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Environmental Life Cycle Assessment of Alternative Fuels for Western Australia's Transport Sector

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Abstract: Alternative fuels for the transport sector are being emphasized due to energy security and environmental issues. Possible alternative fuel options need to be assessed to realize their potential to alleviate environmental burdens before policy formulations. Western Australia (WA) is dominated by private cars, accounting for around 72% vehicles with 87% of those using imported gasoline, and resulting in approximately 14% of greenhouse gas (GHG) emissions from the transport sector. There is an urgent need for WA to consider alternative transport fuels not only to reduce the environmental burden but also to avoid future energy security consequences. This study assesses the environmental life cycle assessment (ELCA) of transport fuel options suitable for WA. The study revealed that ethanol (E65), electric (EV) and plug-in electric vehicle (PHEV) options can decrease global warming potential (GWP) by 40%, 29% and 14%, respectively, when compared to gasoline. The EV and PHEV also performed better than gasoline in the fossil fuel depletion (FFD) and water consumption (WC) impact categories. Gasoline, however, demonstrated better environmental performance in all the impact categories compared to hydrogen and that was mainly due to the high electricity requirement during the production of hydrogen. The use of platinum in hydrogen fuel cells and carbon fibre in the hydrogen tank for hydrogen fuel cell vehicles (HFCV) and Li-ion battery for EVs are the most important sources of environmental impacts. The findings of the study would aid the energy planners and decision makers in carrying out a comparative environmental assessment of the locally-sourced alternative fuels for WA.

Keywords: alternative transport fuel; passenger vehicle; life cycle assessment; Western Australia; environmental performance

1. Introduction

Rising population coupled with intensive industrialization is increasing the demand for conventional fuels, which in turn results in the increase of exploitation of scarce natural resources and environmental degradation. As a consequence, increasing consumption of natural resources and intensifying environmental impacts are becoming more serious concerns globally [1]. Fossil fuels comprise around 80% of the global primary energy consumption, 58% of which is consumed by the transport sector alone [2]. According to the United States Environmental Protection Agency (US EPA), 95% of transportation energy originates from fossil fuel that causes 14% of total greenhouse gases (GHG) [3]. Due to the over-dependence of fossil fuels, there is an immediate need to look out for alternative transport fuel to achieve greater sustainability [4].

Traditionally, fossil fuels have dominated the Western Australian energy supply. The consumption of energy in WA is also growing at around 5% per annum [5]. During 2016–2017, 1179.5 PJ of energy was consumed in WA. Among the total energy consumption in WA, 97% is currently sourced from fossil fuels (coal, oil and natural gas) [6]. WA's transport sector alone consumed 251PJ of energy (19%) which is the second largest energy consumption sector after mining that consumes around 23% [7]. Almost 100% of WA's transport fuel originates from non-renewable fossil sources [8]. The state government is, however, committed to meet a significant portion of energy demand from renewable energy (RE) to achieve Australian's GHG emission reduction target of 26–28% by 2030. The only viable way to achieve this target is to explore various sources of alternative fuels for the transport sector [9].

WA is one of the private car dominated states in Australia, where public transport is not very popular due to disperse locations and distances between population centers [10]. Around 72% of vehicles in WA are passenger cars, and 87% of these vehicles use imported unleaded gasoline [11]. With petrol as the dominant transport fuel, around 14% of GHG emissions are emitted from the transport sector of WA [10]. Heavy reliance on imported fossil fuel can also challenge the state's energy scarcity issue, as the fluctuation of price and geopolitical conflicts impacting fossil fuel supply were observed over recent decades [12,13].

Considering the current situation of WA, it appears that the private passenger car dominant transport sector may suffer from energy security issues and associated environmental complications, such as global warming impact and urban air pollution. Therefore, there is an urgent need for WA to consider suitable alternatives to gasoline as the proportion of gasoline passenger vehicles is quite high (72%) in the state [11]. It is essential to assess the life cycle environmental impact of any alternative fuel as their use may produce less tailpipe emissions but could cause higher emissions during the production of these fuels [10,14]. A life cycle assessment (LCA) approach, which follows ISO 14040-44 and considers all stages of the product life cycle needs to be conducted to determine the environmental impacts of alternative fuels [15].

