The Victorian Electric Vehicle Trial

Environmental Impacts of Electric Vehicles in Victoria

November 2012

State Government Victoria

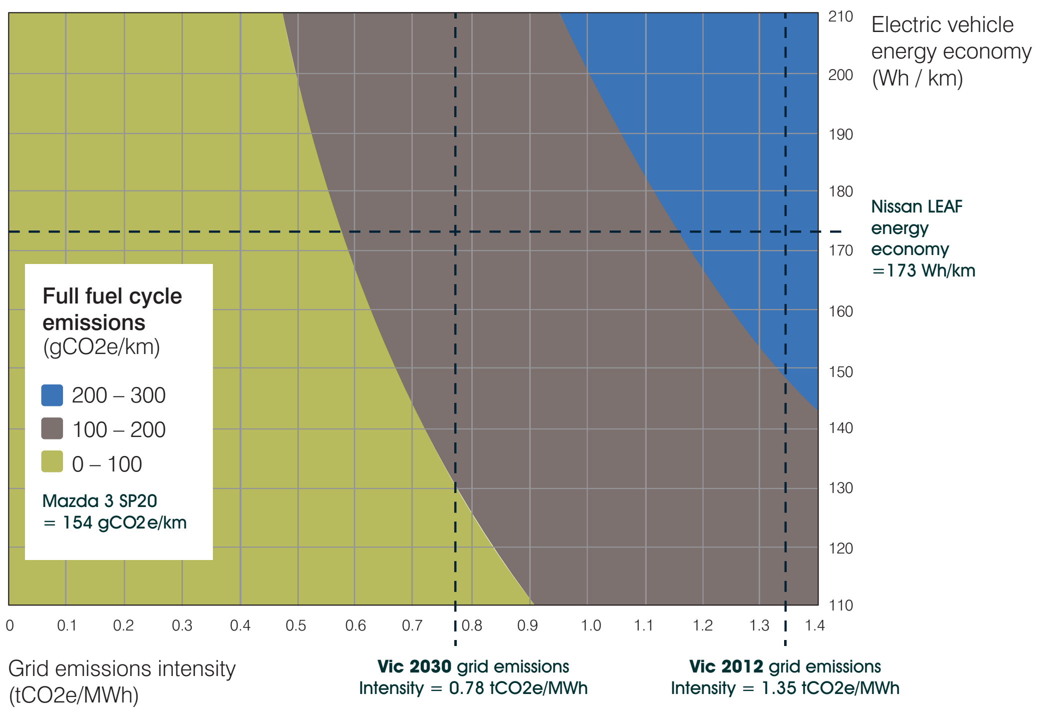
Executive Summary

With the recent arrival of electric vehicles (EVs) onto Victorian roads, it is an appropriate time to consider the environmental impacts arising from this new technology. This paper conducts a comparative assessment of the environmental impacts of electric vehicles relative to their 'conventional' petrol vehicle counterparts in Victoria from now until 2030.

The finding is that the impacts from vehicle operation far outweigh those from vehicle production. This is true even if we allow for an EV battery replacement over the vehicle life. Vehicle disposal impacts, including those of the EV battery, were found to be negligible due to the expected high rate of material recycling.

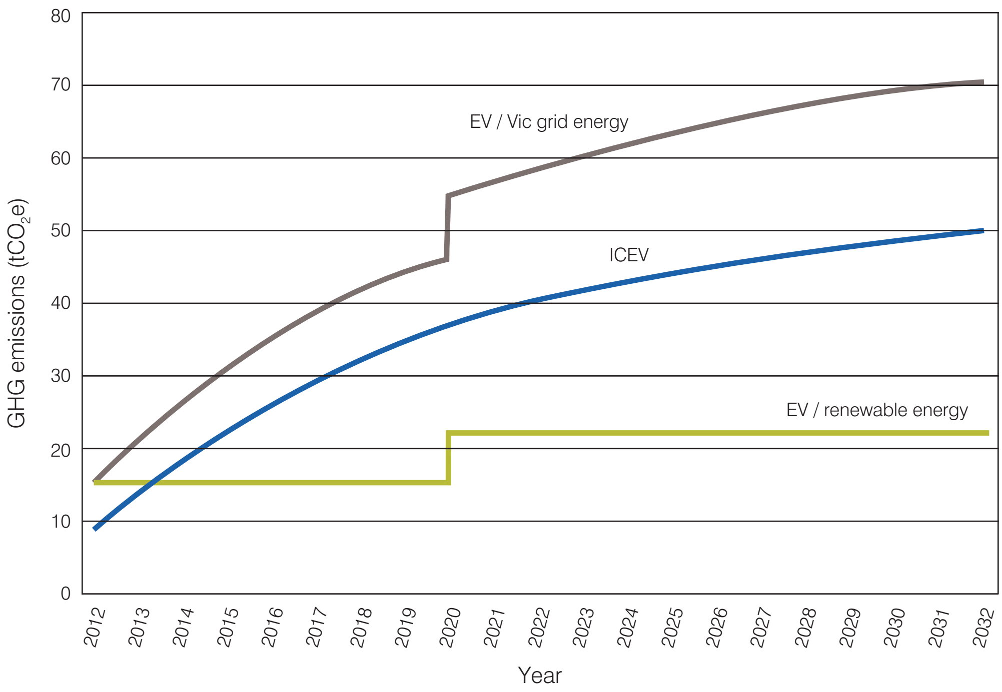
The dominant influence of vehicle operation during the EV lifecycle highlights the importance of the way in which electricity is made, how efficient energy conversion is, and the way a vehicle is used. Figure (a) below shows the impact of electricity production and vehicle energy efficiency on environmental performance.

Figure a. Chart depicting the interrelationship between EV energy economy and and the electricity grid emissions intensity in determining full fuel cycle greenhouse gas emissions, including some pertinent figures for comparison (DIT 2012, DCCEE 2012b, personal communications).



The source of the electricity used to power electric vehicles is a key issue in Victoria. Despite various influences driving decarbonisation of the stationary energy sector, projections indicate that for a vehicle operating on Victoria's grid electricity, the breakeven point in terms of carbon emissions from vehicle operation is some years away. Conversely, an electric vehicle operating on renewable energy may provide a net benefit in terms of lifecycle carbon emissions within three years of operation. Figure (b) below shows how this translates to a saving of over 50 per cent across the 20-year average Victorian vehicle lifetime.

Figure b. Cumulative greenhouse gas emissions calculated over an average Victorian vehicle lifetime for an ICEV and a comparable EV operating on both the Victorian electricity grid mix and renewable energy. The step change in both EV calculations reflects impacts arising from the single battery replacement forecast. (Patterson et al 2012, DIT 2011 and 2012, DOT 2011 personal communications).



Electric vehicles are inherently more efficient than their petrol equivalents at converting energy into motion. This advantage grows as the operating conditions tend towards more 'stop-start' driving such as is found in cities. Given the strong influence influence of vehicle energy economy on overall environmental impacts, better information and guidance on the selection of vehicle technologies, particularly EVs, so as to be 'fit-for-purpose' could provide significant benefits.

Other observations about greenhouse gas emissions from electric vehicle operation include:

- Victorian electricity generation mix characteristics mean that 'demand' charging during peak periods of electricity use is likely to be of lower greenhouse gas emissions intensity than 'smart' charging during off-peak periods.
- Renewable energy charging strategies that depend upon on-site energy generation, such as home solar systems, are complicated by the likely mismatch between energy production and use, and by the electricity market arrangements that relate to grid-connected systems.
- GreenPower or Renewable Energy Certificate purchases are the simplest, most effective path for renewable energy EV charging strategies.
- Publicly-accessible EV charging outlets require transparency and assurances to support renewable energy EV charging strategies.
- Charging network service providers who can provide a clear, independently-verified renewable energy supply commitment may be the simplest, most flexible path to 'zero emissions' EV driving.

As electric vehicles gain in popularity, there are a few existing and emerging risks to the environment to consider. The EV battery and electric motor may cause harmful impacts to land, water and air quality if using raw materials and/or production processes from locations that have weak or poorly-enforced environmental regulations. However, these risks are already evident for the oil and Rare Earth metal extraction and/or processing that supports 'conventional' vehicles operating on Victorian roads.

Nevertheless, greater transparency about the environmental impacts from EV battery production would go some way towards ensuring all of the nominal environmental benefits from EV uptake translate to reality. A further sensitivity relates to battery replacement timeframes, which have the effect of multiplying the uncertain impacts associated with battery production. Despite these uncertainties, current data suggests that up to six battery replacements would be possible over a vehicle life before the greenhouse gas emissions advantage of an EV operated on renewable energy over a petrol vehicle would be lost.

Impacts arising from increases in electricity production are considered to be minimal as a result of Victoria's effective program of environmental management for industrial facilities. Rather, impacts on the environment are likely to be reduced through avoidance of the transferred impacts attributable to oil extraction processes, and from preferential use of renewable energy for EV charging.

Due to Victoria's carbon-intensive electricity production, potential localisation of any aspects of EV production may increase the embodied greenhouse gas emissions of the vehicles. This conclusion draws upon evidence that highlights Victoria's existing vehicle production as being more carbon-intensive than for comparable facilities elsewhere.

Benefits to urban air quality and human health are likely to be minimal as the period of EV market growth corresponds with the implementation of ever-tighter emissions standards for conventional vehicles. A more detailed assessment of this may become available in the near-term as an outcome from the Environment Protection Authority's Future Air Quality in Victoria project.

Environmental impacts arising from EV electromagnetic fields are likely to be negligible, EV near-silent operation at low speeds is likely to be manageable, and EV reduced traffic noise impacts are likely to be beneficial.

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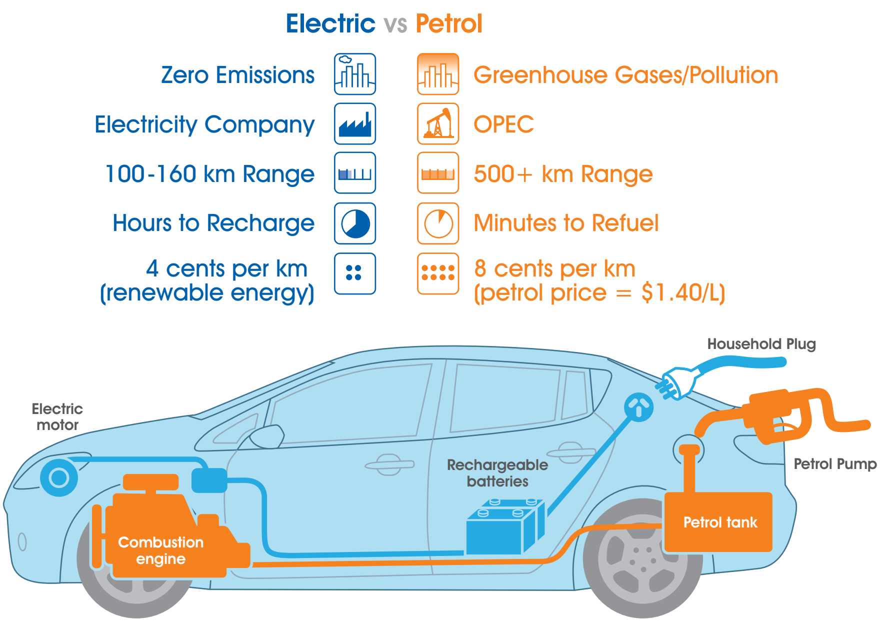
1. Objective

The aim of this paper is to investigate the environmental impacts of Electric Vehicles (EVs) in Victoria, now and out to the year 2030. The outcomes will include key issues that may inform decision-making and potential areas for future work.

2. Background

Electric Vehicles (EVs) have started to arrive on Victoria's roads. Most major vehicle manufacturers are delivering EVs into the market. In 2012, Mitsubishi, Nissan, Holden and Renault will all deliver EVs into Victoria, with Ford, Toyota and BMW having models in the pipeline. As a starting point for this discussion paper, answers to some common EV questions are provided below.

Figure 1. Schematic illustrating the functional and operational differences between vehicle types.



2.1. What is an Electric Vehicle (EV)?

An EV is any vehicle that uses electricity as energy for propulsion. When compared to a conventional Internal Combustion Engine (ICE) vehicle, the main differences are:

- EVs have an electric motor instead of an ICE
- EVs store energy in a battery rather than a fuel tank
- EVs source energy via a plug and cable rather than a petrol bowser.

Refer to Figure 1 below for a diagram that illustrates the functional and operational differences between vehicle types.

2.2. Why EVs?

Nominally, EVs provide a range of benefits when compared to conventional ICE vehicles:

- Operating cost savings, due to the lower costs of electricity relative to liquid fuels, and the higher efficiency and lower maintenance costs of electric drivetrains
- Greenhouse gas emission reductions, particularly when run on renewable energy
- Air quality improvements for populated areas due to the zero tailpipe emissions
- Traffic noise reductions, through the near-silent operation of the electric drivetrain
- Local employment benefits through the use of domestically-produced electricity to replace imported oil (which also assists in reducing our Balance of Payments).

EVs hold much potential to help address the environmental impacts of transport in Victoria:

- Transport makes up 16 per cent of Victoria's emissions – the second-largest sectoral contribution behind stationary energy (DCC 2007)
- Road transport made up over 90 per cent of emissions from the transport sector, with two-thirds estimated as coming from passenger cars (DCC 2007)
- Motor vehicles are the main source of urban air pollution (EPA 2012a) – studies have found that motor vehicle pollution in Melbourne is associated with reduced quality of life and premature death (BTRE 2005)
- Road traffic noise has been identified as the most common noise source in Victoria – it is heard by 70 per cent of residents and significantly 'bothers, annoys or disturbs' 20 per cent of the population annually (EPA 2007).

2.3. What types of EVs are available?

There are different types of EVs that vary according to the extent to which they rely upon electricity as their energy source. The various types can be roughly classified as follows – refer also to Figure 2 below:

- **Hybrid-Electric Vehicles (HEVs)** have been on Victorian roads for over 10 years through cars such as the Toyota Prius and Honda Civic Hybrid. They use liquid fuel (petrol) as their sole external energy source, but supplement this with electrical energy captured from the braking system and stored in batteries.
- **Plug-in Hybrid-Electric Vehicles (PHEVs)** source both electrical energy and liquid fuel from external sources. They vary in their choice of primary energy source, with the Toyota Prius PHEV biased towards petrol and the Holden Volt favouring electricity. They are easily differentiated from HEVs as they have a plug.
- **Battery Electric Vehicles (BEVs)** use electrical energy as their sole energy source. BEVs available in the Australian market include the Nissan LEAF, Mitsubishi i-MiEV and Renault Fluence ZE.

As only PHEVs and BEVs use plugs to source electrical energy, they are collectively known as Plug-in Electric Vehicles (PEVs).

Through the remainder of this paper the term 'EV' will be used to denote vehicles which use solely electrical energy (that is, Battery Electric Vehicles described above).

2.4. How does EV charging work?

Similar to mobile phones or other portable electronic devices, EVs charge their batteries via a plug into an electrical outlet.

As they contain large batteries, EVs can take hours to recharge. But as this process can take place unattended, EVs can charge while they're parked, allowing drivers to get on with living life.

Some EVs will include the ability to swap their depleted batteries for fully charged replacements at dedicated swap stations, while others may be able to use wireless induction-charging similar to electric toothbrushes. The majority of EV charging in the near-term will however occur via a plug/cable combination as for other electrical appliances.

Charging takes place where EVs park – the home, workplace, shopping centre car-parks etc. As charging occurs unattended, EV drivers can simply arrive at their destination, plug in, and walk away. A simplified day-in-the-life of a corporate fleet EV based in Melbourne's CBD is provided in Figure 3 below to help explain how charging works.

Most EVs can be charged significantly more rapidly using high-current, three-phase power delivered through 'quick-chargers'. This quick-charging capability exists alongside the standard charging described above and uses dedicated equipment. Quick-charging is something that most EV drivers would use only occasionally to supplement their standard charging.

Figure 2. Schematic of the various EV types – note that only PHEVs and BEVs draw energy from an external source of electricity via a plug, and so are known as Plug-in Electric Vehicles (PEVs).

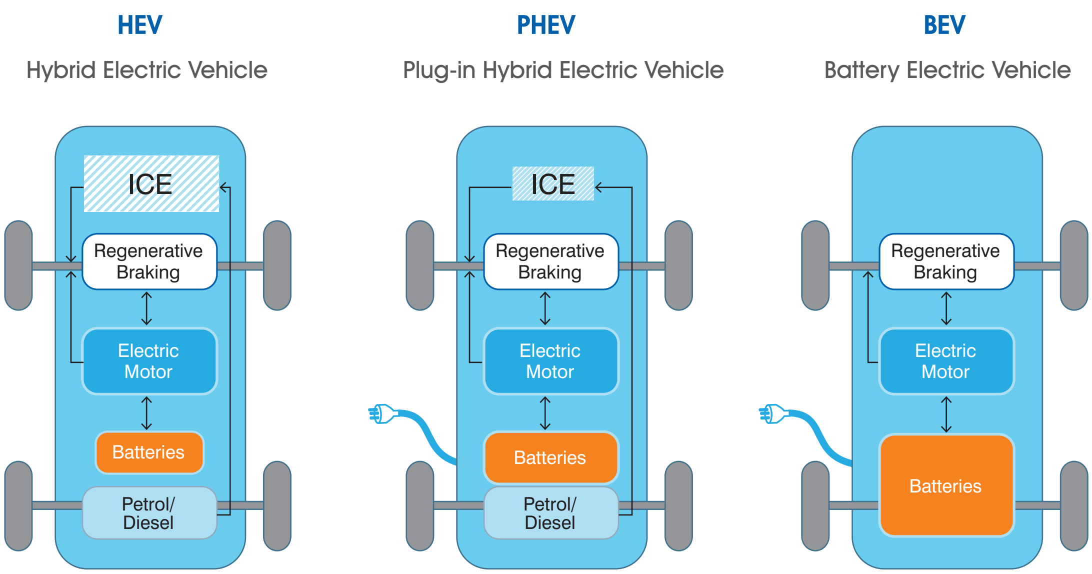
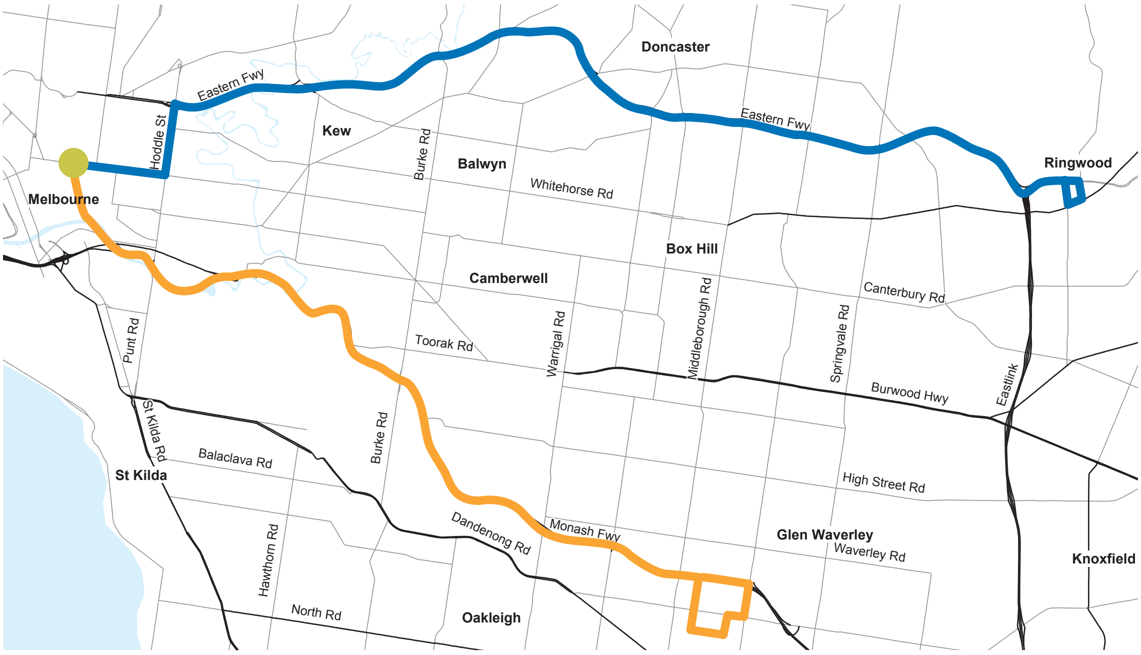
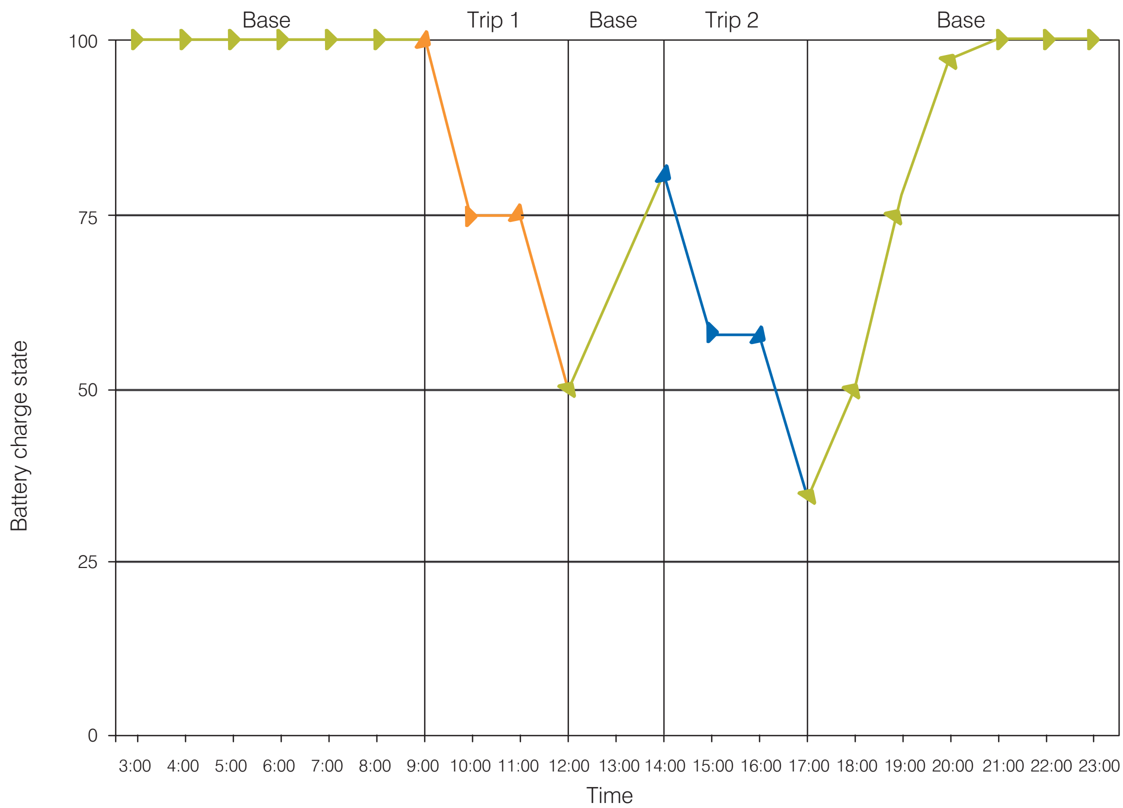


Figure 3. A day-in-the-life of a corporate fleet EV – the map (top) shows the route for two 50 km round-trips taken from Melbourne CBD, while the chart (underneath) shows the battery charge state as the EV completes these journeys along with an "opportunity" charging event between 12 and 2pm and "overnight" charging from 5pm. The figures assume that the EV has a range of around 100 km, a zero-to-full charging time of 6 hours using standard (240 v / 15 A) charging.





2.5. What's the outlook for EVs in Victoria?

Modelling commissioned by the Department of Transport (AECOM 2011) suggests that EVs will be a mainstream market choice by 2020 making up around a quarter of new vehicle sales. Key factors that influence this outcome are oil prices relative to electricity, EV prices relative to ICE vehicles, and the availability of public charging infrastructure.

Deutsche Bank (2010) have published forecasts predicting greater near-term demand for oil, along with rapidly falling lithium-ion battery prices and a greater rate of reduction in batteries and electric drive components. If these forecasts prove correct, the point at which EVs became a more financially-prudent choice relative to ICEVs would occur sooner than what was predicted above.

2.6. Why assess the environmental impacts of EVs?

Environmental costs arising from motor vehicles are significant. In Australia, the number of passenger vehicles grew by 12.6 per cent, from 10.9 million to 12.3 million, in the five years between March 2005 and March 2010 (ABS 2011). Victoria made the second largest contribution to these figures, at 25.6 per cent or 4.1 million. The number of motor vehicles per resident population has also grown. In the five years between March 2005 and March 2010, the number of motor vehicles grew from 686.3 per 1,000 residents to 721.1 per 1,000 residents, representing a growth of 34.8 vehicles per 1,000 residents (ABS 2011). This growth has implications across the vehicle lifetime, from production through the service life up until final disposal. The average age of registered vehicles in Australia was 10.0 years as at March 2010 (ABS 2011), meaning that 6.15 million vehicles will leave the current Australian fleet by 2020. This figure highlights the need to understand the environmental impacts arising from the vehicle disposal phase alone.

