval of the mean is 53 – 79 g CO_2-e/kWh.

These values are significantly lower than the average national emission factor of 90 g CO_2-e/kWh, suggesting this value may be too conservative. The plausible range for the average upstream fuel GHG emission factor for *consumed* electricity in Australia is therefore adjusted to 53 to 104 g CO_2-e/kWh.

Using the different fuel/energy mix for the marginal electricity (ME) and renewable electricity (RE) scenarios, the plausible ranges are adjusted to:

- ME range: 65 – 128 g CO_2-e/kWh electricity consumed,
- RE range: 8 – 14 g CO_2-e/kWh electricity consumed.

Assuming a uniform distribution for upstream fuel GHG emission factors and triangular distributions for battery recharging losses and BEV on-road energy consumption, Monte Carlo simulation estimates upstream fuel GHG emissions per km of driving for BEVs using electricity from the current Australian electricity grid between 10 and 29 g CO_2-e/km, with a mean value of 18 g CO_2-e/km. The 95% confidence interval of the mean is 12 – 25 g CO_2-e/km. It has conservatively been assumed that the proportion of BEV users that generate their own sustainable electricity (solar panels) for battery recharging is zero.

3.5 Fossil fuels for transport – Upstream

Section 3.7 will quantify GHG emissions from ICEVs while driving on the road. However, extraction, transport, production and distribution of refined fossil fuels such as petrol and diesel also require energy and produce GHG emissions.

Well-to-wheel data for petrol, diesel, propane and butane, and methane provisions reveal that up to 14 to 25% of the contained energy in the fuels[3] is consumed within the chain, with an estimated average value of 20%.[9,10,24,27] Combining this range with average fuel consumption (litres per km) for the Australian PV fleet results in an estimate of 37 to 64 g CO_2-e/km, and a typical value of 51 g CO_2-e/km.

Previous studies have reported 0.67 kg CO_2-e per litre of fuel for upstream emissions. This value is an estimate by the GREET life cycle emissions model[4], developed by the Argonne National Laboratory in the USA.[6] Combining this figure with average fuel consumption (litres per km) for the Australian PV fleet results in a higher estimate of 72 g CO_2-e/km. There is substantial variation in reported upstream CO_2 emissions due to fossil fuel (diesel and petrol) production. A uniform distribution is therefore assumed with a range of 37 to 72 g CO_2-e/km.

3.6 Operational (on-road) battery electric vehicles

Indirect emissions due to electricity generation need to be estimated to quantify GHG emissions for BEVs. The Australian Energy Statistics (AES) provide data on the fuel mix used for electricity generation.[34] It includes all electricity generation, e.g. by fossil-fuelled power plants and generation by households and businesses. An overview by fuel type is shown in Table 4. In 2018, 19% of Australia's total electricity production of 263 TWh was produced with renewable energy sources (solar, wind, hydro, biomass). This percentage is slowly climbing up. For instance, in 2019 this percentage was 21%.

Table 4 – Australian electricity generation by fuel type for 2018 (GWh and %).

Coal	Natural Gas	Oil	Hydro	Wind	Biomass	Solar
156,545	51,374	5,422	17,492	16,412	3,554	12,279
60%	20%	2%	7%	6%	1%	5%

[3] In the exceptional case of methane, pumped trough up to 7,000 km from Siberia to Europe, there is a loss of up to 35%.[10]

[4] GREET = Greenhouse Gases, Regulated Emissions and Energy Use in Transportation.

The National Greenhouse Accounts (NGA) provide 'Scope 2' GHG emission factors for electricity production in Australia. These emission factors are provided for Australia, as well as for individual states and territories. The GHG emission factors reflect the electricity fuel mix (fossil fuels, renewables) and include grid transmission loss2.es, i.e. GHG emission rate per kWh consumed at the power point. Renewable energy sources are assumed to have zero GHG emissions. For Australia, the average GHG emission factor is 790 g CO_2-e/kWh for the 2017-2018 financial year. Emission rates vary greatly among jurisdictions, i.e. a minimum of 150 g CO_2-e/kWh (Tasmania) and a maximum of 1,020 g CO_2-e/kWh (Victoria), reflecting differences in the use of fossil fuels and renewables.[33]

Industry reports electricity production and Scope 1 and 2 GHG emissions to the Clean Energy Regulator (CER).[35] These data are publicly available for the individual corporations, which allows for further examination of emission intensity by energy source. For the 2018-2019 financial year a total grid connected electricity generation of 228 TWh was reported, which is lower than the 263 TWh reported by the AES. This is probably because generation by households and small businesses is not included. For instance, the CER data suggest only 1% solar, whereas AES reports 5%. The CER total includes fossil fuels as well as renewables. Total reported CO_2-e emissions are 170 million tonnes. This equates to an average 'grid connected' emission factor of 745 g CO_2-e/kWh *produced*, which is 6% lower than the NGA factor of 790 g CO_2-e/kWh *consumed*. The difference is likely explained with grid transmission losses, which are not included in the CER data.