A comprehensive literature review by Hoque et al. [16] prior to this study in 2018 based on seventy seven (77) LCA articles of alternative fuels suggests that although LCA is a well-established method for environmental assessment, there is still a need for region specific analysis as the generalised results and recommendations for one region may not be replicated in other regions due to regional variations. For example, GHG emissions for a hybrid vehicle varied by more than 100% in different Canadian cities mainly due to the variation in electricity mix [17]. Sources of various feedstocks (or distance travelled) and their long-term availability to produce alternative fuels are crucial for the economic and environmental feasibility of alternative fuel for any region [15,18,19]. The selection of proper indicators is also deemed necessary for a particular region for assessing a reliable sustainability strategy [15,16,20,21]. Besides, most of the studies in the literature (more than 75%) only considered fuel production and/or the use phase of fuel [16]. Life cycle assessment of transport fuels, however, remain incomprehensive if associated changes in vehicles due to the use of alternative fuel is not considered within the system boundary [16].

In Western Australia, some environmental life cycle assessment (ELCA) studies [10,22] also have been conducted to assess hydrogen and electricity as an alternative to gasoline in 2013. The current study, however, investigates further by considering all the possible alternative fuel options based on the availability of feedstocks in WA. Secondly, any modifications and arrangements in terms of material and process changes to make vehicles suitable for alternative fuel use are also incorporated within the system boundary to precisely calculate the environmental performance of these fuels. Thirdly, identification and selection of indicators; and fuel selection based on resource availability and geographical conditions for WA are integrated with ELCA for greater sustainability. This study considers a streamlined environmental life cycle assessment of the selected fuel options; and compares the environmental impacts of alternative fuels. Both sensitivity and uncertainty analyses have been carried out to establish the applicability and validity of the results. The findings of the study would be beneficial for the policymakers in WA for formulating environmental protection policies and strategies.

2. Methodology

This study aims at the environmental life cycle assessment of alternative transport fuel options for Western Australia. The environmental performance of the selected fuels has been assessed and compared with conventional gasoline. The first step of the methodology is to select alternative fuels based on the locally available resources followed by indicator selection, environmental life cycle assessment and finally the interpretation of the results based on per vehicle kilometre travelled (VKT).

2.1. Fuel Selection

The transport fuels that are commonly considered as alternative fuels are ethanol, electricity, biogas and hydrogen [10,23,24]. Based on the availability of resources in WA, E65 (65% ethanol and 35% gasoline) from wheat, straw and Mallee wood; electricity for elective vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs); and hydrogen fuel (produced by water electrolysis) were considered in this study. The reasons for selecting these fuels are described as follows:

Ethanol: Three potential feedstocks, such as cereal residue (straw), wheat grain and Mallee biomass were identified in WA for ethanol productions based on their availability. Table 1 shows the availability of straw in WA. The estimation of the available straw for ethanol production takes into account the following considerations:

- Total non-grain biomass was 3.24 tonnes/ha [25] based on average grain production of 1.8 tonne/ha in WA [26].
- Around 1.5 tonnes/ha was retained on the grain field to prevent soil erosion and enrich soil organic content [25].
- The average maximum cutting height from soil is 20 cm that does not go further due to the unevenness of the grain field [25].
- Two locations (Albany and Three springs) were not considered due to the low resource availability of straw to fulfill the requirements for the plant [27].

Table 1. Estimation of straw for ethanol.

Potential Locations	Average Straw after 1.5 Tonne Retention (Tonne/per ha)	Land Area + (ha $\times 10^3$)	Available Straw on Grain Field (Value * 10^3 Tonne)
Geraldton	(3.24 * − 1.50) = 1.74	267	465
Three springs		85	148
Moora		425	740
Northam		337	586
Merredin		365	635
Lake Grace		304	528
Narrogin		200	348
Katanning		526	915
Esparance		541	941
Albany		67	116
Total		3112	5421

+ Based on the straw availability by Brooksbank et al. [27], * average non-grain biomass 3.24 tonne/ha [25].

The estimated amount of straw was 5157×10^3 tonnes, which could potentially generate ethanol to substitute 35% of gasoline [i.e., (5157/4.32)/ (2262 × 1.51)]. The ethanol blend that can be considered with this amount of ethanol is E53 [i.e., 35 × 1.51], where 2262 ML is the gasoline requirement for WA [28]; and 1.51 is the factor considered for the lower caloric value of ethanol [29]. The estimation also considered 4.32 kg of straw (25% moisture content) for 1 L of ethanol [30].

Wheat: Around 95% of the wheat grain produced in WA (10 million tonnes) is mainly exported to Asia [26]. The allotment of the remaining 5% of wheat for ethanol production could potentially affect the local requirement. Around 0.578 Million tonne (Mt) of wheat has been estimated to produce about 228 ML ethanol (approximately 400 litre ethanol/tonne) to generate E10 (i.e., 0.578 × 400/2262) without affecting the food supply. This 228 ML has been estimated to be 6.6% (i.e., 10/1.51) of gasoline. This small amount of wheat for ethanol may not affect the food supply chain as only the starch part of wheat is required for ethanol production and the remaining amount (around 80%) goes back to the food cycle as wet distiller grains [31].