Much is known about the environmental costs of producing and operating an internal combustion engine vehicle (ICEV) and the effects on the environment. In contrast, information about the wide range of EVs is beginning to emerge as the technology develops. With any new technology it is difficult to understand the full range of impacts that wider acceptance and use will bring over time. For example, while EVs produce no tail-pipe emissions and do not rely on oil/petrol for operation, in Victoria they rely on coal-generated electricity for their fuel source. More EVs will mean more demand on electricity supply – the implications of this in the context of Victoria's historical dependence upon carbon-intensive brown coal should be understood.

EVs also have unique components (for example, the battery) which pose their own issues for production, use and disposal at the end of their life. As EVs are only beginning to arrive in the market, the impacts from a much greater number of vehicles should be investigated to ensure good outcomes.

Although EV technology is highly efficient in terms of energy conversion, the entire lifecycle of the vehicle should be taken into account to determine true environmental impacts. Only through a holistic examination the vehicle lifecycle can conclusions be formed regarding operating benefits and costs, for example taking battery production and disposal into account.

This paper seeks a greater understanding of the environmental impact assessment of EVs. It outlines what is known and what needs to be investigated to plan for the imminent wider use of EVs in Victoria.

3. How to Assess the Environmental Impacts of EVs?

3.1. Environmental Impact Assessment (EIA)

A description of Environmental Impact Assessment (EIA) begins with a definition of key terms.

There are varying definitions of 'the environment', as is illustrated by comparison of some definitions applied in the Victorian context. According to the Victorian *Environment Effects Act* 1978, the environment:

...includes the physical, biological, heritage, cultural, social, health, safety and economic aspects of human surroundings, including the wider ecological and physical systems within which humans live.

In contrast the Victorian *Environment Protection Act* 1970 defines 'environment' as:

The physical factors of the surroundings of human beings including land, waters, atmosphere, climate, sound, odours, tastes, the biological factors of animals and plants and the social factor of aesthetics

Determination of what constitutes 'the environment' is the first step in the design of any EIA process. This definition forms one component of the 'system boundary', which along with other dimensions such as spatial and temporal can be thought of as the EIA scope.

The definition of 'impact' at its most basic level is 'a marked effect or influence' (Oxford 2012). For an EIA this definition may be further nuanced to 'the difference between what would happen with the action and what would happen without it' (IAIA 2009).

In order to conduct an *'assessment'*, each aspect of the environment requires one or more metrics, known as *'environmental indicators'*, which are:

Measurable – able to be quantified in a reliable, robust manner

Meaningful – accepted as being a representative indication of condition for the attribute of the environment that they represent

Comprehensive – collectively account for the definition of the environment adopted

This entails that for any given proposal or activity, an EIA will be a relative assessment between the 'with' and 'without' scenarios inside the defined system boundary.

The process design that will underpin this report varies significantly according to the vast range of potential activities or proposals that may be assessed. In a continuously evolving field, one paper that reviewed EIA methods defined 22 separate approaches as far back as 1997 (IAIA 1997). As a result, the detailed design of an EIA process should be guided by a set of 'best practice' principles set out by the International Association for Impacts Assessment (IAIA 2009):

Purposive – the process should inform decision making and result in appropriate levels of environmental protection and community well-being.

Rigorous – the process should apply 'best practicable' science, employing methodologies and techniques appropriate to address the problems being investigated.

Practical – the process should result in information and outputs which assist with problem solving and are acceptable to and able to be implemented by proponents.

Relevant – the process should provide sufficient, reliable and usable information for development planning and decision making.

Cost-effective – the process should achieve the objectives of EIA within the limits of available information, time, resources and methodology.

Efficient – the process should impose the minimum cost burdens in terms of time and finance on proponents and participants consistent with meeting accepted requirements and objectives of EIA.

Focused – the process should concentrate on significant environmental effects and key issues; i.e., the matters that need to be taken into account in making decisions.

Adaptive – the process should be adjusted to the realities, issues and circumstances of the proposals under review without compromising the integrity of the process, and be iterative, incorporating lessons learned throughout the proposal's life cycle.

Participative – the process should provide appropriate opportunities to inform and involve the interested and affected publics, and their inputs and concerns should be addressed explicitly in the documentation and decision making.

Interdisciplinary – the process should ensure that the appropriate techniques and experts in the relevant bio-physical and socio-economic disciplines are employed, including use of traditional knowledge as relevant.

Credible – the process should be carried out with professionalism, rigor, fairness, objectivity, impartiality and balance, and be subjected to independent checks and verification.

Integrated – the process should have clear, easily-understood requirements for EIA content; ensure public access to information; identify the factors that are to be taken into account in decision making; and acknowledge limitations and difficulties.

Systematic – the process should result in full consideration of all relevant information on the affected environment, of proposed alternatives and their impacts, and of the measures necessary to monitor and investigate residual effects.

An EIA must strike a balance across these principles and be assessed according to how it performs against them.

The output from an EIA will be a report that quantifies impacts using the environmental indicators appropriate to the proposal or activity under consideration.

3.2. Life Cycle Assessment (LCA)

Lifecycle analysis is a widely recognised approach for assessing the whole-of-life environmental impacts of a technology. Life Cycle Assessment (LCA) considers the environmental impacts arising from each stage in the 'life' of a product or process (Thomas 2011). Although LCA may be referred to as a single technique, it involves summing environmental impacts arising from each stage of the supply chain (Horne et al 2009). LCA aims to quantify whole-of-life environmental impacts of a particular process, product or material (Lane 2006). LCA techniques are commonly referred to as 'well-to-wheel' or 'cradle-to-grave' analysis. LCAs are an internationally established scientific technique for identifying environmental impacts and the flow of resources associated with the provision of goods and services (Horne 2009), standardized under the International Standards Organisation (ISO) under the 14040 series.

Whilst LCAs do not provide a solution to environmental issues, they can drive product research and development, informing decisions regarding overall environmental impacts (ALCAS 2011). An LCA approach ensures that the transfers of impacts from one stage of the life cycle to another are recognised and included in environmental analyses and product selection processes. For example, the effects of the acquisition of raw materials may displace the effects of the use and reuse of a product: an LCA will identify this transfer.

Further, environmental impacts may shift to different media. For instance, a change in raw materials may reduce air emissions while increasing volumes of wastewater effluents. A further benefit of an LCA is that it enables air, land and water environmental impacts arising from different life cycle stages to be quantified (ALCAS 2011).

When comparing two products, Option 1 may appear to cause less environmental damage as it generates less GHG emissions in the operation phase than Option 2. However, an LCA could reveal that Option 1 has a larger 'cradle-to-grave' environmental impact when taking into account impacts across all three media, including air, land and water. Option 2, which produces more GHG emissions during operation, may produce less 'cradle-to-grave' environmental impacts due to its low emissions intensity in production.

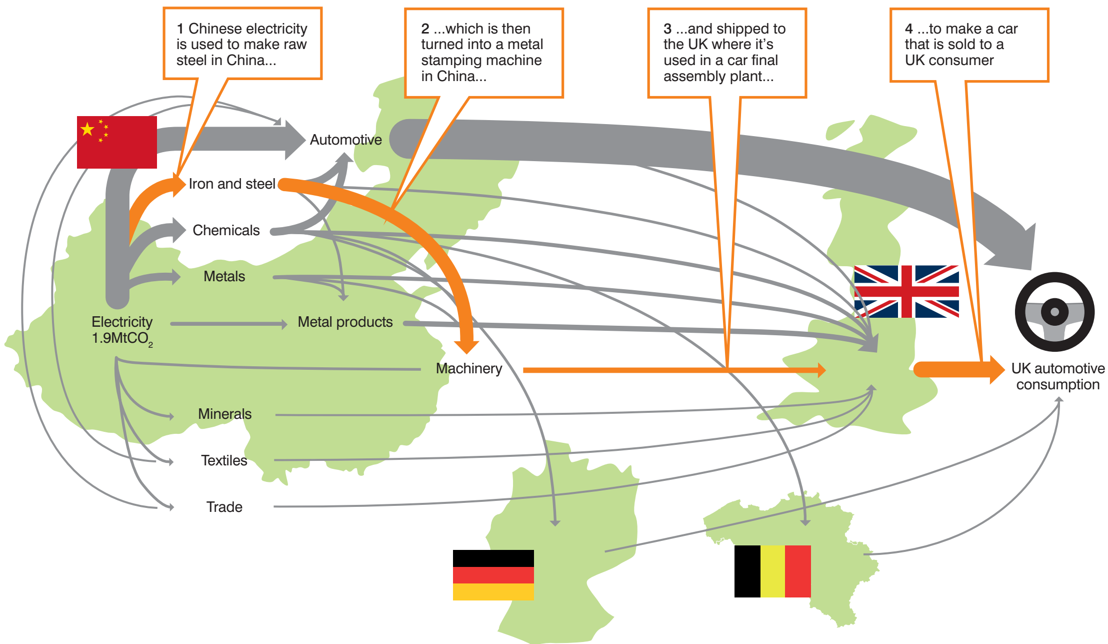
Another issue that lifecycle thinking brings to the fore relates to the nature of global supply-chains. For any processing facility, the choice between raw materials of similar quality will be significantly determined by price. An influence of raw material prices are the regulatory compliance requirements under which a supplier operates, which may significantly vary from one jurisdiction to the next. There is therefore a clear incentive for processors to source raw materials from suppliers which operate under less stringent safeguards against environmental impacts. A robust LCA may identify this sensitivity when considering the potential variations that may exist within lifecycle phases.

The benefits and challenges of lifecycle thinking can also be seen in consumer information mechanisms. Many examples exist of product labeling schemes that allow consumers to take into account the lifecycle impacts of similar products from different production sources – 'free-range' eggs, 'organically-grown' produce, 'dolphin-friendly' tuna, 'fair-trade' coffee. However, the reliability of consumer labeling schemes must also be taken into account. For example, the veracity of 'organic claims' has been subject to review by the Australian Competition and Consumer Commission (ACCC 2012), highlighting the challenges for consumers seeking to apply lifecycle thinking.

A successful LCA rests on asking the correct questions and applying the appropriate context to its results (Horne et al. 2009). Some of the limitations to LCA that need to be taken into account as part of study design and evaluation include:

- The LCA method is complex – refer to Figure 4 below for an illustration of how Chinese electricity ends up in cars on English roads. Results are determined by many factors, from the questions asked and the way they are framed, through to the definitions used and the assumptions made (Matheys et al 2009). LCA studies benefit from continued evolution through sensitivity and data quality analyses, ensuring that conclusions are based on correct assumptions and limitations are quantified when considering future actions (Horne et al. 2009).
- An LCA is merely a 'snapshot' of a product within a specific and confined timeframe that assumes certain constant conditions. Therefore, system adaptability, risks, limits and potential are not considered (Horne et al 2009). Sensitivity analyses may reduce this uncertainty.
- Obtaining accurate, comparable and appropriate data is often a challenge with LCA studies. The International EPD System (2011) recognises that specific LCA data do not exist in all cases. The International EPD System allows producers to use other generic data as substitutes, provided the environmental impacts associated with the materials are lower than 10 per cent of the products' environmental impact.

Figure 4. How Chinese electricity ends up in cars that are made and driven in England – a vivid illustration of the complexities involved in life cycle assessment (The Carbon Trust 2011).



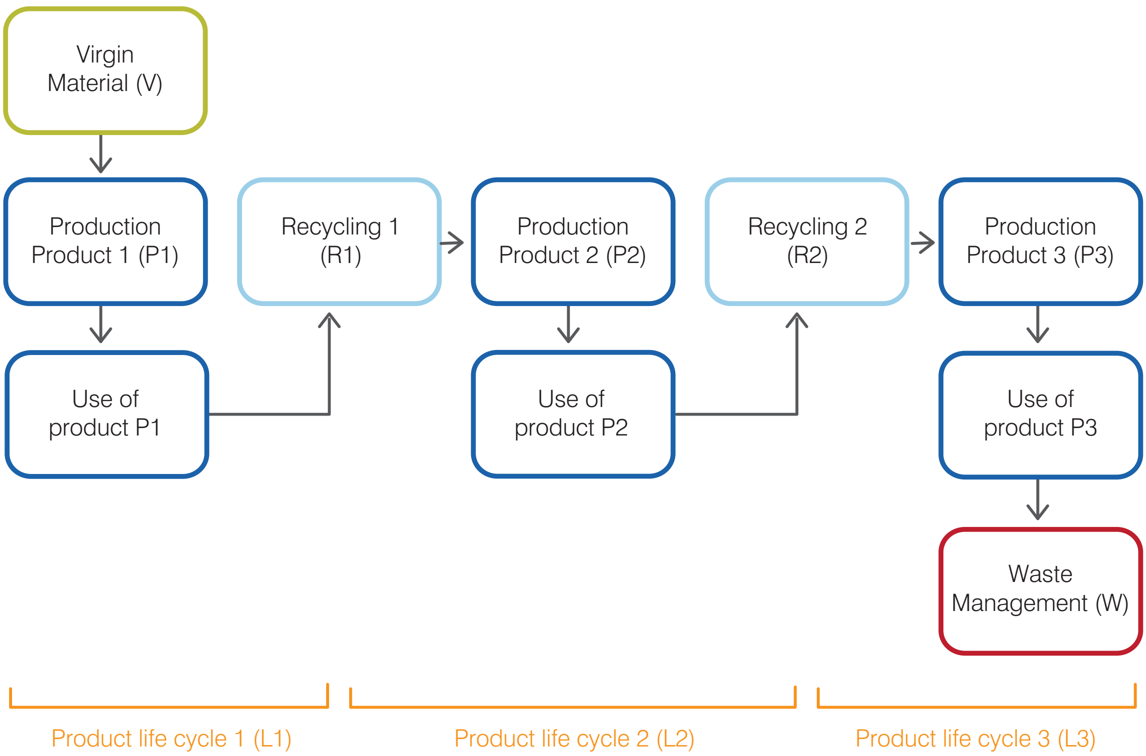
A further complication with LCA relates to the allocation or partitioning of environmental burdens between various co-products or processes with multiple in-flows or out-flows (Nicholson et al 2009). For example, an aluminium can is likely to contain raw material sourced from recycled aluminium products, and will itself contribute raw material to future aluminium products. This particular example is known as 'open loop recycling', a schematic for which is provided in Figure 5 below.

Design of the LCA method to deal with this issue is largely dependent upon the character of the product being assessed (Nicholson et al 2009):

- When the primary energy of one material is much less than the alternative (that is, Va << Vb), the choice of method is does not matter as all incentivize the use of the Material A regardless of the energy use associated with recycling of either material
- When materials have similar primary energy burdens (that is, Va ~ Vb), material preference will change according to the assessment method chosen

Accordingly, the various issues and limitations associated with LCA need to be taken into account through the initial design, application and interpretation of results.

Figure 5. Schematic illustrating open loop recycling, and the challenges that it creates for life cycle analysis of a product (Nicholson et al 2009).



3.3. Application of Life Cycle Assessment to EVs

Life Cycle Assessment (LCA) of EVs will provide insights into the distribution of environmental impacts across the technology lifecycle. Furthermore, by conducting a comparative assessment for Internal Combustion Engine Vehicles (ICEVs), a better understanding can be gained on how these impacts differ from the status quo.

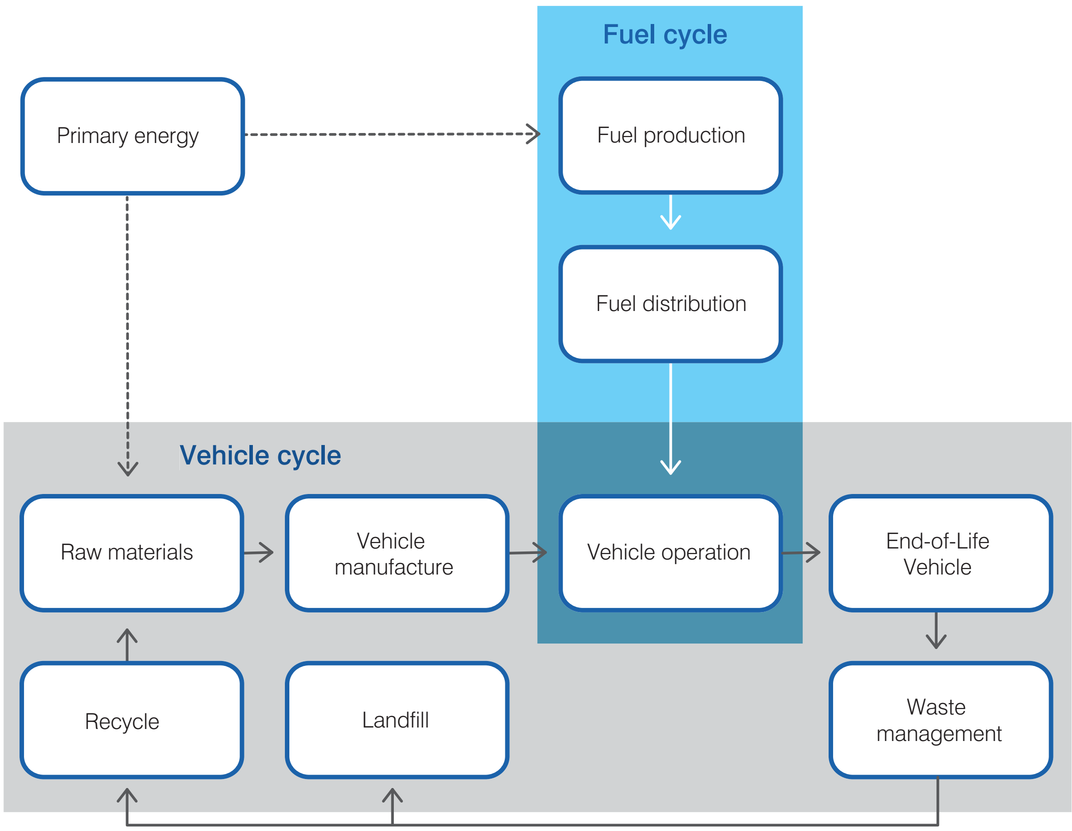
The LCA scope, or system boundary, should be defined as the first consideration. Table 1 below sets out the LCA for EVs in Victoria system boundary along with the supporting logic based upon the IAIA best practice principles (2009) set out in section 3.1 above:

Table 1. The LCA system boundary used in this assessment for environmental impacts arising from electric vehicles in Victoria.

EIA dimension	System boundary	Logic
Physical	Passenger vehicles and their fuel energy – refer to Figure 6 (that is, NOT bikes, scooters, trucks, buses, energy distribution/supply infrastructure) Comparison between similar vehicle types and likely service duties in the Victorian context	Focused, cost-effective, efficient in examining the primary source contribution to the environmental impacts from transport Rigorous, adaptive, credible by striving to preserve comparability and meaningfulness of results
Environmental quality	Environmental regimes = land, waters, atmosphere, climate, sound (that is, not odours, tastes, animals and plants, aesthetics, heritage, culture, economic factors) Environmental indicators = overt use of resources, emission/contamination by regulated pollutants, threats to human health/amenity	Purposive, focused, efficient in examining the primary environmental regimes impacted by transport Rigorous, practical, relevant due to the use of recognized environmental indicators
Temporal	Focus on present day for initial assessment Sensitivity analyses for the period out to 2030	Practical, credible in seeking information about and evaluating the impacts of existing supply-chains and technologies, while acknowledging uncertainties within forecasts beyond this time Adaptive to changes that will occur due to supply-chain and/or product evolution
Spatial	Analysis for vehicles sold/operated in the Victorian market Vehicle and fuel cycle boundaries may extend beyond Victoria	Purposive, practical, focused in examining the supply-chains for products bought and used in Victoria Purposive, credible, systematic by including environmental impacts transferred beyond Victoria's borders
Methodological	Relative assessment of electric versus petrol vehicles/fuels (that is, NOT hybrids, diesel, gaseous fuels etc) Desktop analyses based upon literature review Preliminary/qualitative assessment including sensitivity and data analyses to identify key issues, limitations, knowledge gaps and areas for future work Comparative analysis to inform decisions on end-of-life impacts assessment method	Practical, cost-effective, efficient, transparent, systematic insofar as the preliminary assessment can inform a more detailed investigation should it be warranted, and provides for review/feedback by the public Purposive, relevant in the investigation of the specific differences between internal combustion engine/hydrocarbon fuel energy and electric powertrain/electrical energy Purposive, credible by including environmental impacts transferred beyond Victoria's borders

With reference to Figure 6 below, the physical system boundary can be seen to include the vehicle production, operation (including fuel cycle) and disposal/reprocessing. This structure provides the basis for the preliminary assessment of environmental impacts set out in the report that follows. For each aspect of the lifecycle, key issues, limitations, knowledge gaps and areas for future work will be identified as an outcome from the qualitative LCA, sensitivity and data analyses.

Figure 6. Schematic illustrating the intersecting vehicle and fuel cycles that are the basis for this environmental impact assessment (Lane 2006)



4. Vehicle Production

With reference to Figure 1, an efficient approach to evaluation of environmental impacts arising from vehicle production of EVs is to assess the main differences relative to ICEVs:

- Elimination of the internal combustion engine and fuel/exhaust systems
- Addition of the electric motor and battery system

An assumption inherent in this approach is that other differences in vehicle design make a relatively minor contribution to the overall environmental impacts or effectively cancel each other out. By way of example, the larger ICEV transmission size and relative to that of an EV is assumed to be partly offset by the increased size and complexity of the (regenerative) braking systems on EVs relative to ICEVs.

To gauge the validity of this assumption, Figure 7 below provides an illustration of the various contributions to the total greenhouse gas emissions footprint of 10.313 tCO2e for a locally-produced Toyota Camry.

Figure 7. Carbon footprint of a Toyota Camry (Toyota 2012a)

The greenhouse gas emissions inventory depicted for the Toyota Camry above is often termed the embodied emissions. Assessment of embodied emissions is generally done by breaking the product down into its basic raw material elements, assessing for the embodied energy in the materials, and then adding the emissions associated with the various processes that go into assembly and logistics (The Carbon Trust 2011). This is the approach that will be taken for assessment of the differences between ICEVs and EVs.

Further assumptions that must be made for an assessment of vehicle production environmental impacts relate to location, timing and scale:

- Although Victoria has a globally-significant vehicle production capability, fully electric vehicles are not currently produced in Victoria/Australia. For comparability ICEV and EVs are assumed to be imported, and the import supply-chain impacts are assumed to cancel each other out.
- The regulatory regime under which production facilities operate is likely to vary according to location – for this analysis regulatory issues will be assumed to be similar for both ICEV and EV production facilities.
- The environmental impacts associated with any particular production facility will be significantly dependent upon the sensitivity of the environment in which it is located. For example, the environmental impacts associated with water use by a production facility in a location experiencing extreme drought are likely to be significantly higher than for even the same facility during times of sufficient rainfall. For the purpose of this evaluation these spatial and temporal differences are assumed to be similar for both ICEV and EV production facilities.
- EVs are currently produced in significantly smaller volumes than ICEVs, which entails that the total production facility impacts must be amortized over lower volumes resulting in higher per vehicle impacts. For the purposes of comparability, differences in the per vehicle impacts arising from this 'economy of scale' are assumed to be negligible.

To gauge the validity of some of these assumptions, an assessment can be made for a global vehicle design. Table 2 below lists the global production locations for the Toyota Camry.

Table 2. Toyota Camry production facilities globally, where the vehicle production volume reflects all vehicle types produced at the facility including the Camry (Toyota 2012b, Autonews 2007).

Location	Models produced	Vehicle production
Kentucky, United States of America (USA)	Camry, Camry Hybrid, Avalon, Venza	315,000
Indiana, USA	Camry	79,000
Russia	Camry	20,000
China	Camry, Camry Hybrid, Yaris, Highlander	273,000
Taiwan	Camry, Corolla, WISH, Vios, Yaris, Innova	152,000
Thailand	Camry, Camry Hybrid, Prius, Corolla, Vios, Yaris, Hilux, Fortuner	508,000
Vietnam	Camry, Corolla, Vios, Innova, Hiace, Fortuner	27,000
Australia	Camry, Camry Hybrid	94,000

An initial observation relates to the diversity of global vehicle production – the Camry model is manufactured in eight locations/seven countries, in plants which vary in scale from 27,000 to over half a million units annually, and on production lines which are solely dedicated to the base Camry model, share with Camry model variants or are co-located with production lines for up to six other models. Assessment of the per vehicle impacts for even the 2012 Toyota Camry therefore requires many assumptions to be made of the kind set out above.

Further analysis of the Camry production impacts can be made using Toyota's environmental reporting system. Table 3 below provides an extract of figures from the Australian and American vehicle manufacturing operations, noting that the figures listed for the USA include production of vehicles other than the Camry model family and are recorded on the calendar rather than Australian financial year.

Table 3. Recent statistics for Toyota production facilities in Australia and the USA (Toyota 2012 c and d).