The CER data were used to estimate GHG emission factors for each energy source. A (weighted) bootstrap analysis was used to quantify the uncertainty (95% confidence interval) in these emission factors. The results are shown in Table 5. Uncertainty in fossil fuel emission factors is about ±8% for coal and gas, but larger (about ±35%) for (diesel) oil. Reported GHG emissions for renewables are not zero, albeit relatively small.

Table 5 – Australian electricity generation GHG emission factors by fuel type (g CO_2/kWh).*

Variable	Coal	Natural Gas	Oil	Hydro	Wind	Biomass	Solar
EF Mean	957	512	1,550	45	2	121	6
EF LCL **	890	473	1,008	1	1	34	3
EF UCL**	1,037	553	2,067	94	2	409	11

* Bootstrap simulation

* LCL = lower 95% confidence limit; UCL = lower 95% confidence limit

The bootstrap analysis shows that the uncertainty in the average 'grid connected' emission factor of 738 g CO_2-e/kWh is about ±15%, with a 95% confidence interval of 623 to 831 g CO_2-e/kWh *generated*.

For the alternative scenarios (ME and RE):

- A 'fossil fuels only' (coal, gas, oil) marginal GHG emissions factor for the Australian electricity grid is estimated to be 878 g CO_2-e/kWh, with a 95% confidence interval of 797 to 956 g CO_2-e/kWh *generated*.
- A renewable GHG emissions factor for the Australian electricity grid is estimated to be 95 g CO_2-e/kWh, with a plausible range of 80 to 110 g CO_2-e/kWh *generated*.

Three other variables need to be estimated to quantify operational GHG emissions from BEVs, or rather GHG emission rate per km of driving:

- real-world electricity use per km (kWh/km),
- grid transmission losses (%), and
- battery recharging losses (%).

These variables were discussed previously (Section 3.2). A plausible range for BEV real-world energy consumption in Australian conditions is considered to be 0.18 to 0.21 kWh/km, with a typical value of 0.19 kWh/km. The last two variables are used to estimate emission intensity of total *consumed* electricity (g CO_2-e/kWh). A plausible range for transmission/conversion losses appears to be 5 to 10%, with a typical value of 6%.[4,27,28] A plausible range for battery charging losses appears to be 5 – 27%, with a typical value of about 15%.[10,28-32,42] Assuming a triangular distribution for transmission/conversion and battery charging efficiencies, Monte Carlo simulation estimates a mean combined efficiency of 78%, i.e. a combined energy loss of 22% for BEVs. The 95% confidence interval of the mean combined efficiency is 70 to 86%.

Assuming triangular distributions for 'grid connected' emission rates, grid losses, battery recharging losses and BEV on-road energy consumption, Monte Carlo simulation estimates that the on-road GHG emission rate per km of driving for BEVs is between 131 and 247 g CO_2-e/km, with a mean value of 181 g CO_2-e/km. The 95% confidence interval of the mean is 152 – 213 g CO_2-e/km. It has conservatively been assumed that the proportion of BEV users that generate their own sustainable electricity (solar panels) for battery recharging is zero.

3.7 Operational (on-road) fossil-fuelled vehicles

The Australian Fleet Model (AFM) was used to create an input file for the vehicle emissions software COPERT Australia, reflecting the Australian on-road fleet for base year 2018.

AFM is a fleet turnover simulation software that estimates the on-road vehicle population and total (vehicle) kilometres travelled (VKT) for 1,240 vehicle categories for a prespecified range of base years, e.g. 2010-2050.[1] COPERT Australia v1.3.5 was then used to create a national Australian motor vehicle emission inventory for base year 2018. COPERT Australia predicts emissions for 226 Australian vehicle classes and accounts for the effects of e.g. driving behaviour, meteorology, and fuel quality.