Mallee: There is also a huge potential to grow Mallee in between the narrow long belt of agricultural fields in WA without affecting the current farming practices. Apart from its use as a biofuel, there are several co-benefits as it reduces dryland salinity and waterlogging; prevents soil erosion; and protects biodiversity [25,32]. Mallee trees could provide WA's national fuel security and increase the benefit to the farmers [25]. Around 10% of the area of the WA wheat belt (around 830,000 ha) can supply 10 million gmt (green metric tonne) of woody biomass [33]. It has been estimated that the current available resources of Mallee (around 258 Mt) [34] are enough to generate 1.42% (5.27 kg/L of ethanol) of gasoline replacement in WA. This available resource could produce an ethanol blend equivalent to E2.15 (1.42 × 1.51).

For this study, an ethanol-gasoline blend E65, which consisted of 9.90% wheat based, 2.15% Mallee based and 52.95% straw-based ethanol, was considered.

Electricity: Renewable energy accounts for around 7.5% of WA's total electricity mix (Table 2), and is expected to increase to 37% by 2030 [35]. There is only 28% coal-based electricity in the state. Research suggests that EVs can be powered by the surplus amount of electricity during the off-peak period that can also improve the state's power system management [36]. Currently, the surplus electricity can accommodate around 200,000 EVs (around 10% of the total vehicles in WA) [36]. Looking at its feasibility, the UK and France have already announced bans on gasoline and, promoted electric cars to achieve zero carbon mobility and to reduce health problems [37–39]. Electric and plug-in hybrid vehicles were considered in this study due to their increasing use.

Table 2. Electricity generation mix in Western Australia.

Feedstocks	In GWh [7]	In %	GHG Emission (Low Voltage) [40]
Natural gas	20146	53%	
Coal	10523	28%	
Oil products	4223	11%	
Biogas	126.9	0.34%	0.8753 $kgCO_2/kWh$
Wind	1643.2	4%	
Hydro	206.1	1%	
Solar PV	683.3	2%	
Total	37552	100%	

Hydrogen: Several studies have confirmed that there is a huge potential to produce hydrogen in WA by using RE resources, such as wind and solar [41]. Hydrogen can be refuelled very quickly and it has a high fuel efficiency (i.e., 1 kg hydrogen provides range equivalent 6 to 8 liters of gasoline) [41]. Hydrogen can be produced in WA by an electrolysis process using off-peak electricity [42]. The production of 1 kg hydrogen through electrolysis consumes 9 kg of water [41]. It is thus estimated that only 282.8 million kg of water will be required (i.e., 0.22% of all water requirement of WA) to produce hydrogen to replace all the gasoline consumption in WA.

Biogas: WA has plenty of resources, such as animal manure, municipal waste and sewage sludge to generate biogas. Since these feedstocks are dispersely located in WA, long distance transport would be required to bring these feedstocks to chemical plants for biogas production [27,43]. It is thus considered that the biogas could rather be produced in situ to generate green electricity in WA [27] to power electric vehicles locally.

2.2. Indicator Selection

Indicators need to be selected for a particular region [15,16,21,44]. For this current study, initially, five indicators such as global warming potential (GWP), fossil fuel depletion (FFD), eutrophication, water consumption (WC) and land use were selected by reviewing the local and international literature. An expert survey was then conducted to determine the relevance of the preselected indicators for the Western Australian transport sector [20,21]. The respondents have been classified under academia, government and industry categories. Questionnaires were sent out to experts to conduct the survey after obtaining the necessary ethics approval from Curtin University, Australia. Indicators that were considered important by more than 50% of the experts (i.e., where the total number of survey respondents are 30) were selected for the study. Four indicators namely GWP, FFD, WC and land use were then selected based on the expert opinion. Eutrophication was considered less important for this study by 57% of respondents. Eutrophication may occur in the terrestrial and aquatic environment but later can cause problems in Australia due to the nutrient runoff from the agriculture and conversion stages of alternative fuels. Respondents commented that alternative fuels in WA could be produced in a confined space and feedstocks for the current study might also produce quite a minimal effect on freshwater.