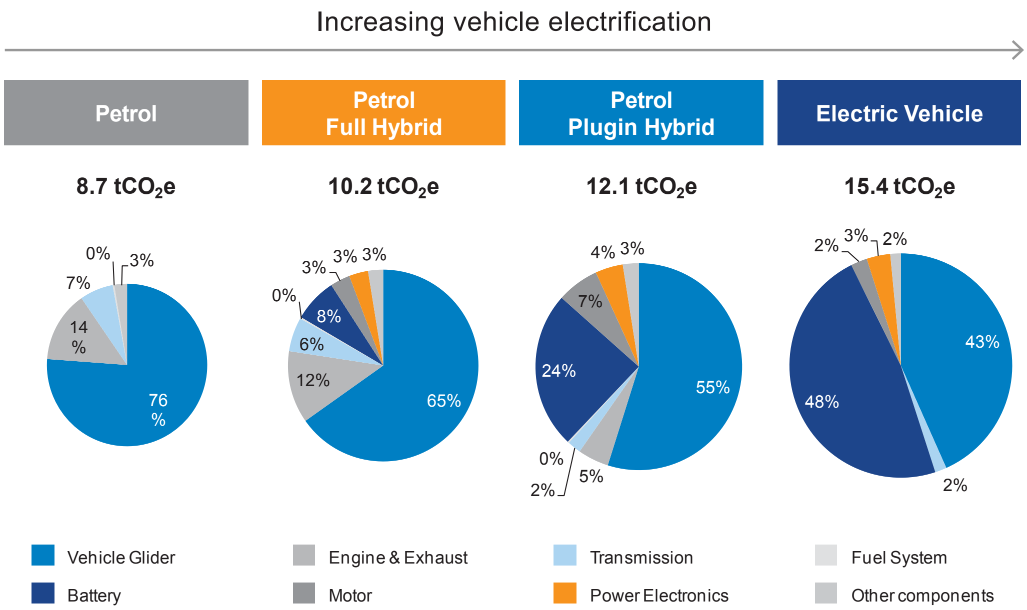
Measure	Australia (2010/11)	USA (2011)	Ratio (USA / Aust)
Vehicles produced (no.)	113,332	1,310,000	11.55
Energy consumption (MMBTu/vehicle)	7.84	7.47	0.95
Greenhouse gas emissions (tCO2/vehicle)	1.28	0.90	0.70
Water consumption (kL/vehicle)	3.46	3.56	1.03

A significant observation can be made regarding the energy consumption per unit vehicle production as compared to greenhouse gas emissions. The significantly higher emissions intensity of Australian vehicle production is likely due to the use of Victoria's carbon-intensive grid electricity, even though a breakdown of the underlying data would be required to confirm this. And regardless of the actual explanation, the pitfalls in generalising vehicle production impacts have been highlighted and are a clear limitation of any general product LCA.

Another observation relates to the reported per vehicle greenhouse gas emissions – those listed in the table above relate to the vehicle production process only, and not the embodied emissions of component part raw materials or assembly. This highlights the importance of the LCA 'system boundary' definition in ensuring fair comparisons are made between products.

Figure 8. Embodied emissions for various vehicle designs, where total emissions increases with increasing vehicle electrification (Patterson et al 2012) below provides a breakdown in embodied greenhouse gas emissions according to vehicle type (Patterson et al 2012). As this analysis provided a direct comparison between vehicle types, the top-line figures used will serve as the basis for analysis in the rest of this paper.

Figure 8. Embodied emissions for various vehicle designs, where total emissions increases with increasing vehicle electrification (Patterson et al 2012)



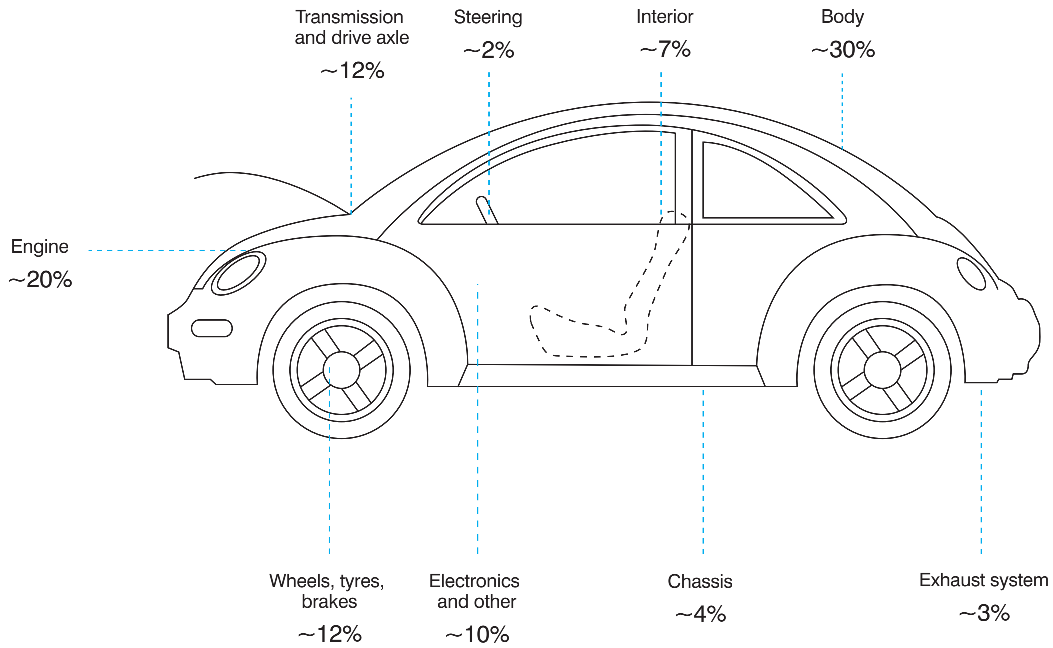
4.1. Internal Combustion Engine, Fuel & Exhaust Systems

Although source data on vehicle components is not widely available, some high-level analyses have been conducted on various component contributions towards the embodied emissions in a car. Figure 9 below provides a breakdown where the largest contribution to embodied emissions in a conventional vehicle is in the body (as a result of both the steel and paint). The next highest contribution is the engine, which drawing upon both Figure 8 and Figure 9, would equate to between 14 and 20 per cent of the total vehicle embodied emissions.

The exhaust system is mostly stainless steel that is designed to withstand high temperatures and corrosion. The catalytic converter also contains quantities of Rare Earth metals to eliminate toxic air pollutants that are an output from the fuel combustion. In contrast with their functional intent, Rare Earth metals are known to cause significant environmental issues during extraction and processing, and automotive exhaust systems are the largest application for these materials (POST 2011). This trade-off is a perfect example of where lifecycle thinking can assist in understanding the net environmental benefits/costs of technology.

Fuel systems utilize a range of polymer, rubber and galvanized steel components which are relatively lightweight by comparison with the rest of the vehicle. This would suggest that their contribution towards the total embodied emissions is relatively minor.

Figure 9. Distribution of embodied emissions in a typical car by component group, based upon analysis of emissions embodied in the materials (The Carbon Trust 2011).



4.2. Batteries, Electric Motors & Power Electronics

In applying lifecycle thinking to assessment of the environmental impacts of EV technologies, the relative immaturity of their design and manufacture compared to ICEV technologies may place them at a potentially significant disadvantage (Horne et al 2009). However, the significant quantities of raw materials, some of them relatively exotic, in electric vehicle systems results in a large environmental 'footprint' for these components (Matheys et al 2009, Hawkins et al 2012). Cheah (2010) observes that the manufacturing of the complex propulsion systems of HEVs and PHEVs in particular results in higher energy requirements during the production stage. Figure 8 above provides a graphic illustration of this, where the base vehicle percentage contribution to total embodied emissions decreases from 76 per cent in an ICEV down to 43 per cent for a full EV despite remaining the same in absolute terms.

Hawkins et al (2012) concluded that the vehicle production impacts of EVs exceed those of ICEVs in terms of CO2 emissions, air pollutant emissions, water resource contamination, and threats to human health, even if they cause less land contamination. It should be noted however that both vehicle production processes cause impacts within each of the environmental regimes listed.

Given the marked impact on embodied emissions through the inclusion of a traction battery and (to a lesser extent) an electric motor and power electronics, it is appropriate to investigate these items in more detail.

EV battery technology has significantly improved in recent times to now have greater life-spans and double the energy capacity of earlier models (Notter et al 2010). Past chemistry types included lead-acid and nickel-metal hydride, but new EVs mainly use lithium-ion batteries. Of the cars used in the Victorian Electric Vehicle Trial, the Nissan LEAF and the Mitsubishi i-MiEV, use lithium-ion, while the Toyota Prius PHEV uses a nickel-metal hydride battery.

Nickel-metal hydride battery technology has a long history in vehicle applications through Toyota's use of it in the Prius family of vehicles. Nickel-metal hydride batteries are mainly made of nickel (Scott 2009), and smaller amounts of rare-earth elements including lanthanum and cobalt. During manufacture, the nickel-metal hydride battery has a lower environmental impact than the lithium-ion battery (Matheys et al 2009).

Traditional lithium extraction processes are a significant influence on the environmental impacts associated with lithium-ion batteries. To reduce the environmental burden of lithium-ion battery production, lithium can be extracted from salt solutions rather than from mineral deposits, reducing the process energy requirements (Notter et al 2010). This illustrates the significant uncertainty associated with new, fast-evolving, proprietary technologies in terms of LCA inputs.

These uncertainties become even more pronounced when the spectrum of opinion regarding future lithium supply chains is taken into account. Notter et al (2010) note that lithium is considered a geochemically scarce metal, only present in less than 0.01 per cent of the Earth's crust. Further, Hoyer et al (2011) assert that mineral deposits are 'geographically concentrated' – in 2008 around 85 per cent of cobalt and lithium supplies were found in only seven countries. It is suggested that this could lead to a shift in dependency from oil producing countries to those countries with EV battery chemical reserves (Hoyer et al 2010).

However, current lithium production utilizes a tiny fraction of known reserves of both lithium salt solutions and mineral deposits distributed around the world, including in China, North America, Australia and Europe. The U.S. Department of Energy (US DOE 2009) modeled lithium supply and demand to the year 2050. It found that lithium supplies are abundant, and would be preserved through expanding the battery recycling infrastructure.

Additional uncertainties relating to battery impacts arise out of assumptions regarding battery composition and energy efficiency, due to the proprietary and closely-guarded nature of the information about the technology (Matheys et al 2009). Hawkins et al (2012) highlight the large discrepancy between calculated embodied emissions within different LCA studies, and suggest that this highlights the need for better information from the battery information. This uncertainty may be partly addressed by running sensitivity analyses by varying input parameters including different sizes and masses of EV battery components – refer to Patterson et al (2012) for an example of this sensitivity analysis.

While this section nominally deals with production impacts, it is noteworthy that the potential advantage in terms of environmental impacts gained by nickel-metal hydride chemistries during the production stage is lost during operation, where the 90 per cent energy efficient lithium-ion chemistry compared has a distinct advantage over nickel-metal hydride at 70 per cent (Matheys et al 2009). Furthermore, lithium-ion batteries are relatively lightweight and have the highest electrochemical potential of all currently available EV batteries. Lithium-ion batteries also have the advantage over many other battery chemistries in that they require minimal maintenance (Notter et al 2010). These advantages have driven a market shift towards lithium-ion battery technology for automotive applications and indicate the value of lifecycle thinking during the initial vehicle design.

The most common type of electric motors for EVs are permanent magnet motors and induction motors (Faria et al 2012). For reasons of cost and technical advantage, other electric motor designs under development include switched reluctance motors (Swinburne 2012).

As for catalytic converters that form part of the emissions control technologies for ICEVs, permanent magnet motors contain Rare Earth metals which are known to have significant environmental impacts (POST 2011).

Despite these issues, literature investigating the environmental impacts of electric motor designs and components is rare. One high-level study indicates that the electric motor contribution to total embodied greenhouse gas emissions for EVs is small at around two per cent (Patterson 2012). It is unclear however which electric motor design was used for this study, or what the wider environmental impacts from electric motor production might be.

The Power Electronics Module (PEM) in an EV controls the electric motor torque, battery charging, and regenerative braking. It also monitors items such as the voltage delivered by the energy storage system, the speed of rotation of the electric motor, and the temperatures of the motor and the power electronics (Faria et al 2012).

Patterson et al (2012) suggest that the embodied emissions associated with production of the PEM represents around three per cent of the total vehicle embodied emissions, making it a relatively minor contributor.

Current battery technology entails that EVs generally weigh more than their ICEV equivalents, for example the Mitsubishi i-MiEV is 180 kg heavier than its petrol-equivalent thanks to its 230 kg traction battery (Mitsubishi 2012a), while the EV Engineering electric Commodore is 150 kg heavier than the Holden Commodore on which it is based (Carey 2012). This has implications for the vehicle operation and disposal lifecycle assessments in sections 5.2.3 and 6.2 below.

Information as relates to environmental impacts beyond embodied greenhouse gas emissions from vehicle production is relatively rare. A comprehensive study recently released by Hawkins et al (2012) suggests that environmental impacts from EV production compared to ICEV are higher for all regimes assessed (indicators in parentheses):

- Climate change (gCO2e) – consistent with the findings above
- Terrestrial acidication (g SO2 equivalent)
- Particulate matter formation (g P equivalent)
- Photochemical oxidant formation (g NMVOC equivalent)
- Human toxicity (g 1,4-DCB equivalent)
- Freshwater toxicity (g 1,4-DCB equivalent)
- Terrestrial toxicity (g 1,4-DCB equivalent)
- Freshwater eutrophication (g 1,4-DCB equivalent)
- Metal depletion (g Fe equivalent)
- Fossil depletion (g oil equivalent)

The negative impacts are mostly attributable to the battery production, which the authors note as containing large uncertainties due to a lack of published information.

Potentially the most significant issue arising from this list of potential impacts relates to the specific environmental management regime applicable to the battery production. For batteries that are produced in locations with relatively low levels of regulation and/or enforcement, these environmental impacts may have significant consequences. Conversely, batteries produced in locations with strict environmental controls are likely to manage these impacts in a way that will minimize their impact upon the surrounding environment.

A final observation as relates to the EV system as compares to the ICEV components that it replaces relates to future performance. All vehicle technologies are subject to significant investment in research and development that will deliver improvements across a range of attributes. Some of this investment will benefit both vehicle types, for example reduced vehicle mass due to lightweight component design – for the purposes of a comparative assessment these can be ignored.

Improvements in battery technology are however worthy of consideration due to their overwhelming relationship to EV performance and impacts. As part of President Barack Obama's 'one million EVs by 2015' target, the United States Department of Energy is tracking progress on battery technology (US DOE 2011). They highlight two areas for immediate improvement relating to greater confidence in battery life and increased production volumes. The improvements will deliver environmental benefits from:

- Reduced battery sizes, which will reduce raw material inputs and promote better energy economy through reduced vehicle mass
- Improved battery life, which will reduce raw material inputs in replacement batteries
- Economies of scale and increased manufacturing know-how, which will reduce the environmental impacts per unit from battery production/replacement

5. Vehicle Operation

The operational phase of the vehicle lifecycle is dominated by the impacts arising from energy production and use, commonly known as the fuel lifecycle. Although there are a range of environmental impacts that should be considered in relation to the fuel lifecycle, greenhouse gas emissions (expressed as gCO2e/km) is emerging as the most common metric against which vehicles are assessed.

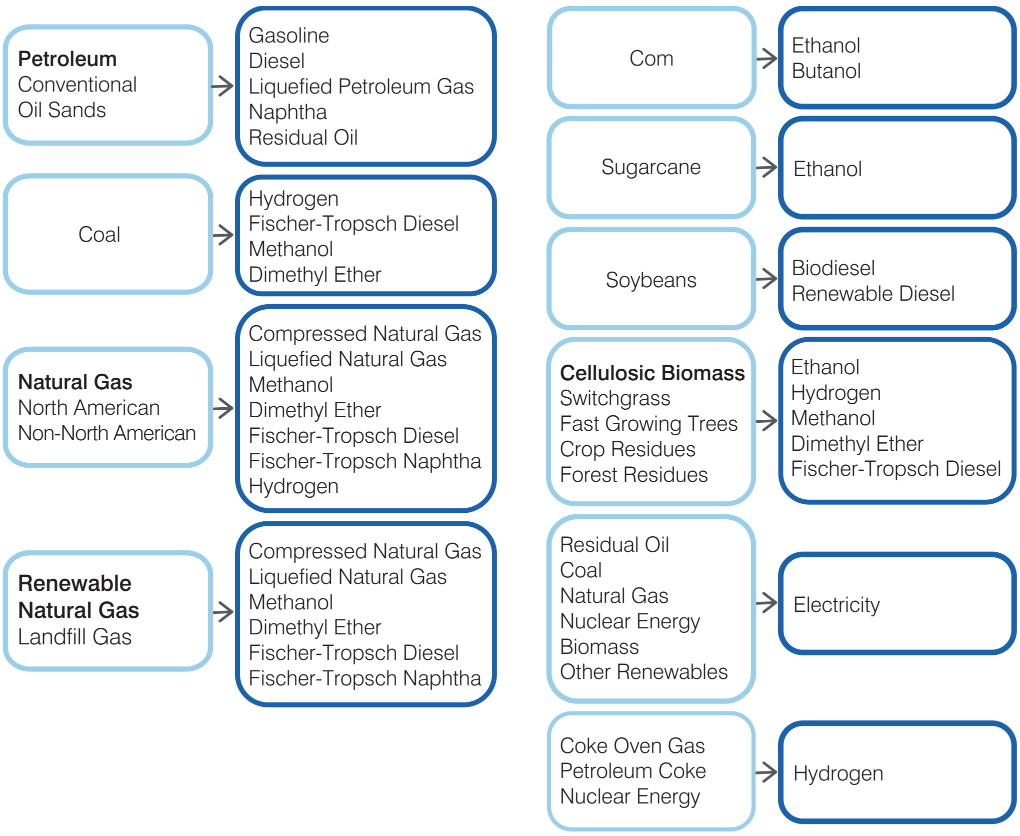
Additional impacts include those relating to noise, electromagnetic fields, and vehicle maintenance.

5.1. Energy Production

A common term for the energy pathway for road transport that captures energy production and distribution is 'well-to-tank', denoting the feedstock, fuel or electricity production/processing (shorthanded to the oil 'well') through distribution and delivery to the vehicle (the fuel 'tank'). The impacts arising from this stage are often termed the 'upstream' impacts (as opposed to 'downstream' impacts explained below).

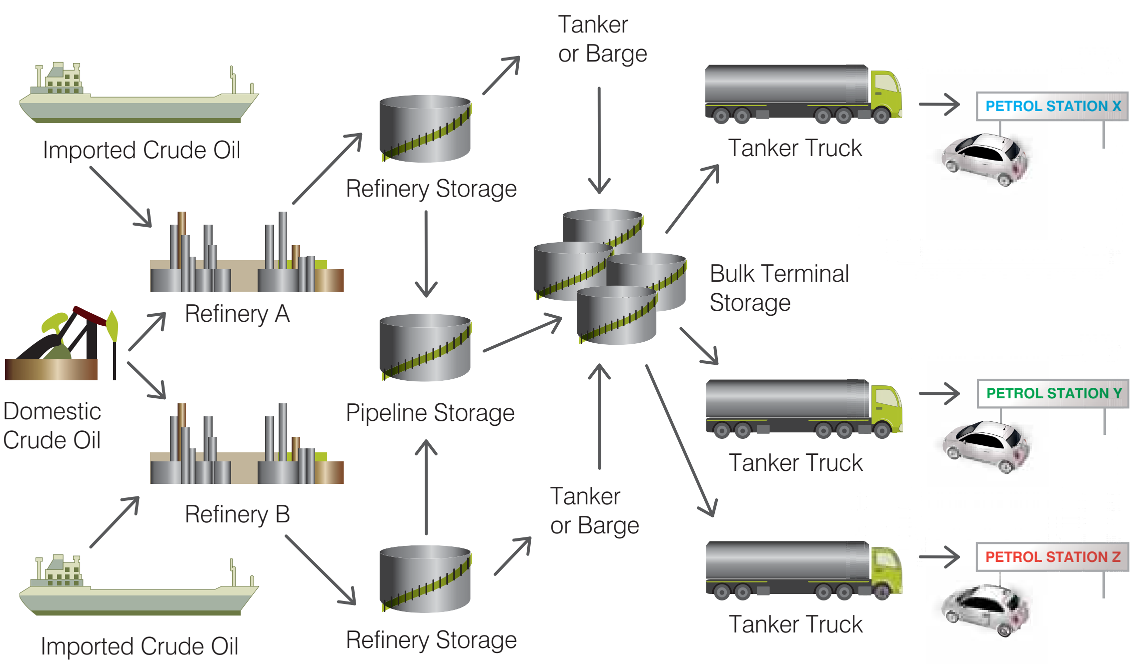
With reference to Figure 10, the wide range of fuel types for road transport along with the almost infinite number of pathways that may be taken through supply-chains for different markets creates an enormous level of complexity in striving to understand the comparative environmental impacts from different fuel choices. In order to conduct a lifecycle analysis of environmental impacts, assumptions must be made regarding the location of origin, processing technology/efficiency, distribution path/method and point of supply into the vehicle.

Figure 10. Schematic illustrating the range of energy sources for road transport (US DOE 2012)



For ICEVs, the wide range of liquid and gaseous fuel sources may be simplified by examining the circumstance within any specific market and concentrating on the main fuel types/sources. By way of example, the overwhelming majority of passenger vehicles in the United States use gasoline (petrol). With reference to Figure 11, petroleum production processes include extracting, separating crude oil and venting, requiring a fuel source for the generation of fuel on site. Pipelines or tankers distribute raw materials to refineries or processing plants for distilling. Distillation products are transported to a terminal via a pipeline, transported by road tankers and finally distributed to fuel stations (Lane 2006).

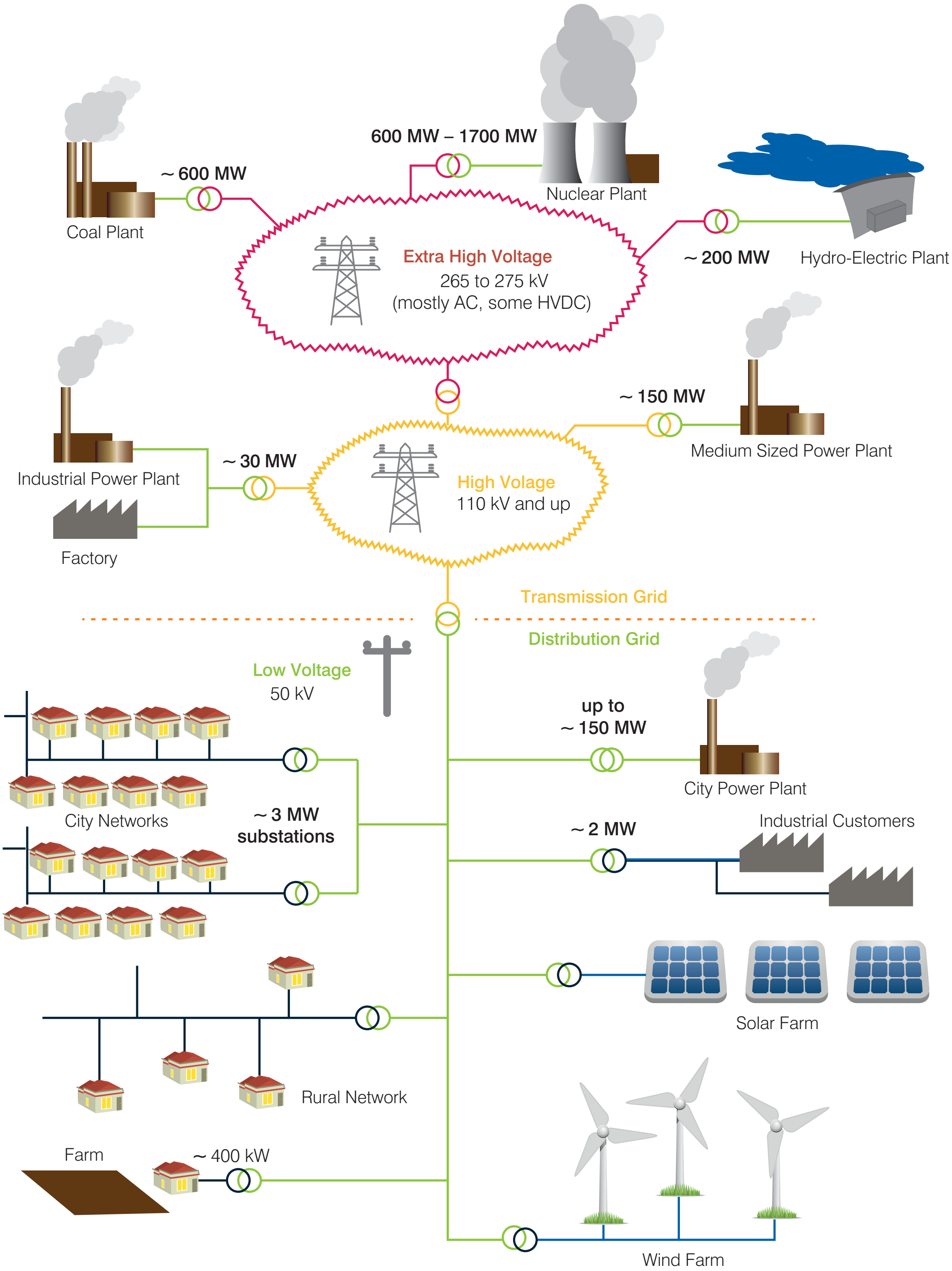
Figure 11. Schematic illustrating the supply-chain complexity for petrol (US EIA 2012)



A clear limitation in this approach is the relative inefficiency that is likely to be a feature for a 'non-traditional' fuel source. For 'mainstream' fuel sources, economies of scale and market-driven supply-chain efficiencies are likely to provide a relative advantage when compared to a non-traditional fuel source/supply-chain. This is a limitation within lifecycle assessment generally, due to the large number of possible variations that inhibit sensitivity-testing.