In addition, total fuel consumption by fuel type was estimated for 2018 using data from the Survey of Motor Vehicle Use (SMVU) published by the Australian Bureau of Statistics, as well as data provided by the Federal Government, i.e. Australian Energy Statistics (AES) and Australian Petroleum Statistics (APS). [34,36,37] Total fuel consumption for road transport by fuel type is shown in Table 6. A total of almost 35 billion litres of fossil fuel was consumed by road transport in 2018.

Table 6 – Fuel consumption for Australian road transport for 2018 (million litres).

Petrol	E10	Diesel	Biodiesel	LPG	CNG	Total
15,099	2,449	15,666	12	1,100	434	34,760

AFM and COPERT Australia slightly underpredicted total fuel consumption with 2%. So VKT was adjusted (calibrated) to ensure total fuel use predictions were equivalent to the values reported in Table 6. COPERT Australia predicts that total GHG emissions from road transport in 2018 equals 85.1 million tonnes of CO_2-e, which is similar to the value reported by the Australian Greenhouse Emissions Information System (AEGIS), i.e. 85.2 million tonnes of CO_2-e [38], a difference of 0.1%.

Analysis of the AFM/COPERT Australia results show that average GHG emission rates are 247 g CO_2-e/km for petrol vehicles and 318 g CO_2-e/km for diesel vehicles. Diesel passenger vehicles have GHG emissions per kilometre that are 28% higher than their petrol counterparts. A recent study found that the main reason for this is that Australian diesel PVs are, on average about 40% heavier than petrol PVs.[1] Other diesel vehicle design parameters also adversely affect CO_2 emission rates, including a higher proportion of 4WD vehicles, 15% higher engine capacity and a low portion of CVT transmissions.[1] The fuel-efficient and climate friendly image for diesel PVs is misconceived in Australia, as they have, on average, significantly higher GHG emission rates (g/km) than Australian petrol PVs.

Further analysis of the AFM/COPERT Australia results show that average fuel consumption rate is 80 g/km. The corresponding GHG emissions rate for the on-road passenger vehicle (PV) fleet (i.e. petrol and diesel cars and SUVs) in 2018 is 257 g CO_2-e/km. A (weighted) bootstrap analysis shows that the uncertainty in this fleet average emission factor is ±8%, i.e. 95% confidence interval is 238-279 g CO_2-e/km.

The SMVU (ABS, 2019) provides information on the uncertainty (relative standard error) of the estimates for total fuel consumption and VKT. This information suggests total fuel consumption for passenger vehicles is accurate within ±5%, whereas this is ±6%, ±11% and ±22% for petrol, diesel and LPG/CNG, respectively. A previous study (ABS, 206) reported that estimates of automotive petrol consumption have been 5-15% lower than petrol sales, so perhaps the uncertainty is larger. Total VKT for passenger vehicles is accurate within approximately ±5%. The bootstrap results of ±8% align with the reported uncertainty in fuel consumption and VKT of 5 – 11%.

3.8 Vehicle recycling and disposal

The assessment of recycling and disposal impacts in an LCA can be prohibitively difficult for a product as complex as a vehicle. GHG emissions from vehicle end-of-life have been found to be small as compared to the operational use phase and are therefore often ignored or included in the vehicle manufacturing LCA aspect.[6,39,40,41] In fact the end-of-life material recycling process of the vehicles and batteries can offset the emissions during manufacturing (extraction of raw material) to a certain level.[13]

Generally, a vehicle's end of life impact (recycling and disposal) reportedly shows a limited contribution in terms of environmental impacts below 1%.[40] The impact is dependent on the amount of recycling of vehicle materials.

The Australian Fleet Model shows that about 14 million passenger vehicles were active in the on-road fleet in 2018 and that about 96% survives each subsequent base year, i.e. 4% of the vehicles are scrapped, which equates to 560,000 vehicles. The average weight of an Australian PV is 1,800 kg, which means that about 1 million tonnes of vehicles are scrapped and recycled each year in Australia.