The new indicators proposed by the experts were also investigated to justify their relevance in this current study. The reasons for inclusion and exclusion of selected and proposed indicators by experts are described in Table 3. Some of the proposed indicators were not included as they were either non-existent or weak for the Western Australian alternative fuel assessment. For example, the human toxicity indicator was not considered for this study in WA due to its low population density (1 people/km^2), geographical specificity (such as the location of WA cities near the sea), and wind speed. Because of this, in Australian cities, the possibility of human exposure to toxic substances was 160 times lower than for Western Europe [45]. Human exposure factors related to toxicity was also 20 times lower in Australia than in Western Europe due to these aforementioned reasons [45]. Besides, biodiversity was suggested but it was ignored because the alternative fuel options for the current study and their feedstocks (such as straw and Mallee and a small portion of wheat for ethanol) are based on existing land and agricultural practices which were not developed through new land/forest clearing [45]. Some of the suggested environmental indicators were already considered as social indicators (such as vehicle exhaust emissions as a measure of human health and direct displacement of food for feedstocks), while some were actually not indicators (such as comparison with fossil fuel and suggestions regarding the consideration of vehicle use phase).

Table 3. Justifications for included/excluded indicators.

Indicators	Justifications
GWP	*Eighty-seven percent (87%) of the respondents considered global warming potential (GWP) as an important indicator for the current study in WA during the survey process.* Different life cycle phases of alternative fuels such as feedstock production, conversion from feedstocks to fuel and transportation are GHG emission-intensive [16]. Around 14% of GHG emission is from the transport sectors of WA [10]. The government of WA is committed to reducing the significant portion of GHG emission from transport sectors through alternative fuels by the year 2031 [9].
FFD	*Sixty-seven percent (67%) of the respondents considered fossil fuel depletion (FFD) as an important indicator.* Almost all the life cycle stages of alternative fuels consume fossil fuel (such as chemicals and fertilizers during the agricultural production of feedstock; transportation of feedstocks; and energy requirements during the conversion stage) [16]. The transport sector alone consumed 251 PJ of energy (19%) which is the 2nd most energy consumable sector in WA [46].
WC *	*Sixty-three percent (63%) of the respondents considered water consumption (WC) as an important indicator.* Agriculture production of feedstock and conversion of alternative fuels requires water as a raw material. Electricity and other fossil fuel requirements in the different stages also have their own water use impacts [47]. Almost all of WA (around 85%) falls under the semiarid or arid climate by nature [48]. Estimations suggest that there could be a possible water crisis in the near future in WA as the water supply is reducing over time from both ground and surface water sources [49–51].
Land use	*Fifty-three percent (53%) of the respondents considered it as an important indicator.* When any feedstock for alternative fuel derived from agriculture may produce higher land use impact than the fossil fuel [52]. Though the WA state has a huge land area (around 2.5 million km^2), additional stress on land for biofuel can produce an impact on food production [53].

Table 3. *Cont.*

Indicators	Justifications
Eutrophication	*Eutrophication was selected initially through review but 57% of the respondents considered it as a less important indicator for the current study.* Eutrophication was identified by the experts as a less important indicator for WA conditions mainly for two reasons. On the production side, as eutrophication results from the direct discharge of effluent to water, it may not be an issue since the alternative fuels are produced in confined spaces and the energy plant wastes are landfilled. Secondly, the alternative fuels are assumed in this study to be sourced from existing agricultural by-products (wheat straw in this study) or, in the case of Mallee, may potentially reduce the nutrient runoff [25].
Human toxicity	*Two respondents from academic and industry categories emphasized the importance of 'human toxicity' due to its importance on human health.* The toxicity indicators are found to be either weak or nonexistent in Australian biofuel and bioenergy projects though upstream agriculture production of feedstock may release a small amount of toxic pesticides but other stages of fuel production are not directly related to emissions (heavy metals, pesticides, hormones, and organic chemical) which cause toxicity [53,54]. It has been found that due to the low population density (one people/km^2 in WA) and geographical specificity (most of the Australian cities are near the sea), toxicity substances emitted to the soil in Australia has 160 times lower possibility for human exposure than Western Europe [45]. The human exposure factor was also found to be 20 times lower for toxic substances emitted to the air and water [45].
Biodiversity	*Two respondents from academic and industry categories had suggested 'biodiversity' as land clearing due to the agriculture production of biofuel can destroy the ecosystem and biodiversity.* Most of the lands in Australia were cleared more than 20 years ago and any new land clearing in the country is under strict policy from the Australian government regarding nature conservation and protected areas [33,52]. Biodiversity is considered important where activities from the life cycle of a fuel disturb the local animals and plant life [45]. Feedstocks for alternative fuel production for the present study such as straw (by-product from current agriculture) and Mallee (grown within the narrow belt of existing agricultural systems) and a small portion of wheat for ethanol (from existing agriculture); electricity for EV; and sea water for hydrogen have no direct relationship with the land/forest clearing which can affect biodiversity or ecosystems.
Vehicle exhaust emissions (as a measure of human health)	*Three respondents from the academic category proposed 'vehicle exhaust emission' as air quality is the important driver for the application of alternative fuel.* In WA, the contribution of atmospheric air pollution from vehicles was quite low compared to mining and industrial applications. However, direct exposure from low elevated vehicle exhaust emissions (such as CO, PM and NO_x) have the potential to cause significant human health problems [45]. Due to this reason, these emissions are considered as social sustainability indicators under the public health category for the current study and were not included here in the environmental life cycle assessment (ELCA) to avoid repetition. Besides, tailpipe CO_2 emissions are already included under the GWP impact.
PM formation	*Two respondents from academic and government categories shared their view regarding 'PM formation' due to its potential damage for human health.* PM emission all over Australia is not the general problem due to the location of its main cities near the sea, its wind speed, flat terrain, mild industrialization and lower population densities [45]. The country is also ranked 2^{nd} in the world according to the air quality index [55]. However, PM as a measure of human health is considered a social indicator under the current project due to the aforementioned reasons in the vehicle exhaust emission indicator.
Comparison with traditional fuel	*Two respondents from industry and government categories advised to include this comparison as singling out alternative fuels for a life cycle assessment without ensuring traditional fuels are being subject to the same life cycle assessment is not reasonable and would work against alternative fuel uptake.* By following the strategy, gasoline as the baseline fuel was compared with alternative fuel options, as gasoline is the predominant fuel for WA transport sectors.
Direct displacement of food (due to feedstocks)	*One participant from the government category highlighted the importance of food displacement as biofuel feedstocks may disturb the food cycle.* As described in detail in the fuel selection (Section 2.1), feedstocks for the current study (such as straw and mallee and a small portion of wheat) may not disturb the food supply chain in WA. Especially, straw and mallee as they are sourced from the unused resources in WA which have no direct relation with food displacement. However, the potentiality of this indicator will be examined in future for the social sustainability part of the current study.