For EVs, the system of energy transmission and distribution (commonly known as 'the grid') is extremely complex. With reference to Figure 12, a range of energy generation sources are linked through the transmission and distribution grid to each end-use. The balance of electricity supply with demand is managed in real-time at the network level, meaning that the grid mix of generation sources varies from moment to moment.

Figure 12. Schematic of an electricity grid showing a range of generation sources (coal, nuclear, hydro-electric, power plants of various types, wind farms) connected to a variety of end uses (factories, industrial customers, city and rural users)



The traditional approach to assessment of impacts arising from electricity production/distribution has been based on the average emissions intensity for all electricity production in the grid region from which the electricity is sourced. By way of example, a survey of the greenhouse gas emissions intensity adopted in recent studies of the environmental impacts of EVs can be found in Table 4 below.

An alternate method for assessment of electricity use impacts involves an evaluation of the likely generation source arising from the additional demand – the 'marginal' impacts (Allan 2011; Ma et al 2012; Anair & Mahmassani 2012). This evaluation takes into account the increased use of electricity due to EV charging beyond 'business-as-usual'.

Most analyses of marginal impacts assign the additional demand to 'peaking' power plants (Allan 2011). However, this analysis suggests that the additional demand adds to the existing peak, which is not necessarily the case if charging occurs during off-peak periods. Should charging occur solely during an off-peak period, this demand is likely to be met using existing capacity from 'baseload' generation (Järvinen et al 2011). This would have a knock-on effect of improving the asset utilization of the baseload asset, thereby improving its cost competitiveness and reducing the incentive for investment in other generation sources (for example, renewables).

The reality is that the exact source of electricity for EV charging will depend upon the specific time, date and location. The electricity mix going into the grid at any one time reflects the balance between supply and demand. The supply mix reflects the forecast demand requirement distributed over the lowest cost generation sources available. In general, renewable energy is the least-cost form of generation, but is only available on an intermittent basis (for example, when the sun is shining or the wind blowing). Furthermore, the likelihood of a direct relationship existing between a source of electricity supply and specific end use increases as the distance between the source and end use decreases. This makes generalizations regarding the environmental impacts arising from EV charging extremely complicated, and probably best addressed through an assessment of likely scenarios and sensitivities.

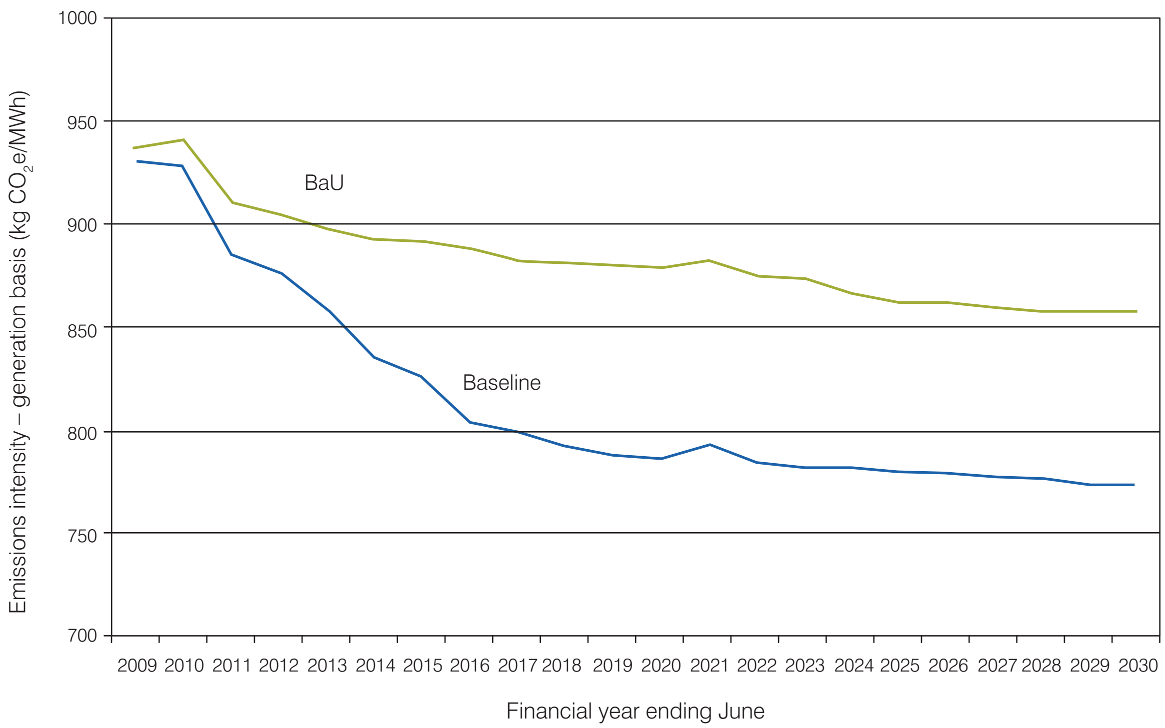
Table 4. A survey of current electricity grid emissions intensities from a range of recent EV environmental impacts assessments compared to that for Victoria. Note that the grid regions reported for the USA are those with the lowest/highest emissions intensities for all USA grid regions.

Location	**Electricity greenhouse gas emissions intensity** (kgCO2e/MWh)	Study reference
NPCC Upstate New York grid region, United States of America (USA)	286	Anair & Mahmassani (2012)
Portugal	390	Freire & Marques (2012)
Czech Republic	560	Hromadko & Miler (2012)
United Kingdom	594	Patterson et al (2012)
WECC Rockies grid region, USA	983	Anair & Mahmassani (2012)
Victoria, Australia	1350	DCCEE (2012b)

A highly pertinent example of this relates to the realities of an EV charging network. Experience from the Victorian Electric Vehicle Trial has shown that the electricity supply arrangements for each charging outlet are specific to the location. By way of example, an on-street charging station will be owned and operated by an EV charging service provider, who most often will have a renewable energy supply arrangement for the site. This same charging service provider may also operate charging stations in a commercial car-park under a service provision agreement with the site owner. The electricity supply for that site may not be renewable, and so an EV driver who is able to access both charging stations may find that they are using renewable energy at one location only. It is possible for the EV charging service provider and/or the EV driver to account for this by maintaining an inventory of their energy use and reconciling this through renewable energy 'offset' products, however some diligence is required to ensure that there is no 'leakage' of energy use through sites/vehicles which are not covered by a renewable energy supply arrangement.

A separate complication associated with energy-use lifecycle emissions calculation is that grid emissions change over time due to changes in the generation sources (from plant upgrades and new capacity). In fact, this is the origin of one of the main benefits associated with a switch to vehicle electrification – as economy-wide efforts to reduce greenhouse gas emissions take effect in the electricity sector, twice the 'bang for the buck' can be obtained by switching transport across to electrification. Consequently, an EV using grid-sourced electricity will become progressively 'cleaner' as the grid is decarbonized – refer to Figure 13 below for an illustration of this for Australia's grid mix.

Figure 13. Australia's projected grid emissions intensity from the generation mix perspective – the baseline scenario (blue) depicts what is forecast including the impacts of planned investment in new technologies/plants and various government policy interventions, whereas the Business-as-Usual (BaU) scenario (green) is what is forecast to occur in the absence of these items (DCCEE 2011b).



Although the discussion above relates to all electricity sources that supply the grid, the specific relationship between EVs and renewable energy is also worth noting. In the absence of other options, sourcing electricity from the grid will entail that the emissions from all generation sources are taken into account. However, if a mechanism exists to allow for electricity use to be reconciled back to renewable sources, emissions from EV operation may become zero.

The two renewable energy options are:

a. On-site renewable energy generation – installing a renewable energy generation source such as a solar photovoltaic (PV) system with sufficient generation capacity to account for the energy use in EV charging; and

b. Renewable energy purchasing programs – through an electricity supply agreement with a retailer who can purchase renewable energy on behalf of the user, or via direct participation in the market for renewable energy.

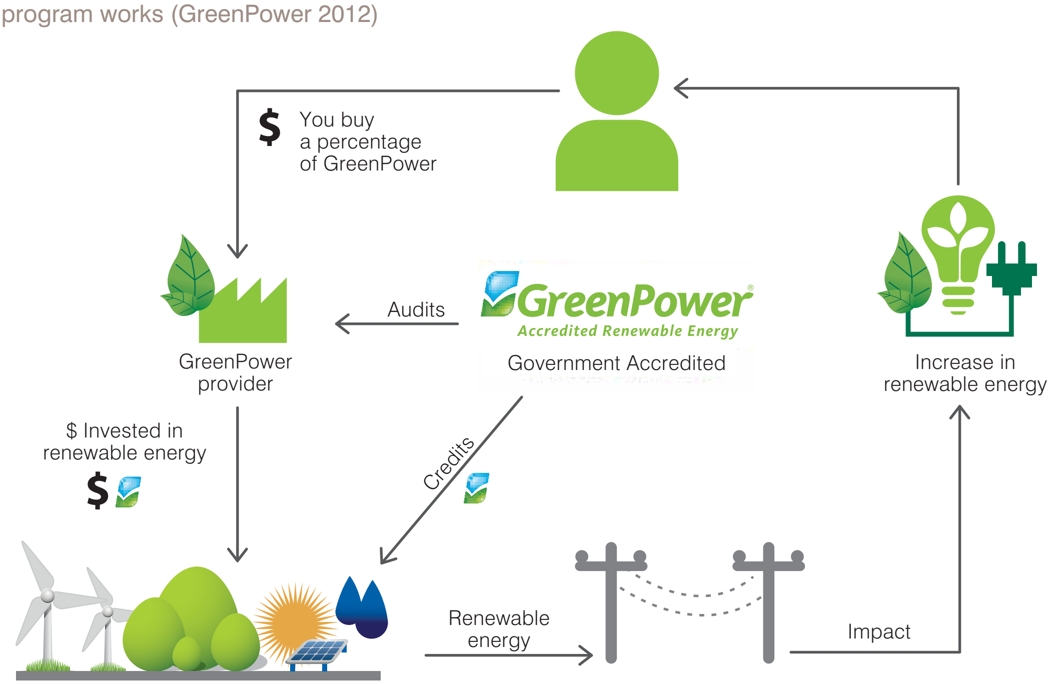
Most on-site generation is grid-connected, meaning that energy is transferred to and from the grid to account for mismatches between the electricity supply and demand. For systems that are not grid-connected, energy storage will generally be required to account for the inevitable mismatches. In these instances energy use may be designated renewable so long as it falls within the generation and storage capacity of the system.

For systems which are grid-connected without storage, as is the case for the majority of residential solar PV, only energy use that falls within the on-site generation envelope at the time of use will be renewable. Energy use that exceeds the instantaneous generation profile will be drawn from the grid, and will be accompanied by the environmental impacts associated with the grid mix.

For energy use in a grid-connected system to be renewable, careful consideration is required of the underlying arrangements for the market in which the system operates. A description of the arrangements for the Victorian market will be provided in section 5.1.2 below.

Renewable energy purchasing programs use the same sort of accounting methods that are used to reconcile electricity generation/use for the grid more generally. In selecting a renewable energy product, the consumer is paying for their electricity retailer to purchase an equivalent amount of renewable energy in the form of certificates that are awarded to generators as they produce the renewable energy. This trading market is a key enabler for investment in renewable energy projects, as well as ensuring that the energy use has been reconciled back to renewable sources – refer to Figure 14 for an illustration of the Australian GreenPower renewable energy purchasing program.

Figure 14. Schematic illustrating how the Australian GreenPower renewable energy purchasing program works (GreenPower 2012)



A separate implication of this relates to the choice in assessment method for electricity market impacts. Investment in renewable energy projects will inevitably take time before the increased generation capacity becomes available. Accordingly, assessment of the marginal impacts from increased demand is potentially relevant to any consideration of EV charging impacts in the near-term, even if a renewable energy product has been purchased.

A final consideration in assessing the link between EV charging and renewable energy is the use of EVs/EV batteries as storage facilities from which electricity can be drawn for other uses (known as Vehicle-to-Grid/V2G, Vehicle-to-Building/V2B or Vehicle-to-Home/V2H). This is a potentially significant enabler for renewable energy , as it enables the energy generated when the sun is shining and/or the wind blowing to be stored for when it is needed (Short and Denholm 2006).

Vehicle-to-Grid services can provide additional benefits to the grid (Paevere et al 2012), and by extension the environment (Sioshansi and Denholm 2009). As energy storage devices, EVs may be charged when the cost of electricity is low and discharged when it is high, decreasing the use of (generally) low-efficiency, high-emissions peaking power plants. In addition to this, EVs may provide 'ancillary services', which is the additional electricity supply maintained to allow for sudden increases in electricity demand or generator outages. Ancillary services are most often maintained through the use of the peaking power plants described earlier or by operating power plants at partial load. By displacing the use of these sources for ancillary services, EVs promote overall network energy generation efficiency and by extension reduce environmental impacts.

Although there are a range of issues that need to be resolved for V2G opportunities to be realized (AECOM 2012), vehicle manufacturers have already begun to offer V2H capability (Nissan 2012a).

Air quality impacts arising from energy production and distribution are an important environmental impact that should not be overlooked. Hydrocarbon fuel extraction, processing and distribution creates a range of air pollutants, as does electricity generation from coal-fired power stations and many other generation sources. Notably however, most developed countries regulate the emission of air pollutants from industrial sources, including refineries and power plants. These regulations are most often expressed as absolute limits rather than prorated according to the amount of production undertaken, meaning that increases in the production of electricity are not necessarily associated with increases in the volume of air pollutants emitted from the production sources (Nopmongcol 2007).

The World Business Council for Sustainable Development provide some insights into the water requirements associated with energy production (WBCSD 2009) – excerpts for the energy sources that are the focus of this report as follows:

Oil extraction & processing *– As easy oil is used up, pumping oil from reservoirs is now associated with more 'water production per amount of oil produced' than ever before (due to aging reservoirs and increased oil recovery operations). The volume of water produced worldwide from the oil and gas industry is still increasing at a rate of about 10 per cent per year. Water to oil ratios ranged from <1 to up to 40 depending on maturity of the field with the lowest ratios generally observed in the Middle East.*

Between 2 and 8 m^3 of water per 1,000 GJ have historically been required to extract oil, including water for drilling, flooding and treating. However, when thermal steam injection or enhanced oil recovery is included in the process, this number can increase, on average, to 1,058 m^3 per 1,000 GJ.

Consumptive water use for processing and cooling in traditional refining facilities in industrialized countries ranges from 25 to 65 m^3 per 1,000 GJ. Please note this figure is only illustrative, as it does not specify if it refers to wet or dry cooling.

For about 800 million gallons of petroleum products refined daily in the US, 1 to 2 billion gallons of water are consumed per day.

Coal-fired electricity generation *– More electricity is generated from coal than from any other fuel – 39% of world generation in 2002.*

Open pit coal mining requires 2 m^3 of water per 1,000 GJ of energy in the coal, while underground mining operations require 3 – 20 m^3 of water per 1,000 GJ.

Renewable energy *– Wind energy and photovoltaic cells that produce electricity directly from sunlight are considered to have negligible water use.*

This general information provides a useful insight into potential water resource impacts associated with energy production, however specific impacts are best considered at the specific source, location and time. Water-borne pollutants may/may not be regulated depending upon the specific location in which they are emitted, and water consumption may be regulated during times of drought. Reprocessing of water may be undertaken at one industrial facility but not the one next door.

5.1.1. ICEV Energy Production & Supply in Victoria

Around 80 per cent of Australia's petrol is sourced from domestic refineries (ACCC 2012). Around 50 per cent of Victoria's petrol needs are met by the Shell Geelong refinery (Shell 2012a), with the balance sourced from the other six Australian refineries and imports (ACCC 2012). As the Shell refinery is the single largest production source for Victoria's petrol, it will be used as the case study in the discussion of the Victorian ICEV energy production and supply chain below.

Individual refineries are configured to process particular types of crude oil, with Australian refineries primarily configured towards processing sweet light crude oil, around 70 per cent of which is imported (ACIL Tasman 2008). Shell's Geelong refinery receives around 90 per cent of its crude oil by ship from the Far East (for example, Vietnam, Malaysia, Brunei and Indonesia), West Africa (for example, Algeria and Gabon), United Arab Emirates, New Zealand, and Australia's own oilfields (Shell 2012a). Notably, the choice of raw material source is a dictated by cost alone.

Once refined, all petrol is transported to terminals for storage and onwards distribution to the point of supply into vehicles, such as retail fuel outlets. About 45 per cent of Shell's Geelong refinery product is transported via pipeline to the Shell Newport terminal for distribution throughout Victoria, and another 15 per cent taken by road to Geelong and other rural areas. The other 40 per cent is sent by ship to Australian coastal cities and New Zealand (Shell 2012a).

Each aspect of the supply-chain network is subject to various regulatory frameworks that strongly influence the environmental impacts.

By way of example, a significant issue may relate to the environmental impacts arising from the extraction processes for oil. The World Bank (2010) has conducted a survey of environmental governance of 32 oil-producing developing nations:

For the majority of countries surveyed, a sufficiently appropriate, but largely theoretical, environmental policy and legal framework is in place. However, the effectiveness of this framework tends to be compromised by a lack of a sufficiently organized administrative structure that enables efficient regulatory compliance and enforcement. Additionally, the human and financial resources needed for effective environmental governance are generally lacking.

Most countries have some form of environmental impact assessment (EIA) process that has been incorporated within their legal and regulatory framework. However much of the emphasis of the EIA process appears to be directed toward approval of oil and gas projects rather than reflecting life-cycle management approach to environmental and social issues. Evidence of this effect is that most countries make use of insufficient – and sometimes totally absent – control and enforcement mechanisms during the post-EIA approval phase.

While this report is not in itself evidence of negative environmental impacts arising from ICEV energy use in Victoria, it clearly highlights the merits in taking a lifecycle approach to consideration of environmental impacts. There is clearly a risk of petrol use in Victoria causing environmental impacts in developing nations that would not be acceptable by Victorian standards.

Consideration of the environmental impacts arising from refinery processes provides a vivid illustration of the standards expected by the Victorian community. Table 5 provides a high-level view of the environmental regulations applicable to Shell's Geelong refinery. While a thorough investigation of applicable environmental regulation to all refinery production sources that supply petrol into the Victorian market has not been pursued, it is almost certain that variations will exist between them entailing variations in the environmental impacts between two otherwise similar industrial facilities.

Table 5. Examples of the environmental legislation/regulation applicable to Shell's Geelong refinery (Shell 2012a, GHD 2009)

Environmental regulation	Environmental regime / impact management measure			
	Climate / greenhouse gas emissions or resource use	Atmosphere / emission of pollutants	Waters / contamination or resource use	Land / contamination or generation of industrial waste
National Greenhouse & Energy Reporting Act 2007, Australia	Public reporting requirement	n/a	n/a	n/a
Clean Energy Act 2011, Australia	Greenhouse gas emissions pricing mechanism	n/a	n/a	n/a
Energy Efficiency Opportunities Act 2006, Australia	Identify / pursue cost-effective energy reduction opportunities	n/a	n/a	n/a
Industrial Waste Management Policy (National Pollutant Inventory) 1998, Victoria/Australia	n/a	Public reporting requirement	Public reporting requirement	Public reporting requirement
Industrial Waste Management Policy (Waste Acid Sulphate Soils) 1999, Victoria	n/a	n/a	n/a	Prevention and management of contaminated land, specifically acid sulphate soils
Industrial Waste Management Policy (Prescribed Industrial Waste) 2000, Victoria	n/a	n/a	n/a	Prevention and management of industrial waste
State Environment Protection Policy (Air Quality Management) 2001, Victoria	n/a	Limits on the emission of regulated air pollutants	n/a	n/a
State Environment Protection Policy (Prevention and Management of Contaminated Land) 2002, Victoria	n/a	n/a	n/a	Prevention and management of contaminated land

Table 5. Continued

Environmental regulation	Environmental regime / impact management measure			
	Climate / greenhouse gas emissions or resource use	Atmosphere / emission of pollutants	Waters / contamination or resource use	Land / contamination or generation of industrial waste
State Environment Protection Policy (Waters of Victoria) 2003, Victoria	n/a	n/a	Framework for protection and rehabilitation of surface water environments	n/a
State Environment Protection Policy (Groundwaters of Victoria) 2007, Victoria	n/a	n/a	Framework for protection and rehabilitation of groundwater environments	n/a
Environment Protection (Scheduled Premises & Exemptions) Regulations 2007, Victoria	n/a	Requirements for construction or modification of facilities or processes, and for operating conditions, discharge limits, monitoring and reporting	Requirements for construction or modification of facilities or processes, and for operating conditions, discharge limits, monitoring and reporting	Requirements for construction or modification of facilities or processes, and for operating conditions, discharge limits, monitoring and reporting
Environment Protection Act 1970, Section 31A Pollution Abatement Notice	n/a	n/a	Prevention of pollution or environmental risk through risk controls and/or changes to on-site processes	Prevention of pollution or environmental risk through risk controls and/or changes to on-site processes
Environment Protection (Environment & Resource Efficiency Plans) Regulations 2007, Victoria	Identify / pursue cost-effective energy reduction opportunities	n/a	Identify / pursue cost-effective water use reduction opportunities	Identify / pursue cost-effective waste reduction opportunities

With reference to the final line item in Table 5, other Australian states do not possess equivalent environmental regulations to the Victorian Environment & Resource Efficiency Plan (EREP) framework (EPA 2012b), meaning that there is less of an imperative to (for example) reduce water use. In 2007 the Shell Geelong refinery was reported as being the region's largest water user, consuming around 5 per cent of the City of Geelong's fresh water as part of refinery processes (Geelong Advertiser 2007). Under the influence of the EREP regulatory framework, Shell has pursued a Water Master Plan project which is saving more than 100 million litres of water per year (Victorian Government 2008).

During June 2012, over 200 million litres of water were released from the West Barwon Reservoir, greater Geelong's most significant drinking water catchment, providing environmental flows into rivers downstream from the reservoir (Barwon Water 2012). Although this release has coincided with a period of significant rainfall, the comparable magnitudes of the water saving and release highlights the complexity and importance of context in assessing environmental impacts.

Air quality impacts are similarly affected by these issues of context. With reference to Table 5 and Table 6, air pollutant emissions from Shell's Geelong refinery are regulated under Victorian legislation. And the ongoing air quality monitoring program maintained by Shell under direction from EPA Victoria takes into account the human exposure risks in the surrounding region (Shell 2012b).

Table 6. Emissions from Shell's Geelong refinery for the 2010/11 financial year as reported under the requirements of the National Pollutant Inventory (NPI 2012).

Pollutant	Emissions (kg)
Total Volatile Organic Compounds (VOCs)	720,000
n-Hexane	36,000
Particulate Matter 2.5 micron	85,000
Ethylbenzene	780
Oxides of Nitrogen (NOx)	1,600,000
Land emissions	-
Water emissions	-

5.1.2. EV Energy Production & Supply in Victoria

Electricity generation contributes in excess of 50 per cent of Victoria's greenhouse gas emissions (DECC 2012c). As a consequence, the grid average emissions factor for Victoria is the highest in Australia and amongst the highest in the world – refer to Table 4 above for an illustration of this.

A simple calculation using some basic assumptions illustrates how this translates in terms of greenhouse gas emissions. A Nissan LEAF EV is reported as consuming 173 Wh/km energy (DIT 2012), which if sourced from Victoria's present grid energy mix with an average emissions intensity of 1.35 tCO2e/MWh (DCCEE 2012b) will translate to 234 gCO2e/km.

By comparison, the current top-selling comparable ICEV, the Mazda 3 SP20, has a reported full fuel cycle emissions of 154 gCO2/km (DIT 2012), which is 79 gCO2/km or one third less than the EV using Victorian grid-sourced electricity.

With reference to Table 7 and Table 8 below, a more detailed analysis of Victoria's grid electricity mix provides the basis for an understanding of the likely impacts arising from common EV charging scenarios.