A general energy consumption of 66 kWh/ton has been assumed for the recycling process.[40] Using this value in combination with the previously discussed average NGA 'grid connected' emission factor for Australia of 790 g CO_2-e/kWh (Scope 2) plus the average upstream GHG emission factor for consumed electricity of 90 g CO_2-e/kWh, i.e. 880 g CO_2-e/kWh, computes 58,545 tonne of CO_2-e each year due to vehicle recycling. Dividing this value by total VKT (i.e. 560,000 vehicles times lifetime mileage), results in a GHG emission rates due to disposal of 0.5 g CO_2-e/km, indeed a low figure. An initial plausible range of 0.1 to 1.0 g CO_2-e/km has been assumed for vehicle recycling and disposal.

The same value is used for ICEVs and BEVs. It is possible that recycling and disposal of BEVs have a higher GHG impact than ICEVs due to batteries. However, BEVs also have a lighter weight than ICEVs, reducing the impact. In addition, BEV batteries can have a second use as stationary applications to act as a storage buffer for fluctuating renewable electricity generation. This can decrease the vehicle's carbon footprint caused by the battery by 50%.[10] Indeed, the recovering and recycling of the materials used in BEV batteries has increased significantly due to the high costs of the raw materials for their production.[40] In any case, the difference between BEVs and ICEVs regarding end-of-life recycling or disposal processes are trivial due to the relatively small impact of this LCA aspect.

4. Conclusions

This study assessed the life cycle impacts of electric and fossil-fuelled passenger vehicles in the Australian market. The need to rapidly decarbonise the transport system and achieve international GHG emission reduction targets will require deep cuts in greenhouse gas emissions from the transport sector. It is therefore essential to know if electrification of the Australian passenger vehicle fleet will reduce GHG emissions, and if so, by how much and when. There is much at stake.

This study has attempted to provide a solid answer to this question by being comprehensive in scope (life cycle assessment), as well as being clear about the level of uncertainty associated with the answer.

The uncertainty in the various inputs was explicitly considered through a probabilistic analysis. This approach is useful as it quantifies the uncertainty in the GHG emission impacts of both electric and fossil-fuelled vehicles, and importantly the difference in their impacts. The method provides information about the robustness of study outcomes in relation to the variability and uncertainty in inputs and reflects the impacts of incomplete knowledge. In addition, probabilistic methods can guide further improvement work through collecting more accurate information for important LCA inputs. This study therefore provides an assessment framework in which study results can be expanded and refined when new information comes to light.

The results of this study shows that, accounting for variability and uncertainty in GHG emission factors in all relevant life cycle aspects of ICEVs and BEVs, electric passenger vehicles are expected to significantly reduce average life cycle GHG emission rates for passenger vehicles with a high level of confidence. These results are in line with other international assessments.[11,13]

The weight of evidence suggests that:

- BEVs will reduce GHG emission rates (g/km) with 28% on average for the current (2018) Australian electricity mix, which is still largely fossil fuels based. The uncertainty in this result is a reduction between 16% to 40% (95% confidence interval).
- BEVs will reduce GHG emission rates (g/km) with 17% on average in a worst case (short term) 100% fossil-fuelled marginal Australian electricity mix. The uncertainty in this result is a reduction between 5% to 29% (95% confidence interval).
- BEVs will reduce GHG emission rates (g/km) with 74% on average in a more renewable Australian electricity mix. The uncertainty in this result is a reduction between 67% to 82% (95% confidence interval).

This study therefore concludes that rapid electrification of the Australian PV fleet is a robust way to reduce GHG emissions from road transport. It will immediately provide significant reductions in GHG emissions per kilometre travelled. GHG emissions will continue to drop further as Australia’s electricity system is increasingly decarbonised, and BEVs penetrate the on-road fleet.

5. Recommendations for further work

Since this work was unfunded, the scope was restricted. Below are suggestions for further work.

- Repeat the study for individual states and territories in Australia.
- Assess the impact of different definitions of plausible range, e.g. 99% confidence intervals instead of 95% confidence intervals.
- Collect more data and information regarding the plausible range of input variables and their associated distributions (e.g. Cauchy distribution) and consider the impacts of these different input distributions on the LCA results.
- Further examine statistical dependencies in the inputs and update the models.
- Perform a sensitivity analysis to identify the most relevant input variables. It is important to identify the key drivers of impact in order to limit the burden and expense of data collection for a better characterization. Moreover, this information helps decision-makers to identify the area that causes the decision to change.[11]
- Expand the LCA models and include additional variables, e.g. driving behaviour (trip statistics), BEV charging patterns, consumer purchasing behaviour, etc.[11] For instance, incorporation of new information on BEV sales (e.g. which BEV make/models replace which ICEV make/models?).

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