* Amount of water which is taken from the environment during the different activities of the product life cycle. Any rainfall during the agriculture of feedstock and water from the sea is not included.

2.3. Goal and Scope Definition

Life cycle assessment for this study follows the ISO 14040-44 [56,57] framework that starts with the goal and scope definition, followed by boundary selection, life cycle inventory analysis, life cycle impact assessment and interpretation of results. The main aim of the study is to evaluate the environmental performance of various alternative fuel options. This study compares the results with gasoline in order to determine the environmental benefits. The functional unit (FU) for this study is VKT (vehicle kilometre travelled) which allows for comparison between the alternative fuel options. The study considers the 'well to wheel' approach to incorporate all the stages of fuel life cycle from resources extraction to its use in the vehicle. Besides, additional vehicle materials (AVM) or arrangements required for vehicles using alternative fuels are included. The mass of the glider was assumed to be the same for vehicles using alternative fuels for fair comparisons [22,58–60]. The end of life stages were excluded in this study as the study focuses only on the fuel life cycle. The emissions during the maintenance activities associated with alternative fuel use were not considered as it generates a tiny fraction (around 1–2%) of emissions compared to the total life cycle of a fuel and vehicle [59,61].

2.4. Life Cycle Inventory Analysis

Life cycle inventory is the collection of data inputs required for each fuel for the assessment, which was calculated based on the functional unit (VKT) and/or per unit fuel (i.e., litre for ethanol).

2.4.1. Gasoline

A consistent reduction trend of 'crude oil' quantity reaching Australia was observed in recent years not only due to the closure of refineries in the country but also due to the reduction of refining in the existing refineries [52]. The crude oil is imported to Australia primarily from UAE (18%), Malaysia (26%) and Indonesia (10%) [52,62]. Besides, the Australian gasoline supply chain shows that it is imported in the refined form to Australia mainly from South Korea (around 45%), Singapore (around 34%) and Japan (around 3%) [62]. Most of these oil exporting countries source their crude oil from the Middle East. The exact locations of these countries [62] helped ascertain the transportation distance. The source of the distances used in this study is the online calculator provided by sea-distances.org (https://sea-distances.org/). The mileage of the vehicle during the usage stage for the alternative fuels was based on the latest survey by the Australian Bureau of Statistics, showing that an average passenger vehicle travels 11,000 km per year in Western Australia [63] and the average age of the passenger vehicle in the state was 10.23 years [64]. Based on this data, the life of the passenger vehicle has been estimated as 112,567 km for the current study. The Toyota Corolla was chosen as the proposed vehicle for the usage of these alternative fuels as it is a widely used passenger vehicle in Australia [64,65]. Fuel consumption values of the latest Toyota Corolla model are reported to be 0.06 L/km [66,67]. The mass of different parts of the Corolla that were incorporated into the existing design were based on the total curb weight (car weight with standard equipment excluding passenger and any other additional items), estimated from Stasinopoulos et al. [61] and detailed inventory for different parts has been readjusted for the Corolla from Notter et al. [60]. Table 4 shows a summary of the inventory for gasoline and other vehicle materials for the current study.