Table 7. Victoria's electricity grid mix, where OCGT = Open Cycle Gas Turbine, CCGT = Closed Cycle Gas Turbine and Solar PV includes small-scale (for example, residential) (ACIL Tasman 2009, CEC 2011, personal communications)

Generator	Type / Fuel	Character	Size (MW)	Emissions intensity (tCO2e/MWh sent out)
Loy Yang A	Steam turbine / brown coal	Baseload	2,120	1.22
Hazelwood	Steam turbine / brown coal	Baseload	1,600	1.53
Yallourn	Steam turbine / brown coal	Baseload	1,480	1.42
Loy Yang B	Steam turbine / brown coal	Baseload	1,000	1.24
Energy Brix	Steam turbine / brown coal	Baseload	195	1.49
Anglesea	Steam turbine / brown coal	Baseload	150	1.21
aggregate	Hydro	Peak	803	0
Mortlake	OCGT / natural gas	Peak	550	0.64
Newport	OCGT / natural gas	Peak	500	0.62
Mortlake 2	CCGT / natural gas	Peak	400	0.41
Laverton North	OCGT / natural gas	Peak	312	0.68
Valley Power	OCGT / natural gas	Peak	300	0.86
Jeeralang B	OCGT / natural gas	Peak	228	0.9
Jeeralang A	OCGT / natural gas	Peak	204	0.9
Somerton	OCGT / natural gas	Peak	160	0.86
Bairnsdale	OCGT / natural gas	Peak	94	0.6
aggregate	Wind	Intermittent	432	0
aggregate	Solar PV	Intermittent	152	0
aggregate	Bioenergy	Intermittent	113	0
aggregate	Wave	Intermittent	0.15	0
aggregate	Solar thermal	Intermittent	0	0
aggregate	Geothermal	Intermittent	0	0

Table 8. Further analysis of Victoria's electricity grid mix based upon Table 7 above.

	Baseload	Peak	Intermittent
Total installed capacity	6,545	3551	697.15
Percentage of total installed capacity (%)	60.6%	32.9%	6.5%
Weighted average emissions intensity (tCO2e/MWh)	1.35	0.53	0

Paevere et al (2012) analysed Victorian travel behavior to develop an EV transport mode model which provides an indication of EV charging energy use by time and location. The three charging scenarios they adopted were demand charging, where vehicles charge solely at their home address upon arriving home; off-peak charging, where EVs charge solely at their home address but charging is delayed until after midnight where possible; and off-peak plus vehicle-to-house, which is the same as off-peak but energy is withdrawn from vehicles to the home during peak demand periods. For the purposes of understanding likely EV charging impacts the third scenario can be ignored.

For the demand charging scenario, the marginal impact analysis method described previously is most applicable. This means that the 'peak' generation capacity weighted average emissions factor of 0.53 tCO2e/MWh would apply, which for the Nissan LEAF would translate to around 92 gCO2e/km or around 60 per cent of the full fuel cycle emissions of the Mazda 3 SP20.

For the off-peak charging scenario, the most likely source would be baseload capacity with a weighted average emissions factor of 1.35 tCO2e/MWh. For the Nissan LEAF this would translate to around 234 gCO2e/km or around 1.5 times the full fuel cycle emissions from the Mazda 3 SP20.

Limitations in this approach are significant:

- The highly variable contribution of renewables to the energy mix is not taken into consideration
- Variations to the actual supply mix will be occurring continuously as a result of demand variation – forecast and actual
- The contribution of EV charging to overall electricity demand is likely to be small at the outset of the EV market development, meaning that they may be absorbed through ancillary services (which could be either baseload or peak generation)
- As the contribution of EV charging to electricity demand is factored into forecasts, reliance on peak generation will decrease

Despite these limitations, it is likely that off-peak charging using Victoria's present grid mix will result in more greenhouse gas emissions than charging during peak periods. This result runs counter to wider policy objectives regarding cost and reliability of electricity supply.

With reference to Figure 13, Table 7 and Table 8 above and Table 9 below, this situation can be expected to improve as the various influences driving decarbonization of Victoria's grid come to bear. A report commissioned by the Victorian Department of Primary Industries forecast that EVs using Victoria's grid energy would provide a net emissions reduction relative to ICEVs around 2021 (MMA 2009). Key inputs into this analysis include emissions intensity reductions and vehicle energy economies for both EVs and ICEVs – refer to section 7.1 for a more detailed and up to date analysis using the improved forecasts outlined in this section.

Charging specifically using renewable energy presents an alternative path to minimize environmental impacts in Victoria in the near-term. This may be achieved via the two paths set out previously – on-site renewable energy generation or through purchase of renewable energy.

On-site (or distributed) energy generation can utilize a range of sources including solar photovoltaic (PV), wind, biomass etc. In Victoria the most common residential distributed energy source is solar PV (VCEC 2012). Based upon reported figures (DIT 2012), a Nissan LEAF that travels the Victorian average of 40 km per day (DOT 2012) will consume around 6.9 kWh. According to the Clean Energy Council (2012), the Melbourne average daily energy production of a 2 kW solar PV system is 7.2 kWh.

However, although this provides a guide as to the distributed energy system specification that would be required to supply an EV with renewable energy, there are significant issues that need to be dealt with before EV charging can be claimed to be using renewable energy.

Moment-to-moment variations will occur both in the renewable electricity generated and EV charging required. For example, solar PV generation may vary from negligible production across a dark day of full cloud cover, to double the daily average on a day of uninterrupted sunshine. To account for this most renewable energy systems are grid-connected, or require a storage facility to 'smooth out' these inevitable supply-demand mismatches.

In the latter instance linking EV energy use to renewable energy generation is straightforward so long as the system is "closed", meaning that the only energy supplied into the system is that generated locally. The closed system may however create limitations in terms of the available energy for charging at any time and correspondingly on the vehicle utility. A building energy management system optimized for the EV driving and charging needs may address this limitation, however this technology has yet to emerge in the market.

Table 9. Forward projections for Victoria's electricity grid mix, where the projections detailed for the brown coal generators reflect impacts from the Energy Security Fund buybacks set out as part of the Australian Government Clean Energy Act 2011 (Deloitte 2011).

Generator	Type / Fuel	Character	Forward projection	Emissions intensity (tCO2e/MWh sent out)
Loy Yang A	Steam turbine / brown coal	Baseload	Partial retirement of 150 MW	1.22
Hazelwood	Steam turbine / brown coal	Baseload	Full closure by 2020	1.53
Yallourn	Steam turbine / brown coal	Baseload	Full retirement by 2030	1.42
Loy Yang B	Steam turbine / brown coal	Baseload	Partial retirement of 130 MW	1.24
Energy Brix	Steam turbine / brown coal	Baseload	Full closure by 2016	1.49
Anglesea	Steam turbine / brown coal	Baseload	Small derating	1.21
aggregate	CCGT / natural gas	Peak / baseload	Growth, transition from peak to baseload	0.41
aggregate	Wind	Intermittent	Growth	0
aggregate	Geothermal	Intermittent	Growth	0

For the more commonplace grid-connected systems, energy production and use profiles along with the electricity market arrangements behind the system must be taken into account.

For owners of grid-connected renewable energy systems installed before 2011, the renewable energy generated by their system is accounted for through Renewable Energy Certificates (RECs). RECs are a tradeable commodity within the renewable energy market and are the means by which "liable entities", or organisations which have a legislated requirement to purchase amounts of renewable energy, are able to meet their obligations. As the total number of RECs across the market reflects the amount of installed capacity, if a system owner sells their RECs they are effectively trading the quantity of renewable energy produced by their system. On this basis, for the system owner to claim their EV charging energy to be renewable they must:

- Ensure that the amount of energy produced by the system will satisfy their EV charging needs, and
- Voluntarily surrender the corresponding amount of RECs (rather than sell or trade them), or avoid creating RECs in the first place.

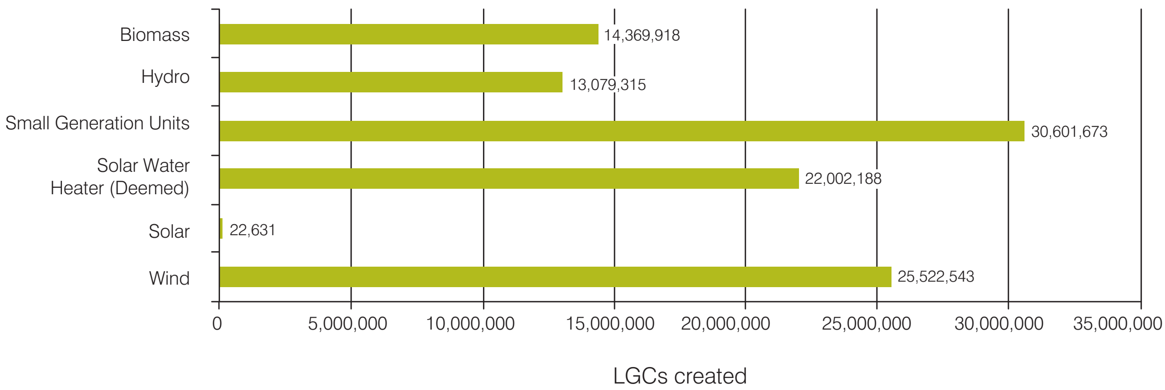
For owners of small-scale systems (such as rooftop solar cells) that were installed any time from 2011 onwards, the new form of REC called a Small-scale Technology Certificate (STC) is accounted for in a way that means the owner retains renewable energy created.

In this instance for changing energy to be renewable, the amount of renewable energy generated simply needs to equal or exceed the EV charging energy use. Due to the daily variation in both of these, average values should be calculated for periods of not less than one month.

For owners of large-scale systems that were installed any time from 2011 onwards, the market works as for the pre-2011 systems however the RECs are now known as Large-scale Generation Certificates (LGCs). This is the market in which the GreenPower renewable energy purchasing program operates.

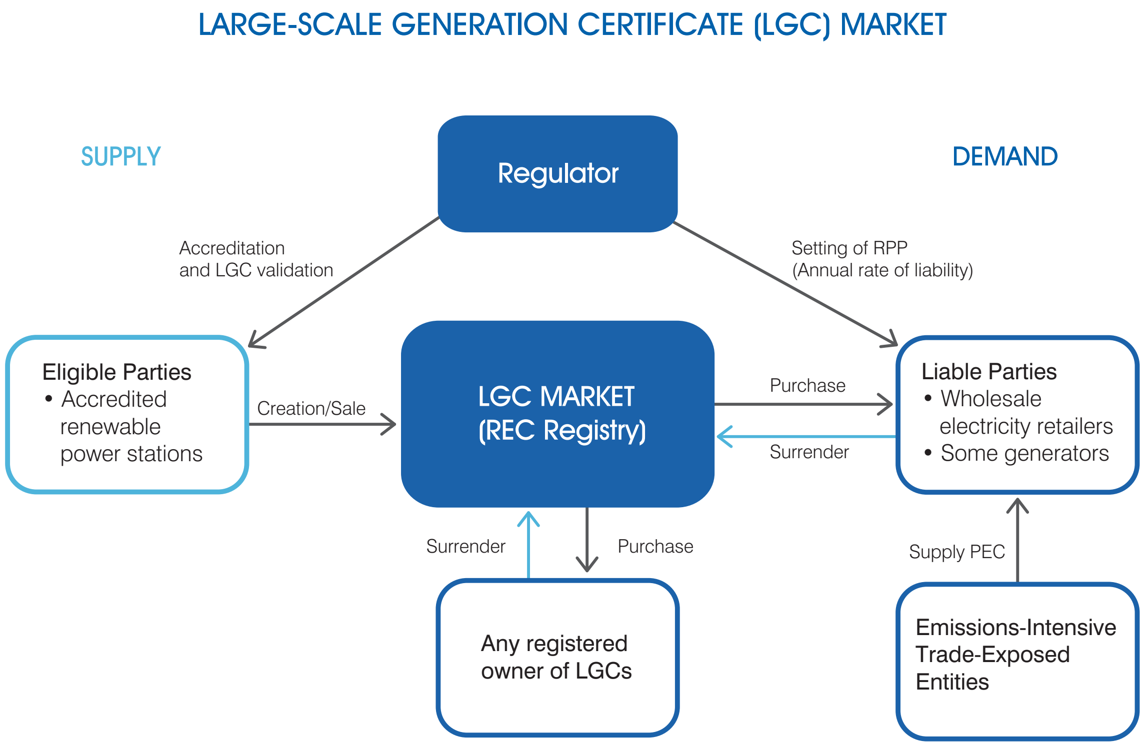
Using GreenPower addresses these issues and provides more flexibility for the EV driver. With reference to Figure 14 above, GreenPower is a government-accreditation program that enables electricity retailers to purchase renewable energy on behalf of consumers (GreenPower 2012). In selecting GreenPower, a consumer is instructing their electricity retailer to purchase an equivalent amount of renewable electricity through the trading market in Large Generation Certificates (LGCs). One LGC is awarded to an approved renewable energy generator for each MWh of renewable energy they create – Figure 15 below depicts the renewable energy sources of LGCs for 2011.

Figure 15. Large-scale Generation Certificates (LGCs) created in 2011 according to renewable energy source (ORER 2012).



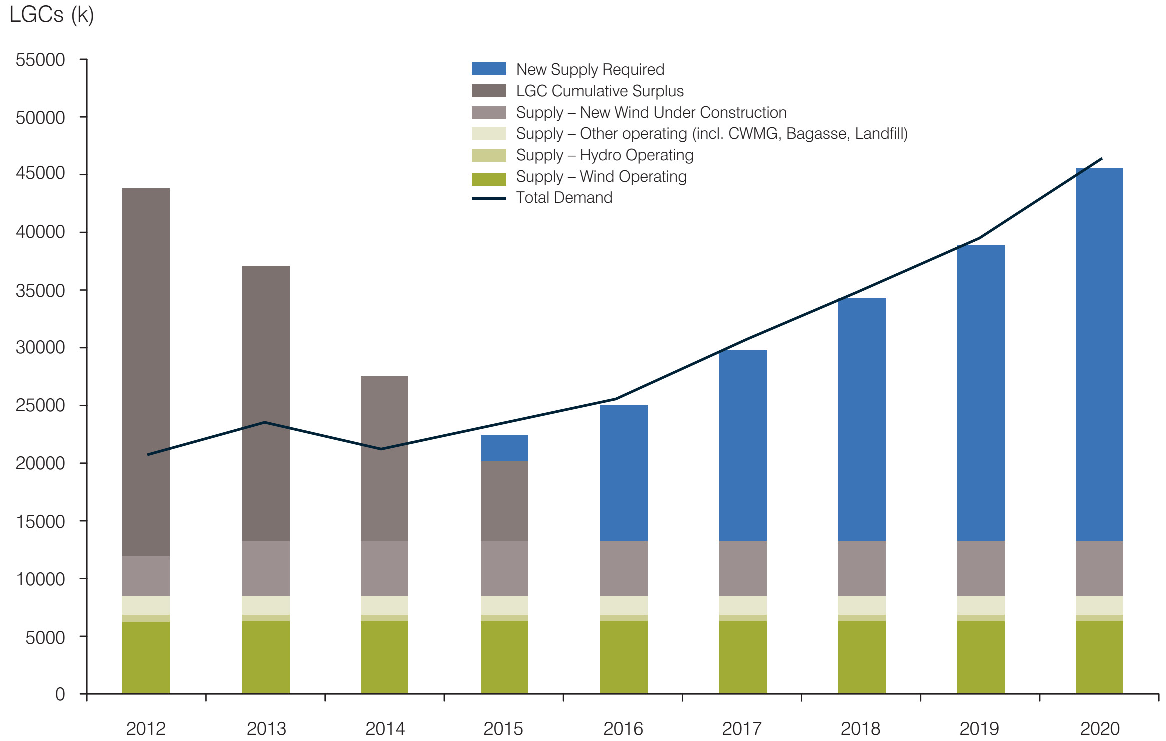
Renewable energy generators sell their LGCs into the trading market at a price that is determined by the balance between supply and demand for the certificates – refer to Figure 16 below for a schematic of the LGC market. The GreenPower purchase obligation for retailers sits above their existing obligations under programs such as the national Renewable Energy Target. In meeting their GreenPower purchase commitment, the electricity retailer will 'surrender' an equivalent number of LGCs to the market, meaning that they are permanently removed and cannot be re-traded. This process is the key to ensuring that a GreenPower purchase means that renewable energy is being used.

Figure 16. Schematic illustrating the trading market in Large-scale Generation Certificates (LGCs), where the GreenPower program is forms part of the purchase and surrender of certificates by any registered owner of LGCs. Increased demand due to LGC purchases through the GreenPower program create upwards pressure on LGC values, thereby promoting investment in large-scale renewable energy projects (Clean Energy Regulator 2012).



The increased demand for LGCs through the GreenPower purchasing program increases LGC values in the near-term, which then promotes increased supply of renewable energy. Between 2008 and 2011 the GreenPower program raised above $80 million per annum consistently for the purchase of between 20 and 25 per cent of the LGC market. With reference to Figure 17 below, the supply and demand projections for the LGC market can be seen.

Figure 17. Graph depicting supply and demand forecasts in the trading market for Large-scale Generation Certificates (LGCs). Demand increases as depicted by the black line drive investment in additional renewable energy supply as depicted by the blue bar (Nelson et al 2012).



The GreenPower program design and operation ensures that only large-scale renewable energy generation projects that meet strict environmental standards are supported – examples of energy generation NOT allowed under the accreditation program include:

- Pre-existing renewable energy generation prior to 1997
- Hydro-power where significant river diversions have taken place as part of the hydro station being built
- Biomass using native rainforests
- Coal seam gas
- All types of non-renewable generation including coal-fired, natural gas, oil and nuclear

Aside from the additional environmental benefits above, it is possible for individuals to mimic the GreenPower program by purchasing RECs from a trader and voluntarily surrendering them to the regulator. By monitoring the amount of charging energy used and reconciling this with REC purchases/surrenders, EV drivers may operate a robust, flexible and possibly cheaper renewable energy charging strategy.

Unfortunately complications remain, as regardless of whether GreenPower or direct REC purchase, the likely mismatch between renewable energy generation and EV charging demand profiles suggests that consideration of the marginal impacts should be taken into account.

Other potential electricity market impacts from EV charging by Victorian drivers are worthy of consideration. Victoria has invested in an Advanced Metering Infrastructure that is a key enabler for both 'smart' charging and Vehicle-to-Grid (V2G) interactions (Järvinen et al 2011).

The benefits arising from these charging scenarios fall primarily to the distribution network operators in the form of deferred investment in infrastructure upgrades and improved asset utilization, but also to both coal-fired and renewable energy generators in similarly improved asset utilization. While assessment of the benefits arising from these options is challenging, Usher et al (2012) have estimated that 'smart' charging would deliver around $150 per annum of network benefits and V2G may deliver around $1300 per annum at the outset decreasing to $350 per annum as more vehicles took up the opportunity. These benefits are likely to translate to reduced environmental impacts due to improved resource efficiencies arising out of improved asset utilization and deferred asset investments.

Victoria's electricity generation occurs within the same environmental regulation framework as was set out for the Shell refinery in section 5.1.1. This being the case, the various environmental impacts generally attributable to coal-fired electricity generation will be managed to the same standards as for petrochemical production in Victoria. For the purposes of comparison with the figures provided for the Shell refinery in Table 6 above, Table 10 below sets out the emissions reported for the Loy Yang A, Victoria's largest electricity generation source, under the National Pollutant Inventory.

It is worth noting however that renewable energy generation creates very little environmental impact. Wind farms, the most common large-scale renewable energy source, may impact upon local flora, fauna and human amenity. As for other industrial facilities, these impacts will be managed through the planning approvals process to meet community standards (DPCD 2012).

Table 10. Emissions from Loy Yang A for the 2010/11 financial year as reported under the requirements of the National Pollutant Inventory (NPI 2012).

Pollutant	Emissions (kg)
Particulate Matter 2.5 micron	2,300,000
Polychlorinated dioxins and furans (TEQ)	0.018
Hydrochloric acid	9,500,000
Oxides of Nitrogen (NOx)	23,000,000
Sulfur dioxide	52,000,000

There is a final consideration that must be made regarding electricity distribution in Victoria as relates to the ability for a vehicle to roam around the EV charging network as described in section 5.1. As individual EV charging outlets generally use electricity supplied as part of the overall building/site supply arrangements, the nature of the electricity being used will vary from outlet to outlet. There is a clear case therefore for each charging outlet to be clearly identified as renewable or non-renewable to ensure drivers are able to both choose and verify the electricity source should they be committed to running their vehicle on renewable energy.

Alternatively, charging network service providers should provide a clear statement of commitment relating to renewable energy supply arrangements across their networks. Where this commitment has been given, the service provider should account for all energy used within their network and reconcile this through renewable energy supply arrangements that are independently verified. Once these arrangements are in place, customers can charge using (zero emissions) renewable energy at any time or place within the service provider's network.

5.2. Energy Use

Impacts arising from energy use in vehicles are often termed 'downstream' impacts, in that they occur downstream from the energy production supply-chain. The key influences on downstream impacts are the energy conversion characteristics of the technology, and the way in which the technology is used (which can be termed the 'duty cycle').

5.2.1. ICEV Energy Conversion

ICEVs are defined by the process which takes place at their core – combustion of a hydrocarbon-based fuel-source to produce energy that can be harnessed for propulsion. The chemical reaction which is the combustion process creates a range of by-products aside from energy that are emitted from the engine exhaust. These by-products include water, air and heat, and a range of pollutants that must be managed to minimize their impacts on human health and the environment.

Vehicle emissions regulations were first implemented in the 1970s and have been progressively tightened ever since. Individual pollutants are regulated in new and in-service vehicles. Due to the global nature of the automotive industry and the costs associated with proliferation of standards, emissions regulations are gradually harmonizing even if still at varying levels from one market to the next.

With the relatively slow turnover of the fleet the effect of new emission standards is incremental, and offset by the increase in vehicle transport activity and population exposure. According to EPA Victoria, motor vehicles are the state's major source of air pollution (EPA 2012a). In 2006 motor vehicle emissions contributed the following levels of pollutants to Melbourne's overall air quality:

- 72 per cent of all carbon monoxide emissions
- 70 per cent of all nitrogen oxides (NO_x) emissions
- 28 per cent of all volatile organic compounds (VOCs) emissions
- 31 per cent of all emissions of particles smaller than 2.5 microns ($PM_{2.5}$)
- 27 per cent of all emissions of particles smaller than 10 microns (PM_{10})
- 6 per cent of all sulphur dioxide emissions (SO_x)

Nitrogen dioxide (N_2O) is known to affect the throat and lungs. Particles can aggravate existing lung and heart diseases, and the smaller the particle the greater its effect. NO_x and VOCs can react in the presence of sunlight to form ozone, which affects the lining of the throat and lungs and increases the risk of respiratory infections. SO_x is known to attack the throat and lungs, leading to increases in respiratory illnesses like chronic bronchitis.

An assessment conducted by the Bureau of Transport and Regional Economics estimated that for Victoria in the year 2000 between 262 and 1220 people suffered a loss of quality of life due to ill health attributable to motor vehicle emissions (BTRE 2005). In addition to this, 243 to 547 early deaths could be attributed to motor vehicle emissions, with the central estimate being 393. When this figure is considered relative to the 287 Victorians who died due to road accidents in 2011 (VicRoads 2012), it is clear that air pollution arising from motor vehicles is a serious problem for Victoria.

EPA Victoria is currently working with CSIRO to get a better understanding of the likely trends in Victoria's air quality over the next few decades (EPA 2012c). Indications are that the continuing improvements to motor vehicle emissions arising from the progressive tightening of emissions standards will significantly reduce the impacts of carbon monoxide, nitrogen dioxide and air toxics by 2030.

Motor vehicles are also a significant source of Victoria's greenhouse gas emissions. With reference to Figure 18, transport is the second-largest sectoral contribution to Victoria's greenhouse gas emissions inventory behind stationary energy (DCCEE 2012c). And in 2010, cars contributed 54 per cent of all Victoria's greenhouse gas emissions attributed to fuel combustion by transport (DCCEE 2012a).

While greenhouse gas emissions from Australian motor vehicles are currently unregulated, car manufacturers are required test and report on the level of emissions produced by their vehicles under standardized test procedures (DSEWPC 2012). The figure, commonly known as the vehicle tailpipe emissions, reflects the amount of greenhouse gas emissions that the vehicle will emit on average per kilometer travelled. This figure does not include emissions arising from the fuel production process, which represent around 5 to 10 per cent of the full fuel cycle emissions (DIT 2012).

The average tailpipe emissions from new motor vehicles sold in Australia annually has gone down from 252.4 gCO2/km in 2002 to 212.6 gCO2/km in 2010 (NTC 2012). However when compared internationally Australia lags most other developed nations. In 2009 the average emissions for new passenger vehicles sold in Europe was 146 gCO2/km as compared to 210 gCO2/km in Australia, or 44 per cent higher than the European average.

The energy conversion efficiency of ICEVs can be expected to improve with time, particularly under the influence of regulatory measures relating to both greenhouse gas and air pollutant emissions (DIT 2011). This improvement should be considered as part of any comparison between vehicle technologies of the future.

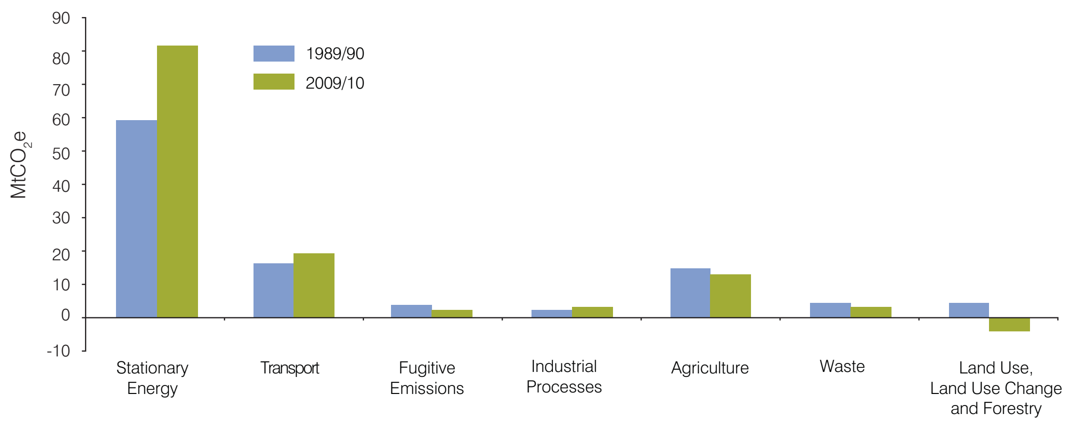
5.2.2. EV Energy Conversion

As was alluded to in section 4.2.2, electric motors use magnets to create motion. By utilizing the electromagnetic properties of materials, electric motors are able to convert energy into motion much more efficiently than internal combustion engines (ICEs). Typical ICE efficiency is around 28 to 30 per cent, compared to 85 to 95 per cent for electric motors (Faria et al 2012). This is a significant advantage in terms of lifecycle environmental impacts.

Another characteristic of energy conversion into motion through the electromagnetic properties of materials is that it creates zero emissions. This is why electric motors are able to be operated in enclosed spaces, such as indoor living areas or workplaces.

For both of the above reasons EVs are the top performers in the Australian Government's Green Vehicle Guide (DIT 2012). With zero tailpipe emissions (greenhouse gases and air pollutants), EVs achieve a perfect score with regards their environmental performance (DIT 2012).

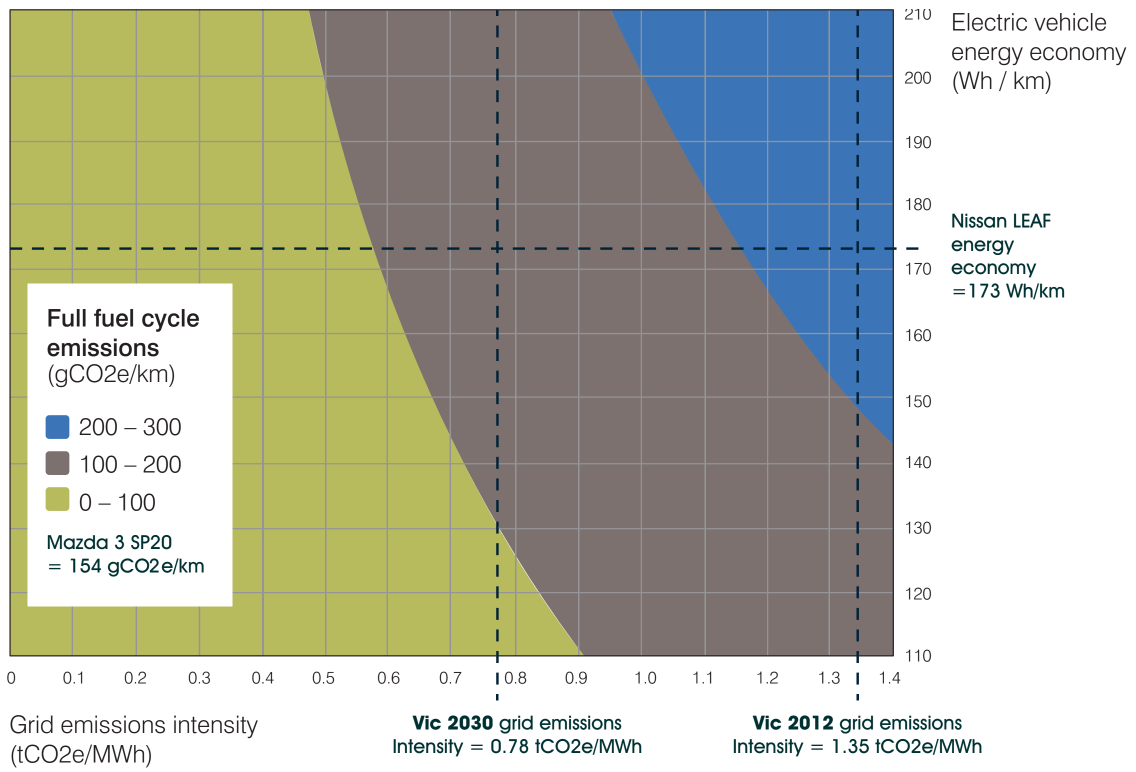
Figure 18. Victoria's greenhouse gas emissions for 2009–10 according to sector (DCCEE 2012c).



The zero emissions rating is however misleading due to its representation of tailpipe emissions only – this is discussed further in section 5.2.3 below. Rather, the full fuel cycle relationship to both EV energy economy and the emissions intensity of the electricity generation source should be taken into account. Figure 19 below provides a graphic illustration of this interdependency, where the different colour regions represent 100 gCO2e/km increments in full fuel cycle emissions performance. The greenhouse gas emission implications for the Nissan LEAF can be seen via the dashed lines which intersect at 235 gCO2e/km for the 2012 Victorian grid mix, and 135 gCO2e/km for the forecast 2030 Victorian grid mix. The Mazda 3 SP20 by comparison would sit around midway of the middle colour band at 154 gCO2e/km full fuel cycle greenhouse gas emissions.

As for ICEVs, energy conversion efficiency of EVs is expected to improve as an outcome from extensive research and development into batteries, electric motors and power electronics (US DOE 2011). This improvement should also be taken into account as part of any evaluation of future vehicle technologies.

Figure 19. Chart depicting the interrelationship between EV energy economy and the electricity grid emissions intensity in determining full fuel cycle greenhouse gas emissions, including some pertinent figures for comparison (DIT 2012, DCCEE 2012b, personal communications).

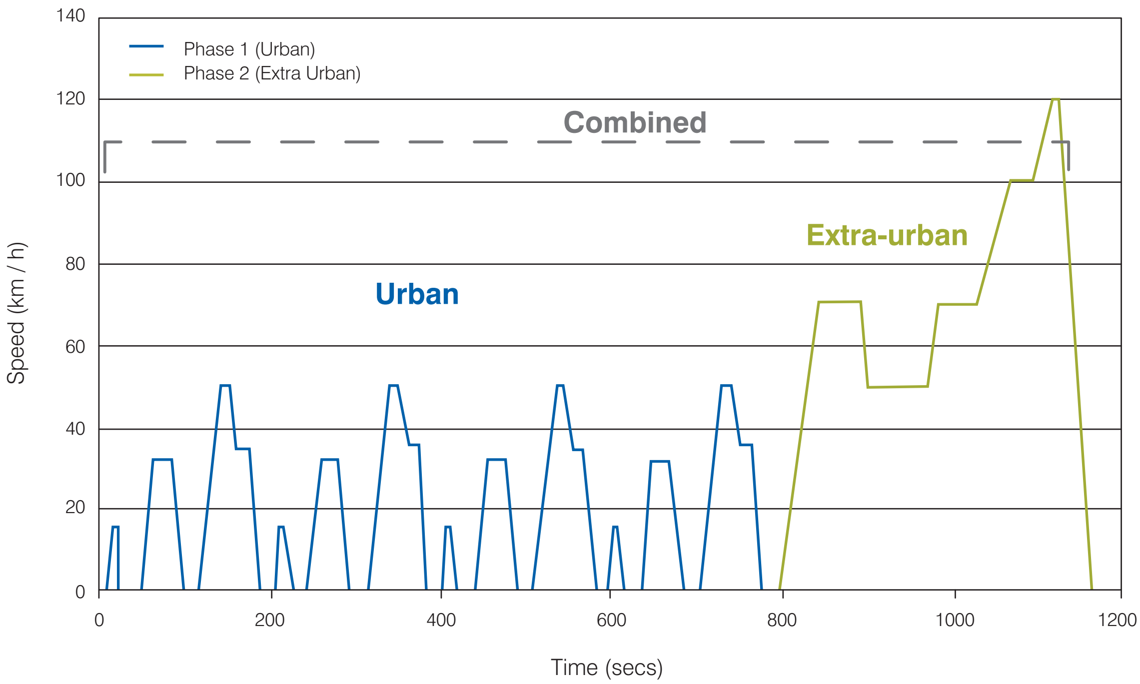


5.2.3. Duty Cycle

The phrase 'duty cycle' relates to the way in which vehicles are driven. Cars may sit at idle, they may undertake smooth or abrupt accelerations/decelerations, they may travel at a constant speed of anywhere between near-stationary and as fast as they will go, they go up and down hills, they may carry only the driver or a full complement of passengers and luggage, and they may travel in hot or cold weather with various accessories on or off. Driver behavior, trip purpose and road/traffic conditions determine ultimately how cars are driven. Vehicle technology may be optimized according to a specific duty cycle, or a compromise solution that supports a wide spectrum of uses.

Consumers however need a reliable framework in which to assess vehicle performance for their needs. To ensure that vehicles are able to be compared, they are tested and certified according to standardized test procedures (DIT 2012). These test procedures utilize set driving routes known as drive-cycles. A drive-cycle is a condensed and idealized version of the driving conditions that it is meant to represent, such as city/heavy traffic driving. Drive-cycles are themselves a compromise between the costs associated with testing on different and/or longer cycles, the need for consistency so as to not invalidate the knowledge acquired over the history of drive-cycle based vehicle development and subsequent real-world performance, and the goal to resemble specific real-world driving conditions as closely as possible. An outcome of this compromise may be discrepancies between reported and actual energy economy.

Figure 20. The UN ECE drive-cycle used for testing and certification of vehicles sold in Australia. Tailpipe emissions of CO_2 and other air pollutants are measured from vehicles as they traverse the drive-cycle described by the speed/time plot above. The 'urban' section resembles stop-start city driving, 'extra-urban' resembles suburban highway driving, while the 'combined' top-line figure is that most commonly used for compliance and comparison (DIT 2012).



New vehicles sold in Australia must be certified according to the Australian Design Rules (DIT 2012). As part of efforts to reduce the barriers associated with selling vehicles into the Australian market, the Australian test methods adopt the United Nations ECE regulations – refer to Figure 20 for a schematic illustrating the test cycle. For ICEVs, fuel economy and greenhouse gas tailpipe emissions are required to be tested and certified according to an urban drive-cycle, which resembles congested city driving, and an extra-urban drive-cycle, which more closely resembles suburban freeway commuting. The two figures are combined through a pre-determined ratio for a top-line figure. EVs are currently tested and certified for their combined drive-cycle energy economy only.

An important issue with regards the certification figure is that it represents emissions measured at the tailpipe only. This means that emissions 'upstream' from the vehicle are not taken into account, explaining why EVs are currently certified as emitting zero emissions of any kind (DIT 2012).

A robust LCA must take upstream emissions into account, which is why the full fuel cycle sits within the scope defined for this assessment.

Despite the effect of other variables being minimized in controlled drive-cycle testing, ICEVs exhibit significant variability in reported fuel economy between the urban and extra-urban drive-cycles. By way of example, Australia's highest selling car, the Mazda 3 SP20, has a reported fuel economy of 8 L/100km on the urban drive-cycle and 5 L/100km on the extra-urban (DIT 2012). With reference to Table 11 below, EV energy economy is similarly subject to variation due to driver inputs (Carlson et al 2010, Faria et al 2012). Not only is there significant variation in both the urban and extra-urban test results according to different driver behaviours, but all test results are less than the reported combined figure (which should be a combination of the two results, and therefore somewhere between them). Clearly therefore, driver inputs strongly influence actual EV energy economy.

Table 11. Results from real-world drive-cycle testing of a Nissan LEAF EV, examining the effect of drive-cycle, speed, driving style, and vehicle operating mode choice. Notable is the strong effect of driving style on the study results, as evidenced by the contrasting figures between slow/fast acceleration and ECO/normal (= non-ECO) operating modes, and the contrast with the reported combined energy economy figure (Faria et al 2012, DIT 2012).

Drive-cycle	Max speed (km/h)	Median speed (km/h)	% of test > 50 km/h	Other	Energy economy (Wh/km)
Urban	73	16	98.7	Fast acceleration	141.8
Urban	61	42	99.8	Slow acceleration	95.5
Urban	86	43	47	Fast acceleration	155.4
Urban	96	58	56	-	135.1
Urban	86	47	41	-	126.6
Urban	82	45	78.5	ECO mode	103.9
Urban	71	42	56.7	ECO mode	114.9
Urban	77	37	88.4	-	129.3
Extra urban	100	60	40.7	ECO mode	129.3
Extra urban	115	63	46.5	Fast acceleration	157.2
Extra urban	118	75	43.8	-	141.8
Extra urban	100	67	37.7	-	143
Extra urban	100	77	19.6	-	132.8
Extra urban	85	70	24	-	138.1
Combined	-	-	-	-	173

Taking all of this into account, modeling and/or measurement of energy use and emissions from different vehicle technologies is highly sensitive to the assumptions necessary for the assessment to be made. The choice of drive-cycle as an input into modeling makes a large difference to the conclusions reached (Sharma et al 2012). Similarly, real-world test results often bear little similarity to those from either certification or modeling, but have limitations in terms of their comparability across assessments.

One study subjected 51 electric, hybrid and internal combustion engine vehicles to comparative energy consumption measurements on a 95 km urban/extra-urban test route (Howey et al 2011). The results indicated a clear energy efficiency advantage in favour of vehicle electrification, with the average energy economy for the electric, hybrid and ICE vehicles being 0.62, 1.14 and 1.68 MJ/km.

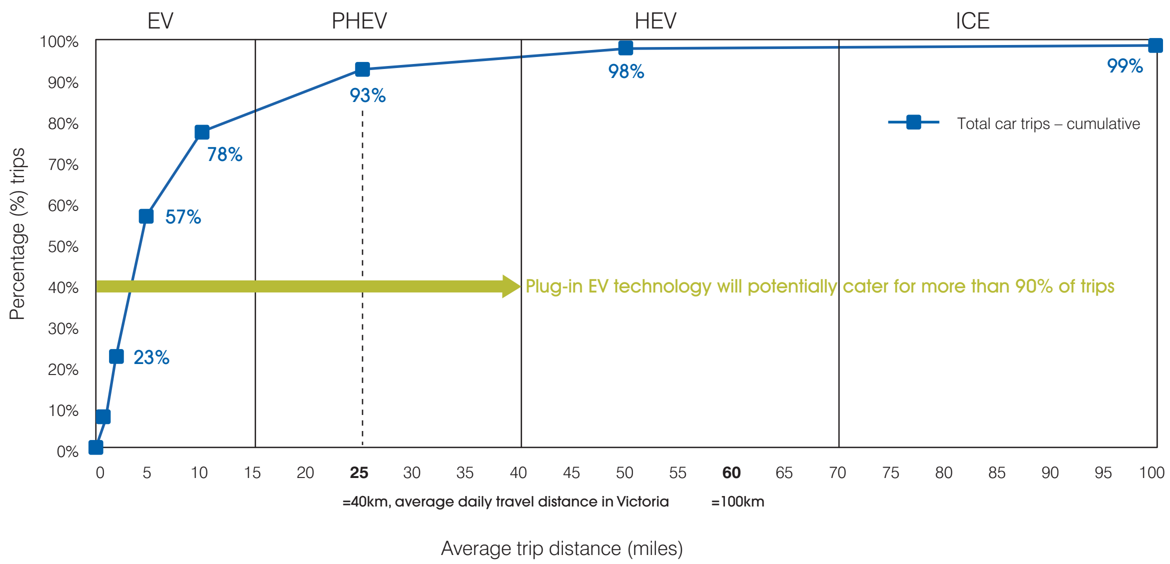
Reported energy economy figures support this conclusion. United States Government data for the Nissan LEAF EV, Chevrolet Volt PHEV, Toyota Prius HEV and Mazda 3 ICEV shows that energy economy improves with vehicle electrification (US Govt 2012). Using miles per gallon equivalency calculations to allow a comparison between electric and petrol technologies, the reported figures are respectively 99, 94, 50 and 27 (where a higher figure indicates better energy economy).

These results can be predominantly attributed to the inherent energy conversion efficiency of electric motors versus internal combustion engines – typical ICE efficiency is 28 to 30 per cent, versus 85 to 95 per cent for an electric motor (Faria 2012).

Notably however, there is a contrasting trend in the reported energy economy figures for the city versus highway driving for EVs versus ICEVs. The Nissan LEAF EV is reported as delivering 106 miles per gallon equivalent in city driving as compared to 92 on the highway. Conversely, the Mazda 3 returns 24 miles per gallon in the city versus 33 on the highway. This highlights the sensitivity of energy economy to the drive cycle when comparing different vehicle technologies.

Another way of looking at the contrasting characteristics of different vehicle technologies is to take a 'horses for courses' approach to selecting the technology for the task. Analysis by the automotive powertrain design and development consultants Ricardo suggests that average trip distance is a good indicator of vehicle technology choice – refer to Figure 21 below.

Figure 21. An analysis of the passenger vehicle fleet task for the United Kingdom in terms of average vehicle trip distance, which shows that 93 per cent of trips taken are less than or equal to 25 miles. An interpretation of the appropriate vehicle technology choice according to average trip distance has been included, showing that plug-in vehicles (EVs and PHEVs) are suited to 93 per cent of the trips taken (Archer 2010).



Drawing upon the various test and modeling results above, it is likely that EVs will be purchased for primarily city-driving (where their operational cost advantage over ICEVs is most significant). This would suggest that the duty-cycle selected for a relative comparison with ICEVs should be biased towards city driving, such as the 'urban' component of the UN ECE drive-cycle. It would be wise however to include an assessment of other duty-cycles as part of sensitivity testing.

The operational life of the vehicle should also be considered as part of the duty cycle. Noting that the average age for a passenger vehicle in Victoria is 10 years (ABS 2011), the average life can be approximated as 20 years. With reference to Figure 22 below, the total distance travelled over the 20 year vehicle life has been estimated as 274,000 km based upon data obtained from the Australian Bureau of Statistics.

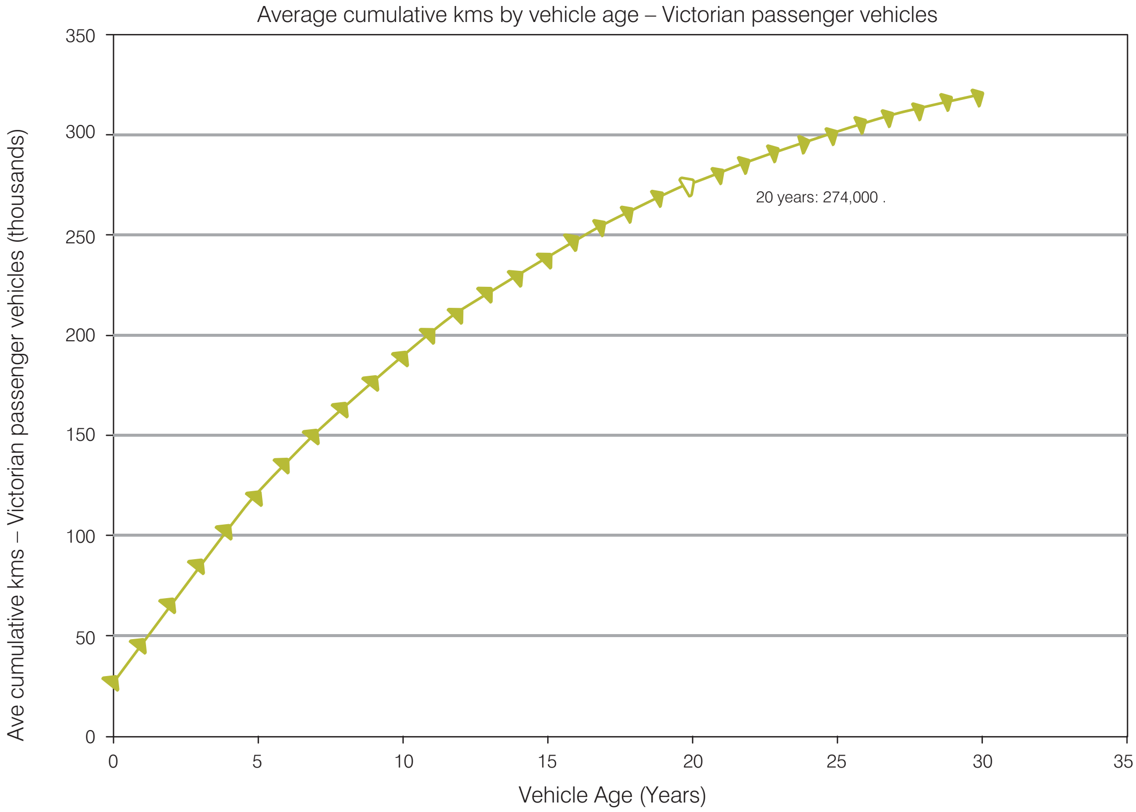
An additional consideration on the duty cycle relates to vehicle mass. As outlined in section 4.2, EVs bear a mass penalty compared to ICEVs primarily as a result of the battery pack. The benefits arising from extensive research and development investment into batteries will include both improvements in the energy conversion efficiency and mass reduction, both of which will contribute towards energy economy improvements (US DOE 2011).

5.3. Noise

An inherent feature of electric vehicles is their quiet operation when compared to conventional vehicles. This characteristic presents both opportunities and risks.

Seventy per cent of Victorians can hear traffic noise in their homes, and over one million are annoyed by it (EPA 2007). Due to its prevalence and high noise levels, traffic noise disturbs sleep and interrupts reading, relaxing and quiet activities.

Figure 22. Estimation of distance travelled over the average Victorian passenger vehicle lifetime, based upon data sourced from the Australian Bureau of Statistics (DOT 2011).



Mass adoption of electric vehicles may provide benefits in the form of reduced traffic noise for the wider community. And in noise-sensitive environments, individual EVs may be a key enabler for continued activity. An example of this is for late-night freight deliveries in residential neighbourhoods, where near-silent EVs may operate outside of the curfew periods that would apply to conventional vehicles.

The near-silent operation of EVs does however pose a potential risk to vulnerable road users who may rely to some extent on hearing road hazards. One famous study undertook a statistical analysis of many years of accident data and found there was an increased incidence of pedestrian and bicyclist crashes involving hybrid-electric passenger vehicles (NHTSA 2009). Further studies have found that EVs and HEVs are significantly quieter than ICEVs only at speeds of less than 15 km/h (Sandberg 2010). This is likely to be an issue for pedestrianized locations such as intersections, car-parks and driveways.

As a result, both automakers and regulators have moved to address the potential risks posed by the near-silent EV operation at low speed (Car Advice 2011). Nissan and Toyota have developed low-speed warning sounds for their vehicles. And regulators from the United States, European Union and Japan are investigating regulations that would require the vehicles to emit noise when operating at low-speeds.

5.4. Electromagnetic Fields

Electric and magnetic fields exist wherever electric current flows – in power lines and cables, residential wiring and electrical appliances, including electric vehicles. The World Health Organisation (2012) has noted that there are short-term effects on human health associated with exposure to strong magnetic fields, and the possibility of increased cancer-risk associated with long-term, low-level exposure.

Studies have been carried out to assess the potential risk to human health posed by electromagnetic fields of the type that exist in EVs (Kavet 2010). Measurements have found that the field strength not only resembles the exposure levels experienced in the home, but also what is experienced in conventional vehicles. These exposure levels are far less than the current safety standards associated with strong fields.

5.5. Maintenance

The environmental impacts associated with vehicle maintenance fall into two distinct categories:

i. Impacts associated with vehicle operating condition as an outcome from maintenance practices, and

ii. Impacts associated with the by-products of vehicle maintenance.

Maintaining vehicles in the correct operating condition according to the manufacturer's design intention is a critical determinant on its performance and consequential impacts to the environment. By way of example, the tailpipe emissions figures that are a regulatory reporting requirement reflect the optimal performance of the vehicle within the design parameters. Should this vehicle be allowed to depart from the designer's intent, energy conversion efficiency will decrease as the production of pollutants increases. Vehicle service intervals are designed to address this issue and strike a balance between cost and benefit. For the purposes of this study it is assumed that both ICEVs and EVs are maintained as per the manufacturer's recommendations, and that variations in operating condition within this maintenance regime make only a minor contribution to the overall vehicle environmental impacts.

By-products of vehicle maintenance are however worthy of further consideration. There are two areas in which differences may arise between ICEVs and EVs:

i. Operating fluids, such as lubricants and coolants

ii. Parts replacement

ICEVs require a range of lubricants and coolants that are related to the operation of the internal combustion engine. In particular, motor oil picks up a variety of hazardous contaminants when used in engines and transmissions (DEWHA 2010). These contaminants include lead, cadmium, chromium, arsenic, dioxins, benzene and polycyclic aromatics. If used motor oil and the contaminants it contains are disposed of inappropriately and released into the environment, they can harm humans, plants, animals, fish and shellfish.