Table 4. Summary of inventory for gasoline vehicle (GV), electric vehicle (EV), plug-in hybrid electric vehicle (PHEV) and Nickel metal hydride battery (HFCV) (functional unit (FU) = per vehicle kilometer travelled (VKT)).

Parameter	Unit	GV	EV	PHEV	HFCV	E65
Hydrogen tank	kg	-	-	-	7.77×10^{-4}	-
Battery *	kg	-	3.37×10^{-3}	1.07×10^{-3}	2.03×10^{-4}	-
Fuel cell with assembly	kg	-	-	-	9.50×10^{-4}	-
Motor	kg	-	6.11×10^{-4}	4.82×10^{-4}	6.27×10^{-4}	-
Inverter	kg	-	1.03×10^{-4}	7.09×10^{-5}	1.05×10^{-4}	-
Converter	kg	-	2.20×10^{-4}	1.52×10^{-4}	2.26×10^{-4}	-
Motor controller	kg	-	7.82×10^{-5}	5.40×10^{-5}	8.03×10^{-5}	-
Transmission differential and others (cables, cooling unit)	kg	7.55×10^{-4}	5.51×10^{-4}	6.98×10^{-4}	6.65×10^{-4}	7.55×10^{-4}
charger	kg	-	6.37×10^{-5}	3.50×10^{-5}	-	-
Internal combustion engine	kg	1.31×10^{-3}	-	9.14×10^{-4}	-	1.41×10^{-3}
Fuel system	kg	1.60×10^{-4}	-	1.38×10^{-4}	-	1.62×10^{-4}
Exhaust system	kg	2.13×10^{-4}	-	1.83×10^{-4}	-	2.13×10^{-4}

* EV and PHEV: Li-ion battery; HFCV: Nickel metal hydride battery (according to manufacturer specifications).

2.4.2. Ethanol

Three feedstocks such as wheat, straw, and Mallee have been considered as the source of E65 for WA. Figure 1 shows the supply chain scenario of ethanol considered for this study. Data related to farm inputs of wheat production were collected from Northam, located in the central wheat belt of WA [68,69]. The average yield of wheat in WA is 1.8 tonne/ha [26]. So, a farm with an average yield of 1.9 tonne/ha was selected for estimating LCI inputs for wheat-based ethanol production. The transport distances of all chemicals were obtained from the respective organizations. The location of the ethanol (E65) plant was considered to be in the Kwinana Industrial Area (KIA) adjacent to the BP oil refinery.

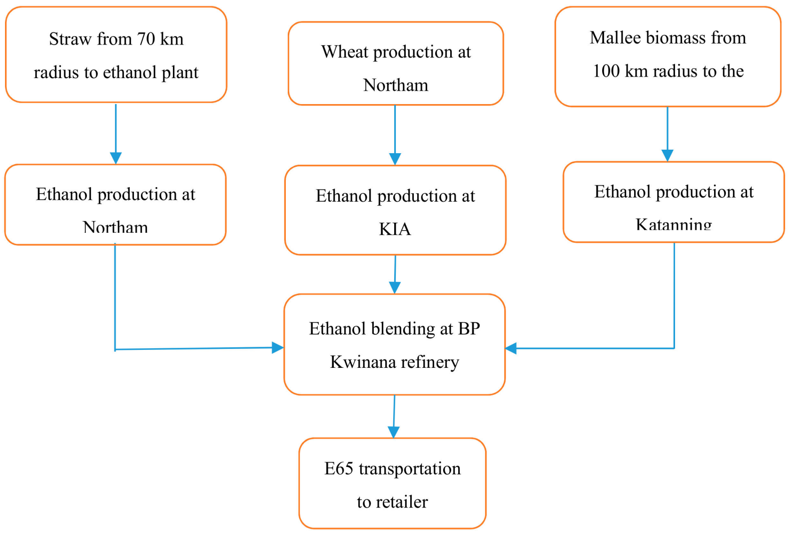


Figure 1. The ethanol (E65) supply chain.

N_2O emission from soil is one of the major contributors to GHG emission during agricultural production of feedstocks [69]. The field measurement of N_2O emission factor from N fertilizer in WA was found to be as low as 0.1% compared to the IPCC (Intergovernmental Panel on Climate Change) default value of 1% [68,70]. Table 5 provides a summary of direct and indirect emission factors used for N_2O and CO_2 from the field. Besides, the conversion factors for C to CO_2 and N to N_2O were used as 3.667 and 1.57, respectively [71].