Although around 250 million litres of used motor oil is recycled in Australia each year, it sometimes ends up in landfill, contaminating soil and groundwater (DEWHA 2010). In Victoria, motor vehicle repair and service premises are regulated – refer to Figure 23 below for guidance on vehicle washing and cleaning (EPA 2009). Safe disposal points for used motor oil are provided by councils across the state (SV 2012).

The existence and operation of these facilities is in part due to the Australian Government Product Stewardship for Oil program (DSEWPC 2012).An inherent design advantage of EVs over ICEVs is the reduction in parts requiring maintenance.

Mitsubishi (2012b) lists a range of ICEV-specific parts that need replacing over the vehicle life, but don't exist in an EV:

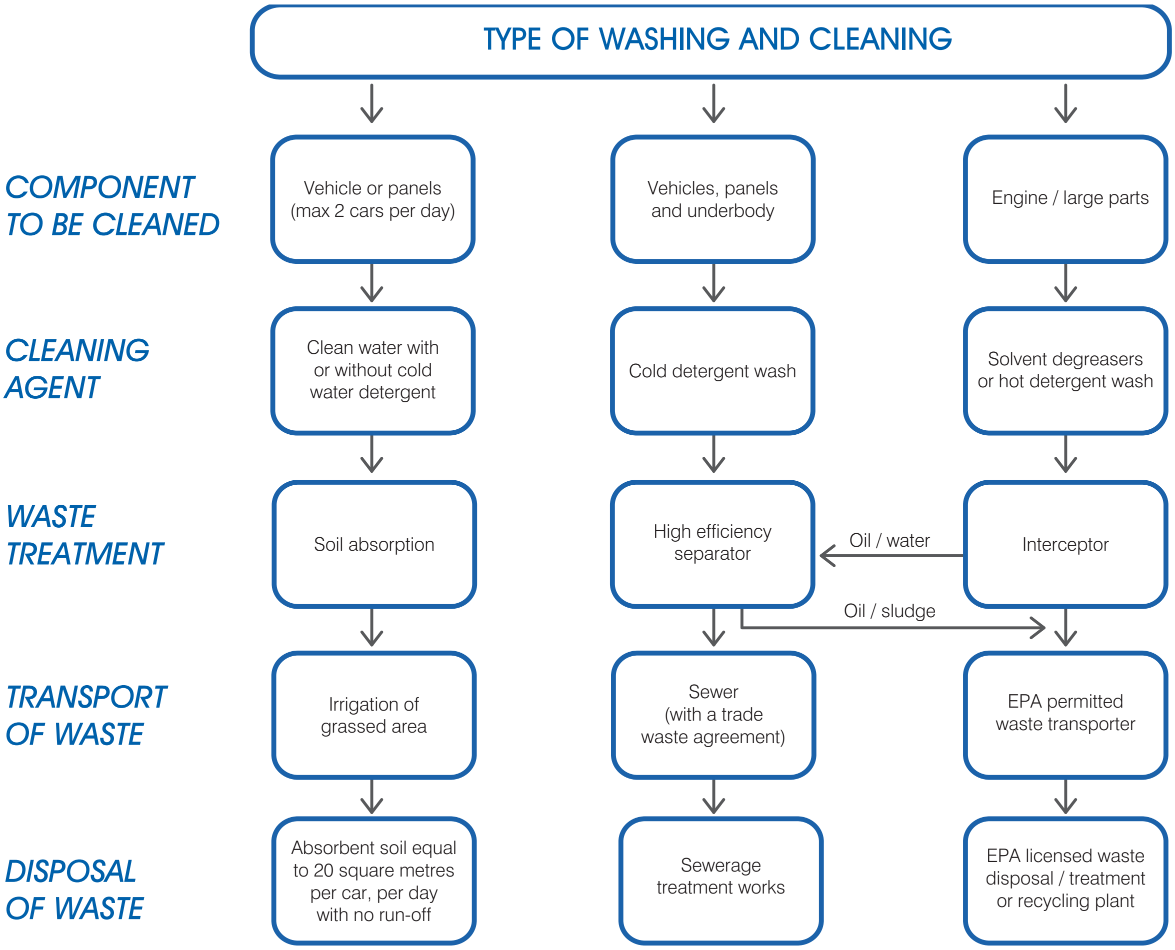
- Engine oil
- Oil filter
- Fuel filter
- Engine air filter
- Fuel-injection components
- Spark plugs
- Muffler
- Exhaust system
- Smog-control system
- Fan belt
- Others

The environmental impacts associated with the production, installation, removal and disposal/reprocessing of these components should be taken into account when considering potential differences between EVs and ICEVs, even if insufficient data is available to undertake this analysis here.

The main maintenance concern for EVs when compared with ICEVs is the battery. According to manufacturers, EV 'traction' batteries are designed to last the life of the vehicle (Toyota 2008, Nissan 2012b). From the manufacturers perspective this translates to up to ten years of normal use. Given that the average age of registered motor vehicles in Victoria is ten years (ABS 2011), this would suggest that most Victorian EVs are likely to undergo at least one battery replacement within the vehicle life.

Consideration of the battery reprocessing/disposal impacts is undertaken in more detail within section 6.2 below.

Figure 23. Vehicle washing and cleaning guidelines provided to Victorian motor vehicle repair and service providers, including reference to the regulatory requirements for management of pollutants (EPA 2009).



6. Vehicle Reprocessing & Disposal

Once a vehicle has reached the end of its operating life, its various components must be reprocessed for other uses or disposed of as waste. The pathway taken for any component will reflect (DEH 2002):

- warranties, which for engines are generally 5 years on new vehicles thereby reducing demand
- the reliability and longevity of the original components on vehicles, which are generally improving
- new vehicle costs, which are reducing in real terms and thereby reducing the appeal of second-hand and/or repaired vehicles
- new component costs, which are highly variable and influenced by design issues such as the use of sub-assemblies including large numbers of components which may need to be replaced whole if bought through the new component network
- repair costs, which are going up due to reduced demand and increased labour costs
- reprocessing costs, influenced by the ease of the component recovery, logistics and labour costs
- regulatory requirements, which may drive re-use of parts due to avoided disposal costs etc

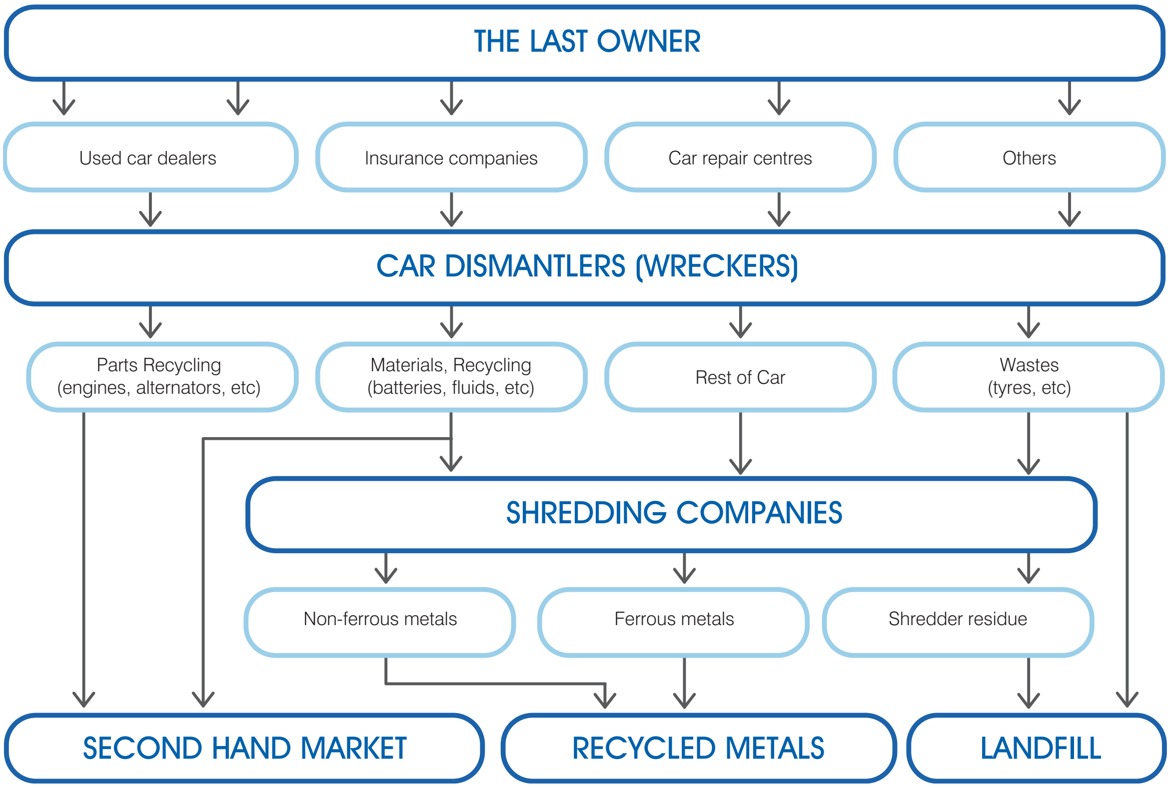
Reprocessing costs are themselves influenced by regulation. Avoided costs of compliance will drive identification of alternative uses and innovative reprocessing techniques. Well-designed legislation may also drive down reprocessing costs as has been the case in Europe, where end-of-life vehicle legislation applicable to automakers has resulted in improved vehicle design for disassembly and disposal (EC 2012).

In Australia there is presently no end-of-life vehicle legislation. As a result, vehicles disposed of at the end of their life form a large part of the volume of waste in Victoria. In 2006 alone, approximately 135,000 end-of-life vehicles generated over 200,000 tonnes of materials requiring processing (SV 2007).

However, mass is not the only indicator of the environmental impact of from end-of-life vehicles. With reference to Figure 24, the flow of materials out of end-of-life vehicles to various final destinations can be seen. Some vehicle parts can be reused whilst others, particularly fluids, must be removed and disposed of. Industry representatives estimate that shredding makes up about 70 per cent of metal recycling at 105,000 tonnes, landfill is estimated at 45,000 tonnes and plastics recycling at 5,000 tonnes (SV 2007). Of the materials remaining after shredding, 33 per cent is resins, 16 per cent is urethane foam and 15 per cent is fabric. In addition to these there are lesser proportions of other materials like iron, glass, rubber, non-ferrous metals, wood and paper.

The key technology for the recycling of materials from end-of-life vehicles is the automated ‘shredder’ (DEH 2002). Metal shredders can process end-of-life vehicles at a rate of 200 per hour, reducing them to fist-sized pieces of ferrous and non-ferrous scrap of a high physical and chemical quality. The efficiency of the highly expensive machines is a key element in the profitability of the metal recycling industry, and by extension the re-use of these materials. It has been suggested that Australian equipment is at least as efficient as those in use internationally.

Figure 24. End-of-life vehicle material flows in Australia (McNamara 2009)



As was outlined in section 4, ICEVs and EVs share many components to the extent that much of the material flows will remain the same. The key differences lay in the ICEV engine, fuel and exhaust systems, and the EV battery, electric motor and power electronics systems. Noting the complications associated with end-of-life environmental impact allocations described in section 3.2, objectives for this assessment should be to understand:

- the relative extent to which materials recycling occurs or is likely to occur in each system
- the relative primary energy burdens associated with production of the raw materials in each system
- the existence of potentially significant impacts within various environmental regimes arising from the disposal or reprocessing processes

6.1. Internal Combustion Engine, Fuel & Exhaust Systems

While parts that are of sufficiently high value are likely to be repurposed through the second-hand market, all parts will ultimately end up being reduced to their basic materials and processed accordingly. Engines, fuel and exhaust systems are mostly made of metals, entailing that in Victoria they will be mostly recycled. The predominant materials in modern-day vehicles will be aluminium in the engine block and cylinder-head, and steel in the other components.

As was described in section 5.5, ICEVs use a range of fluids such as lubricants and coolants that must also be dealt with at the end of the vehicle life. General process requirements dictate that fluids should be removed from vehicles prior to shredding, however the time imperative creates substantial pressure to process end-of-life vehicles as is (DEH 2002). Although the extent of contamination occurring at automobile parts recycling facilities in Australia has not been surveyed, there is no reason to believe that the situation would be markedly different from what is the case elsewhere. In the United States it is stated that, 'motor vehicle salvage facilities, the infrastructure through which cars are recycled, are extremely polluted… At least 50 of Minnesota's 436 facilities were found to be polluted enough to require intense clean-up efforts' (DEH 2002).

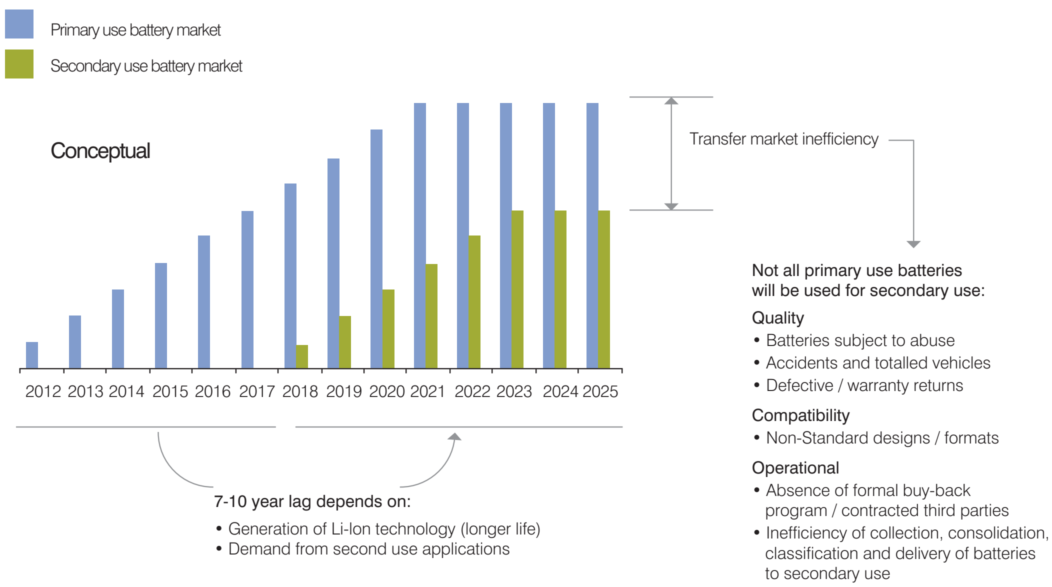
6.2. Batteries, Electric Motors & Power Electronics

Consideration of the likely processing path for EV batteries that have reached the end of their vehicle life provides a vivid illustration of how the re-use of any component is dictated by the scarcity and costs of supply evaluated against its demand and substitutability. The consultants P3 North America (2012) provide a concise account as to why redeployment of EV batteries beyond their useful vehicle life will be preferred to materials recycling and/or disposal:

- Increased resale values for the battery will reduce EV ownership costs
- EV battery technology is long life, higher performance and more safe than non-automotive battery technology
- The cost of end-of-vehicle-life batteries will make them accessible to non-automotive applications
- A battery that has reached the end of its vehicle life retains useful life for non-automotive applications
- Critical raw materials such as lithium can be conserved and reused without processing/recycling

Despite these compelling reasons, P3 also point out that not all end-of-vehicle-life batteries will be repurposed to the secondary use battery market. Figure 25 below illustrates their projections for the secondary-use battery market, including an explanation of this 'transfer market inefficiency'.

Figure 25. A conceptual model for the secondary-use battery market for end-of-vehicle-life EV batteries (P3 2012).

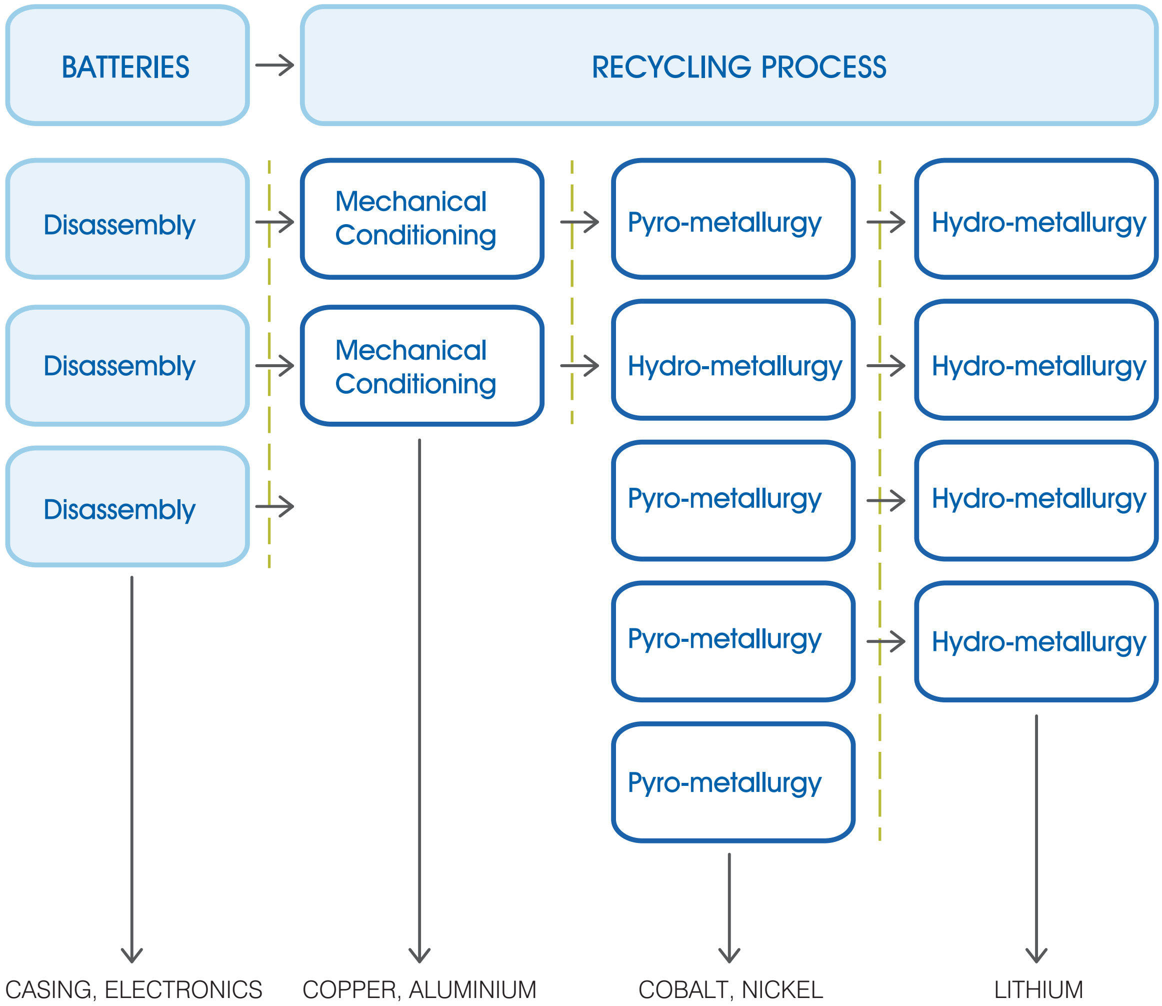


Upon reaching the end of their useful life for all applications, Hoyer et al (2011) propose a possible way forward for the design of a lithium-ion battery recycling network. An efficient recycling process operates in Germany where legislation prohibits the incineration of EV batteries or their disposal into landfill. Lithium-ion batteries are recycled there at an efficiency of 50 per cent.

Better Place Australia (2011) finds that lithium-ion batteries are over 95 per cent recyclable. It is possible to recover individual metals from end-of-life batteries using various mineral processing techniques; however it is not common commercial practice. Bertuol, Bernardes and Tenório (2009) show that some processes can recover 98 per cent by weight of Rare Earth metals. In the future it may be possible to recover groups of metals (Scott 2009): an LCA would need to factor in the most up-to-date processes in this area.

Figure 26 below provides a snapshot of current battery recycling processes, including lithium-ion. It shows that a variety of battery recycling processes, including mechanical conditioning, pyrometallurgy and hydrometallurgy, can be used to recover major components of lithium-ion batteries, including the casing and electronics, copper, aluminium, cobalt, nickel and lithium.

Figure 26. Battery recycling processes and recovery of materials (Hoyer et al 2011)



Lessons drawn from the experience of hybrid vehicle batteries support the approach proposed for recycling of lithium-ion batteries. Ahead of the Victorian market launch for the Prius hybrid vehicle in 2001, Toyota had established a recycling process for the nickel-metal hydride batteries (Toyota 2008). Toyota and Lexus dealers act as collection points for the batteries, which are then transferred to recycling facilities in Australia and overseas that maintain environmental management systems in compliance with the international standard ISO14001. The battery's plastic, metal and copper wire are recycled locally, where circuit boards and battery elements are exported for recycling. The hybrid battery recycling process reuses in excess of 98 per cent of materials contained in the recovered battery.

As was outlined in section 4.2, electric motors and associated electronics contain quantities of Rare Earth metals. These materials are highly valuable and therefore very likely to be recycled for other uses. Notably, a recent announcement was made in Japan by the Ministry of Economy, Trade and Industry who are teaming up with Toyota amongst others to develop technology for recovering and recycling Rare Earth metals (EV Update 2012). The partnership may allow Japan to reduce its Rare Earth metal imports by at least 10 per cent by 2025, noting that over 80 per cent of Rare Earth metals used in Japan are imported from a single source, China.

Patterson et al (2012) suggest that the embodied emissions arising from EV production are around 77 per cent higher than for a comparable ICEV – refer to Figure 8. Embodied emissions are a reasonable indicator for energy inputs, and so with reference to section 3.2 the choice of LCA method for assessment of the recycling impacts may be largely academic. However as improvements in battery technology reduce the difference in embodied emissions between EVs and ICEVs (section 4.2), the choice of LCA method for assessment of the recycling impacts may become significant.

Little information is available regarding environmental impacts that may arise from the recycling processes above.

7. Inventory of Environmental Costs & Benefits of EVs

Drawing upon the systematic analysis of the vehicle lifecycles above, an inventory of impacts for each environmental regime can be derived for a comparative assessment of EVs relative to ICEVs in the Victorian context.

An early observation that is applicable to all environmental regimes relates to the transfer of impacts between locations. For energy and/or material production processes that exist in locations with relatively lenient environmental management frameworks, there is clearly a higher risk in terms of consequence (World Bank 2010). An LCA may highlight potential risks in terms of outputs (emissions or waste products), however it will not identify actual impacts as it does not consider context or outcome.

The implications of this finding can be seen in the following areas:

Vehicle production – due to the highly diversified global supply-chains for vehicle production, which includes the harmful outputs arising from component production processes for the EV battery and Rare Earth materials in both the ICEV exhaust and the EV electric motor

ICEV energy production – due to the extraction processes associated with oil

Quantifying these impacts arising from these outputs is extremely challenging due to the variability of the associated supply chains in context, nature and over time, along with the proprietary character of the key information. As a result, this risk transfer issue can be highlighted in prospect only.

Another pertinent finding relates to the overwhelming influence of battery technology on the environmental impacts of EVs. The challenge in arriving at firm conclusions on the environmental impacts of EVs are apparent with this dependence is considered alongside the uncertainty within the limited amount of publicly-available information about EV battery technology, and the rapid change unfolding in battery design and production processes, including the global supply-chain pathways.

As a result, findings arising from this assessment must be considered in this context.

7.1. Greenhouse Gas Emissions

The two most pertinent evaluations of greenhouse gas emission impacts are:

i. Total lifecycle emissions comparison, denoting the cumulative emissions arising from vehicle production, operation and reprocessing/disposal; and

ii. Breakeven date for full fuel cycle emissions, denoting the point at which emissions arising from an EV using Victorian grid-sourced energy equates to that from a comparable ICEV.

The total lifecycle emissions evaluation should account for:

- Embodied emissions arising from vehicle and replacement part production, primarily the battery
- Changes in both the energy mix and vehicle distance travelled over time
- Consideration of renewable energy use impacts
- Consideration of drive cycle impacts

Table 12. Comparison of the cumulative greenhouse gas emissions over the Victorian average 20-year vehicle lifetime for an ICEV (Mazda 3 SP20) and EV (Nissan LEAF) using Victoria's forecast grid-sourced electricity mix and renewable energy. The EV calculation includes an allowance for a single battery replacement at eight years in service (Patterson et al 2012, DIT 2011 and 2012, DOT 2011, personal communications).