Table 5. Emission factor used for soil emission.

Types of Emission	Emission Factor	Corresponding Reference
Direct N_2O emission from N fertilizer	0.1%	Biswas et al. [69]
Fraction C in Urea for Urea hydrolysis	0.2	Klein et al. [71]
CO_2 emission factor for lime	0.12	Klein et al. [71]
Emission from leaching		
N fraction lost due to leaching	0.3	Klein et al. [71]
N_2O emission due to leaching	0.0075	Klein et al. [71]
NH_3 volatilization		
Fraction of fertilizer N will be emitted as NH_3	10%	Barton et al. [72]
Emission factor for N_2O emission	0.08%	Barton et al. [72]

Whether leaching is happening or not depends on the ratio of evapotranspiration (Et) to annual precipitation (P). Leaching is considered when $Et/P < 0.8$ or $Et/P > 1$ [70,73]. The last 7 years of data (Et/P) of the location (31.47113° S, 116.52287° E) confirms that leaching is unlikely to happen on site. Farm machinery production data for WA and the associated emissions were collected from Biswas et al. [69]. Economic allocation was considered in this study to allocate environmental burden to the co-products for all fuel options based on the current prices in WA [52]. During the farming stage, the environmental burden for wheat was 78.14% compared to straw (16.26%) and remaining residue (5.60%). For the ethanol conversion stage, a 79.47% burden was allocated to ethanol compared to 20.53% for dried distiller grain (DDGS). These allocations were found to be consistent with the existing literature, such as Grant et al. [52] and Muñoz et al. [74] for ethanol versus DDGS allocation; and Zucaro et al. [75] and Borroin et al. [76] for wheat versus straw allocation.

As described in Section 2.1, a large amount of cereal straw is produced in WA. Wheat comprises around 70% (around 10 million tonnes out of 14 million tonnes) of total cereal production in WA [26,77]. Therefore, wheat straw was considered to provide 16.26% of the environmental burden. The same farm was considered to supply both wheat and straw. The excess straw that remains after the soil amendment was 1.92 tonnes/ha [25]. Due to the use of straw for fuel production, some additional fertilizers may be required for some farms depending upon the soil conditions, and as such, this study considered a moderate replacement amount of 4 kg Di-ammonium phosphate (DAP), 11 kg Urea and 10 kg K_2O fertilizer (Table 6).

Table 6. Nutrient replacement due to straw removal.

Fertilizer	Amount Which Can Be Required Per Tonne of Straw, Kg [25]	Amount Considered for This Study Per Tonne of Straw, Kg
N	2–10	6
P	0.2–1.5	0.8
K	6–16	7

For Urea, transport by sea was considered for importing from Qatar [78,79]. Due to the low bulk densities of straw, the location of the ethanol production plant should be near the farm to reduce transport emissions [25]. A 70 km radius was considered for transporting the straw from farms to the plant [27]. Figure 2 illustrates the process of ethanol production from lignocellulosic feedstocks (such as straw and Mallee for this study). Enzyme was considered to be produced onsite based on Mu et al. [30].

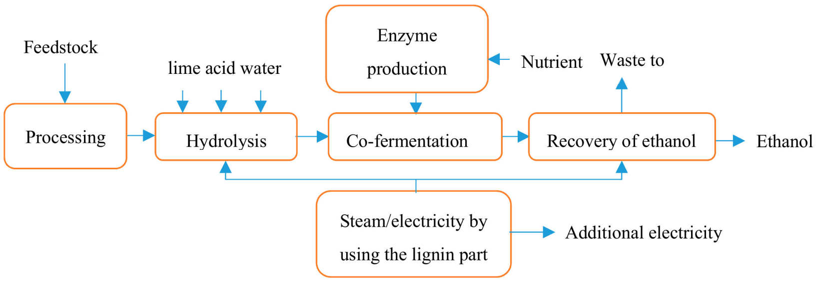


Figure 2. Schematic diagram of straw based ethanol production.

Like straw, the ethanol plant for Mallee was considered from the farms around Katanning [80]. The Mallee farm input for production was gathered from Crossin [81]. The life of the Mallee tree was considered as 30 years with an initial harvest at 6 years age followed by 6 harvests at 4 year intervals. Besides, the average harvest of biomass was found to be 16 gmt per harvest per ha [81]. Mallee trees have a high nutrient efficiency and also receive an additional amount of fertilizers from nearby grain fields [25]. Hence, a moderate amount of fertilizers (50 kg DAP, 50 kg Urea and 20 kg Muriate of potash per ha) were considered for this study after each harvest of Mallee [32]. Following the harvest, the biomass was considered to be transported to a processing farm that was 100 km away from the plantation site [81].