Year	Distance travelled (km)	ICEV			EV						
					EV / Vic grid energy					EV / renewable energy	
		Fuel lifecycle emissions (gCO2e/km)	GHG emissions (tCO2e/yr)	Cumulative GHG emissions (tCO2e)	EV energy economy (Wh/km)	Vic electricity emissions factor (tCO2e/MWh)	EV emissions using grid energy (tCO2e/yr)	EV cumulative emissions using grid energy (tCO2e)	Difference between cumulative figures – ICEV / EV using grid energy (tCO2e)	EV cumulative emissions using renewable energy (tCO2e)	Difference between cumulative figures – ICEV / EV using renewable energy (tCO2e)
Embodied emissions	-	-	-	8.70	-	-	-	15.40	6.70	15.40	6.70
2012	23,200	154	3.57	12.27	173	1.31	5.24	20.64	8.37	15.40	3.13
2013	21,800	154	3.36	15.63	173	1.29	4.85	25.49	9.86	15.40	-0.23
2014	20,400	154	3.14	18.77	173	1.25	4.41	29.90	11.13	15.40	-3.37
2015	19,100	154	2.94	21.71	173	1.22	4.04	33.94	12.22	15.40	-6.31
2016	17,900	154	2.76	24.47	173	1.19	3.68	37.62	13.15	15.40	-9.07
2017	16,800	154	2.59	27.06	173	1.12	3.27	40.89	13.83	15.40	-11.66
2018	15,700	154	2.42	29.47	173	1.07	2.90	43.78	14.31	15.40	-14.07
2019	14,700	154	2.26	31.74	173	0.99	2.52	46.31	14.57	15.40	-16.34
2020	13,800	154	2.13	33.86	173	0.94	2.24	55.25	21.39	22.10	-11.76
2021	12,900	154	1.99	35.85	173	0.93	2.08	57.33	21.48	22.10	-13.75
2022	12,100	154	1.86	37.71	173	0.91	1.90	59.23	21.52	22.10	-15.61
2023	11,300	154	1.74	39.45	173	0.90	1.76	61.00	21.54	22.10	-17.35
2024	10,600	154	1.63	41.09	173	0.89	1.63	62.62	21.54	22.10	-18.99
2025	9,900	154	1.52	42.61	173	0.86	1.48	64.10	21.49	22.10	-20.51
2026	9,300	154	1.43	44.04	173	0.85	1.36	65.46	21.42	22.10	-21.94
2027	8,700	154	1.34	45.38	173	0.83	1.25	66.71	21.33	22.10	-23.28
2028	8,200	154	1.26	46.65	173	0.81	1.15	67.87	21.22	22.10	-24.55
2029	7,700	154	1.19	47.83	173	0.79	1.06	68.92	21.09	22.10	-25.73
2030	7,200	154	1.11	48.94	173	0.78	0.97	69.89	20.95	22.10	-26.84
2031	6,700	154	1.03	49.97	173	0.76	0.88	70.77	20.80	22.10	-27.87
2032	6,300	154	0.97	50.94	173	0.74	0.81	71.58	20.64	22.10	-28.84
TOTAL	**274,300**	**-**	**42.24**	**50.94**	**-**	**-**	**49.48**	**71.58**	**20.64**	**22.10**	**-28.84**

Table 12 above and Figure 27 below provide a comparison of cumulative greenhouse gas emissions over the expected 20 year vehicle lifetime. The results clearly illustrate the necessity for EV operation in Victoria to utilize renewable energy to deliver a net benefit in terms of greenhouse gas emissions reduction. In that instance the expected lifetime greenhouse gas emissions benefit relative to a comparable ICEV is nearly 29 tCO2e, which is four times the initial embodied emissions penalty arising from the vehicle production (that is, the 'EV penalty' associated with predominantly the battery). This initial penalty (which has been accounted for as part of the assessment) is paid back in the second year of operation.

Uncertainty in relation to the battery replacement schedule is placed into some context by the overwhelming influence of the vehicle operation phase. If the difference in embodied emissions of 6.7 tCO2e calculated by Patterson et al (2012) is used as a conservative estimate of the penalty associated with a battery replacement, a renewable energy powered EV may have six batteries replaced during its operating life before it loses its overall lifecycle greenhouse gas emissions advantage to a comparable petrol vehicle.

The significance of the vehicle operation phase on the total lifecycle greenhouse gas emissions for either vehicle technology highlights the importance of vehicle energy conversion efficiency, the emissions intensity arising from energy production, and the duty cycle of the vehicle.

With regards the duty cycle, this finding highlights the importance of vehicle technology selection so as to be 'fit-for-purpose'. Based upon the limited information available, the energy conversion efficiency advantage of EVs grows significantly as traffic conditions become more congested. This would translate to an even greater benefit in terms of avoided environmental impacts for an EV using renewable energy over a comparable ICEV, and highlights the importance of appropriate technology selection for the task in terms of optimizing efficiency.

The breakeven date for full fuel cycle emissions should include consideration of:

- Changes in the energy mix over time
- Improvements in vehicle energy conversion efficiency over time

Figure 27. Cumulative greenhouse gas emissions calculated over an average Victorian vehicle lifetime for an ICEV and a comparable EV operating on both the Victorian electricity grid mix and renewable energy. The step change in both EV calculations reflects impacts arising from the single battery replacement forecast. (Patterson et al 2012, DIT 2011 and 2012, DOT 2011, personal communications).

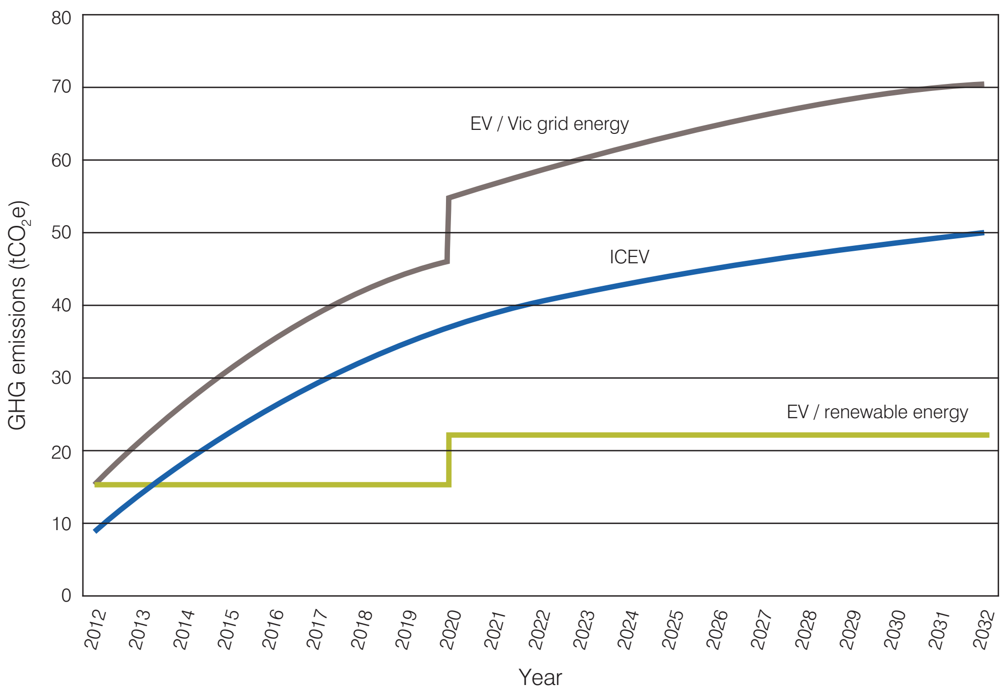
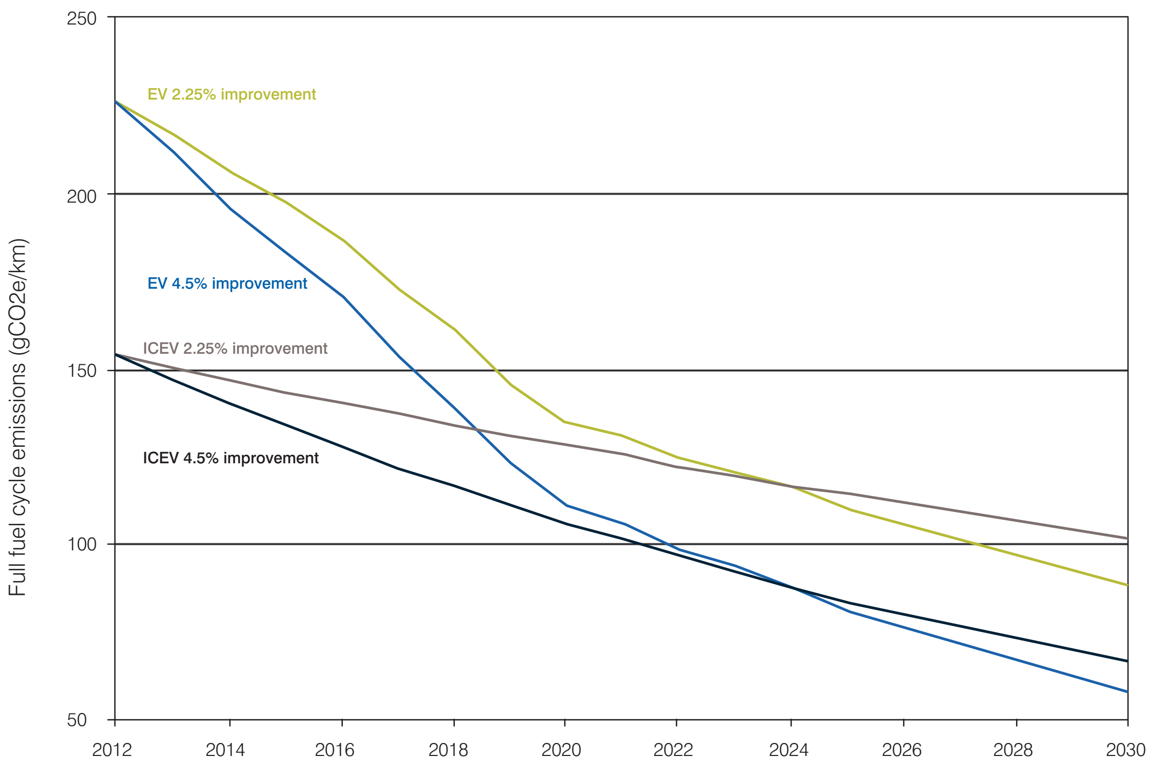


Figure 28 below provides an illustration of the interdependency of energy economy and fuel emissions intensity. Based upon forecast improvements in Victoria's electricity grid emissions intensity, the expected breakeven date for the full fuel cycle emissions from both vehicle technologies is around 2024 if the energy conversion efficiency of both technologies improves at a similar rate. This date shifts significantly if one or other technology improves at a faster rate. If the energy conversion efficiency of EVs improves at double the rate of ICEVs, this would bring the breakeven point forward to 2018. Conversely, if ICEVs improve at double the rate of EVs, the breakeven date would be some way after 2030 (the limit of this analysis).

Noting the increasing energy economy advantage of EVs with increased urban driving, this estimate is likely to be conservative if the most probable uses for EVs are taken into account.

Figure 28. Forecast full fuel cycle emissions comparison for EVs versus ICEVs based upon Victoria's expected electricity grid mix. The energy economy of both vehicle technologies has been estimated to improve at 2.25 per cent per year and 4.5 per cent for sensitivity testing (DIT 2011 and 2012, personal communications).



Other observations of note as relate to greenhouse gas emissions from EV operation:

- Based upon the Victorian grid mix characteristics, 'demand' charging during peak periods of electricity use is likely to be of lower greenhouse gas emissions intensity than 'smart' charging during off-peak periods
- Charging an EV using grid-connected on-site renewable energy generation, such as a home solar system, is complicated and requires careful accounting and reconciliation of energy production and use to provide a robust renewable energy charging strategy
- Noting the challenges in linking on-site generation of renewable energy with EV charging, ensuring EV charging utilizes renewable energy is best achieved through the GreenPower or Renewable Energy Certificate purchases (even for those with on-site renewable energy)
- Publicly-accessible EV charging outlets should be clearly identified as renewable or non-renewable to ensure drivers are able to both choose and verify the electricity source should they be committed to running their vehicle on renewable energy. Alternatively, charging network service providers should provide a clear, independently-verified statement of commitment relating to renewable energy supply arrangements across their network.Charging network service providers who can provide a clear, independently-verified renewable energy supply commitment may be the simplest, most flexible path to 'zero emissions' EV driving.

7.2. Air Quality Impacts

Air pollutant emissions differ from greenhouse gas emissions in two key ways, neither of which is captured by lifecycle analysis:

i. The impacts arising from air pollutant emissions are highly contextual due to their link to population exposure (that is, local not global), and

ii. Air pollutants are subject to environmental controls that take this contextual issue into account.

As a result, consideration of the air quality impacts arising from EVs as compared to ICEVs should include the following:

- Emissions arising from vehicle production, primarily as an environmental impact transferred outside of Victoria
- Emissions arising from energy production, which are most likely to have impact in specific regions of Victoria
- Emissions arising from vehicle operation, which will have impacts wherever cars and people coexist (that is, everywhere)

EVs have been found to be responsible for more air pollutant emissions arising from vehicle production processes than ICEVs by Hawkins et al (2012). Their assessment identifies the battery as being the main source of these emissions, even if it also notes high variability in the findings from other studies and large uncertainty in the source data. Noting that batteries are expected to be produced outside of Victoria for the foreseeable future, this is an example of the transfers that LCA is good at identifying.

Air quality impacts arising from energy production are most likely going to be felt and managed in Victoria, even if a significant volume of Victoria's petrol is produced elsewhere. With reference to Table 6 and Table 10, significant volumes of air pollutants are emitted from both the Shell refinery (Victoria's largest petrol supplier) and Loy Yang A (Victoria's largest electricity generator). As the air pollutants emitted differ for each energy type, direct comparison in terms of environmental impacts is complicated. It is noteworthy however that both production facilities sit within Victoria's regulatory framework (refer to Table 5), and are therefore being managed to the same community standards. By way of example, each facility requires an EPA licence under the Victorian *Environment Protection (Scheduled Premises & Exemptions) Regulations* 2007. This licence sets operating conditions for the site, including air pollutant emissions and waste discharge limits.

The clear advantage of EVs in terms of tailpipe emissions is reduced by their slow rate of market uptake likely coinciding with the continuing tightening of vehicle emissions standards. Preliminary modeling by EPA Victoria (2012c) indicates that the latter will deliver the most significant benefits in terms of Melbourne's air quality by 2030. The final output from the EPA *Future Air in Victoria* project will provide more insights into this situation including the potential benefits from increased EV uptake.

Air pollutant impacts arising from vehicle disposal/reprocessing for both technologies are unclear. The disposal of fluids and oil filters from ICEVs is regulated in Victoria as is air-conditioning gases for either vehicle. As the bulk of the disposal/reprocessing will most likely occur within facilities that are governed by Victoria's environmental management framework, the risk to air quality is not thought to be significant.

7.3. Water & Land Impacts

Environmental impacts to water and land resources arise from each of vehicle production, operation and disposal/reprocessing.

As was outlined in section 7.2 above in relation to air quality impacts arising from vehicle production, Hawkins et al (2012) have identified the EV battery is the main point of difference between EVs and ICEVs in terms of impacts on waters and land. As was also described above, this is an example of transferred impacts due to the production of batteries taking place outside of Victoria.

Although there are a wide range of water and land resource impacts arising from vehicle operation, these are not generally technology-specific. The point of difference between EVs and ICEVs arises from the energy production, where the similarity to the discussion on air quality impacts above holds once more. Industrial facilities operating under Victoria's regulatory framework will be managed to similar standards in terms of impacts upon the environment and human health.

Based upon the assessment in section 6 of vehicle reprocessing and disposal impacts, there are two issues which may have implications for water and land resources:

iii. ICEV fluids not being properly removed/disposed of within the vehicle scrappage process, and

iv. EV battery recycling impacts, which will be likely transferred elsewhere.

Both of these issues are expected to be minor in comparison with battery and energy production.

7.4. Human Health & Amenity

Human health and amenity impacts relate to:

- Climate change
- Air quality
- Water and land
- Noise and electromagnetic fields

The first three of these have been discussed above, even if the direct relationship to human health and amenity is implied rather than explicit.

Noise impacts may be both positive and negative. Reductions in traffic noise will enhance the quality of life for most Victorians, however some road users rely on vehicle noise to help them get around. Given that Victoria is an EV 'technology taker' for the foreseeable future, global efforts to address this risk without losing the potential benefit are likely to yield a net benefit overall.

Studies into electromagnetic fields have failed to discern any appreciable difference between EVs and ICEVs, suggesting that there is negligible risk to human health.

8. Conclusions & Areas for Future Work

EV technology is gaining momentum internationally as a transport alternative with potential for lower impacts on the environment. This study has sought to undertake a preliminary assessment of the environmental impacts of EVs in the Victorian context using accepted methods and a wide-ranging literature survey.

Key findings from the study are as follows:

- Victorian EVs must be run on renewable energy to provide a total lifecycle greenhouse gas emissions benefit relative to ICEVs
- If run on renewable energy, EVs will pay back the embodied greenhouse gas emissions penalty primarily associated with the battery production in the second year of operation, and are expected to provide around 29 tCO2e, or around 50 per cent, saving over the vehicle lifetime even with a replacement battery
- The breakeven point in terms of full fuel cycle emissions from EVs and ICEVs in Victoria is expected to arrive around 2024, however this figure is highly sensitive to the relative improvements in both vehicle technologies
- EVs will deliver even greater benefits if selected preferentially for city-driving, however more information is required to guide vehicle selection both in relation to profiling the service duty and matching it to the vehicle technology
- Based upon the Victorian grid mix characteristics, 'demand' charging during peak periods of electricity use is likely to be of lower greenhouse gas emissions intensity than 'smart' charging during off-peak periods
- Renewable energy charging strategies that depend upon on-site energy generation are complicated by the likely mismatch between energy production and use, and by the electricity market arrangements that relate to grid-connected systems
- GreenPower or Renewable Energy Certificate purchases are the simplest, most effective path for renewable energy EV charging strategies
- Publicly-accessible EV charging outlets require transparency and assurances to support renewable energy EV charging strategies
- Charging network service providers who can provide a clear, independently-verified renewable energy supply commitment may be the simplest, most flexible path to 'zero emissions' EV driving
- While EVs will provide an air quality benefit to the state that will mean improved health for Victorians, the continued tightening of vehicle emissions standards will deliver a greater benefit in the near-term
- EV uptake in Victoria creates a significant risk of environmental impacts from battery production being transferred elsewhere, however it reduces the existing risk in relation to oil extraction processes
- Within the existing Victorian vehicle reprocessing and disposal supply-chains, the environmental impacts of end-of-life EVs are likely to be minimal
- EV-related human health and amenity impacts are negligible due to electromagnetic fields, manageable as relate to their near-silent operation at low speeds, and beneficial as relates to traffic noise

9. Acronyms and Units of Measure

A – ampere (electrical current)

BEV – Battery Electric Vehicles

EIA – Environmental Impact Assessment

EPD – Environmental Product Declaration, as in International EPD system

EREP – Environment & Resource Efficiency Plan

EV – Electric Vehicle

gCO2e – grams of carbon dioxide equivalent (a volume of greenhouse gases)

GHG – Greenhouse Gas

HEV – Hybrid Electric Vehicle

ICE – Internal Combustion Engine

ICEV – Internal Combustion Engine Vehicle

km – kilometre

kwh– kilowatt hours (a unit of measure of electrical energy)

LCA – Life Cycle Assessment

LGC – Large Generation Certificates

OPEC – Organisation of the Petroleum Exporting Countries

PEM – Power Electronics Module

PEV – Plug-in Electric Vehicle

PHEV – Plug-in Hybrid Electric Vehicle

PV – Photovoltaic

PM2.5 – Particulate Matter of 2.5 microns or less in diameter, sometimes known as 'fine particles' (an air pollutant)

MMBTu – Million Metric British Thermal units (a measure of energy)

MWh – Megawatt hours (a unit of measure for electrical energy)

N_2O – Nitrogen dioxide (an air pollutant)

NO_x – Oxides of Nitrogen (an air pollutant)

SO_x – Sulfur oxides

SO_2 – Sulfur dioxide

STC – Small-scale Technology Certificates

tCO2e – tonnes of carbon dioxide equivalent (a volume of greenhouse gases)

V – volt (electrical potential)

VOCs – Volatile Organic Compounds (an air pollutant)

Wh/km – Watt hours per kilometre (a measure of EV energy economy)

10. Glossary

Ancillary services – the additional electricity supply maintained by the network operator to allow for sudden increases in electricity demand or generator outages

Advanced Metering Infrastructure – or *Smart meters*, a type of a high technology electrical meter that identifies consumption in more detail than a conventional meter and communicates that information by way of a network back to the local utility for monitoring and billing purposes

Balance of Payments – a system of recording all of a country's economic transactions with the rest of the world over a period of one year

Baseload – or *baseload demand*, is the minimum amount of power that a utility or distribution company must make available to its customers, or the amount of power required to meet minimum demands based on reasonable expectations of customer requirements

Charge state – the amount of electrical energy stored in a battery as a reflection of its total storage capacity

Charging event – the activity of supplying electrical energy to an EV from an external source, for example via a plug/cable

Charging infrastructure – the dedicated equipment used for delivering electrical energy to EVs via *Charging events*

Coal-generated electricity – electricity generated from burning coal

Cradle-to-grave – a total product lifecycle assessment

Demand charging – or *Convenience charging*, are *Charging events* that commence as soon as a vehicle is plugged in (as opposed to a later time based upon other considerations)

Duty cycle – the way in which vehicles are driven, taking driver inputs, traffic conditions, vehicle payload in terms of passengers and cargo etc

Economy of scale – savings in the per unit costs of production that are gained through production of larger quantities, for example via amortization of the production facility overheads across larger volumes

EV charging network – the network of *Charging infrastructure*

Grid – a network of cables designed to connect power stations with their customers in offices, homes, schools and factories

Induction motors – or asynchronous motor, is a type of alternating current electric motor where power is supplied to the rotor by means of electromagnetic induction

International EPD System – or International Environmental Product Declaration System, is an internationally-recognised information-sharing system for quantified environmental product data according to the requirements of the international ISO 14025 standard

Lead-acid battery – an electricity storage device based upon a lead (Pb) and sulphuric acid (H2SO4) electrochemical cell

Lithium-ion battery – an electricity storage device based upon the family of lithium (Li) electrochemical cells

Nickel-metal hydride battery – an electricity storage device based upon the nickel (Ni) and metal-hydride (MH) electrochemical cell

Offsets – or *Carbon offsets*, are a mechanism by which reductions or removals of greenhouse gases from the atmosphere are made relative to a 'business-as-usual' baseline

On-street charging – *Charging events* which take place using *Charging Infrastructure* located on public lands ('on-street')

Open loop recycling – a classification of recycling under Life Cycle Assessment (refer below), whereby the raw material for/from a product both draws on and supplies recycled material from/to other products, for example an aluminium can

Peak / off-peak – periods of greater or lesser demand for something; in the context of this paper, the term will relate to electricity demand

Permanent magnet motors – a type of direct current electric motor that uses permanent magnets

Primary use / secondary use battery market – terms to distinguish the two markets for electrical storage batteries (new and used)

Quick chargers – a high current/voltage *Charging infrastructure* device that reduces the amount of time needed to charge an EV

Range – the distance a vehicle can travel based upon the amount of energy stored and the energy conversion efficiency of the vehicle technology

Rare Earth metals – or *Rare Earth elements*, are a collection of seventeen chemical elements in the periodic table, namely scandium (Sc), yttrium (Y), and the fifteen lanthanides (Ln), that are key materials for automotive catalytic converters and a range of electrical equipment

Regenerative braking – a method of braking whereby the kinetic energy that is normally lost as heat during stopping is instead gathered and stored for re-use

Renewable energy – energy generated from renewable sources such as the sun and wind

Smart charging – sometimes known as *Off-peak charging*, are *Charging events* that are scheduled to take place during periods of low electricity demand

Standard charging – *Charging events* that are based upon the standard domestic electrical supply (240 v in Australia)

Supply chain – a system of organizations, people, technology, activities, information and resources involved in moving a product or service from supplier to customer

Swap stations – a proprietary *Charging infrastructure* technology where depleted EV batteries are swapped out of the vehicle for fully-charged equivalents in automated facilities

Switched reluctance motors – or synchronous motor, an electric motor with wound field coils as in a permanent magnet motor, but without magnets or coils attached to the rotor

System boundary – the scope of an Environmental Impact Assessment as defined by the physical, temporal, spatial etc limits for the assessment

Tailpipe emissions – a term to describe the measured quantities of air pollutants emitted from a motor vehicle exhaust

Tank-to-wheel – a vehicle lifecycle assessment term that relates to the *Upstream impacts*

Torque – the measure of rotational force that is the basis for vehicle acceleration

Traction battery – the propulsion energy electrical storage device in an EV (as opposed to the 12 v battery that is used to operate the ancillary systems such as lighting, security etc)

Upstream/downstream impacts – the outcomes from different aspects of a vehicle lifecycle that relate to the fuel energy cycle (upstream) and the vehicle energy conversion cycle (downstream)

Vehicle-to-grid/ vehicle-to-building/ vehicle-to-home – scenarios where an EV is used as an electrical storage device

Voltage – electrical potential

Well-to-tank – a vehicle lifecycle assessment term that relates to the *Downstream impacts*

Well-to-wheel – the total vehicle lifecycle assessment, also known as *Cradle-to-grave*

Wireless induction charging – a type of *Charging infrastructure* technology that utilises electromagnetic induction to transfer energy as opposed to conduction through a plug/cable arrangement

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