Since electricity is generated as a co-product with ethanol in the plants using straw and Mallee as feedstock, the environmental burdens allocated to ethanol were 91% and 89.28%, produced from straw and Mallee, respectively. Inventory inputs for E65 production from all three feedstocks is presented in Table 7.

Table 7. Summary of inventory for 1 L ethanol production from wheat, straw and Mallee after allocation *.

		Chemical/Energy	Unit	Wheat	Straw	Mallee
Fuel Production	Agriculture	Urea fertilizer	kg	-	-	3.85×10^{-3}
		Di-ammonium phosphate (DAP) fertilizer	kg	7.99×10^{-2}	2.78×10^{-2}	3.85×10^{-3}
		Muriate of potash (MOP) fertilizer	kg	-	-	1.54×10^{-3}
		Flexi-N fertilizer	kg	7.92×10^{-2}	2.75×10^{-2}	
		Herbicide & pesticide	kg	1.57×10^{-3}	5.46×10^{-4}	3.06×10^{-5}
		Diesel for farm machinery	L	9.48×10^{-3}	3.30×10^{-4}	1.44×10^{-3}
		Diesel for harvester	L	4.90×10^{-3}	1.77×10^{-3}	7.70×10^{-4}
		Lime application to paddock	kg	8.17×10^{-2}	2.84×10^{-2}	-
		Farm machinery	AUD	5.59×10^{-3}	1.25×10^{-3}	-
		Harvester for Mallee	P	-	-	3.89×10^{-4}
		Transportation of chemicals and diesel	tkm	4.21×10^{-2}	1.40×10^{-2}	3.99×10^{-2}
	Feedstock transportation to ethanol plant		tkm	2.6×10^{-1}	2.35×10^{-1}	5.27×10^{-1}
	Ethanol conversion	Feedstock	kg	1.99	3.35	5.27
		Water	L	0.25	7.02	4.02
		Enzyme	kg	-	1.88×10^{-2}	1.92×10^{-2}
		Lime	kg	-	8.63×10^{-2}	7.58×10^{-2}
		Sulfuric acid	kg	-	3.79×10^{-2}	1.04×10^{-1}
		Corn steep liquor	kg	-	2.58×10^{-1}	4.08×10^{-2}
		DAP	kg		4.74×10^{-3}	4.8×10^{-3}
		NaOH	kg		1.66×10^{-3}	1.71×10^{-3}
		Heat	MJ	4.05	-	-
		Electricity	kWh	8×10^{-2}	-	-
		Transportation of chemicals	tkm		1.65×10^{-1}	2.17×10^{-1}
Distribution & Transport	Transportation to blending stations		tkm	-	1.03×10^{-1}	1.03×10^{-1}
	E 65 Transportation to retailers (1 L)		tkm		1.65×10^{-1}	

* DAP: Di-ammonium phosphate, MOP: Muriate of potash; p: process.

Owing to the presence of oxygen in the ethanol molecule and its water absorption, the fuel system component systems are prone to corrosion [82,83]. Therefore, this study considered the use of stainless steel for the fuel tank material such as used for the Holden Commodore [82]. Accordingly, the aluminium components for the injection system and synthetic rubber of the fuel line were replaced with stainless steel and polypropylene respectively [84]. Fuel consumption (0.078 L/km) and tailpipe emission for E65 were based on Jin et al. [85].

2.4.3. Electricity

The current electricity mix of Western Australia (Table 2) was used for charging the EVs. Most of the EVs were considered to be charged overnight during the off-peak period at home as this charging system is already available in Western Australia [86]. The low voltage electricity system caused 2.7% and 5.28% transmission and distribution losses for WA, respectively [40]. To compare with gasoline vehicle (GV), a first-generation Nissan Leaf, with 120–135 km range, was considered as the EV in previous studies [58,61]. Vehicle driving range from a single charge, however, is one of the main barriers to the EV uptake in Australia [87]. By considering the dispersed locations and large distance between population centres of WA, a new generation Nissan leaf released in 2018 was chosen for this study for comparison. This EV contains a 40 kWh Li-ion battery pack, and a 110 kW motor (comparable with GV power) to provide a driving range of 270 km [88,89]. Data for 100 kW EV materials and powertrain were collected from Miotti et al. [58] and adapted for 110 kW for the current study. This approach was found to be employed by other studies in the literature for consistent comparison among different vehicles [23,58,90]. A similar plug-in hybrid vehicle, Toyota Prius Prime, was chosen for comparison. Inventory for the EV and PHEV vehicles is given in Table 4. Most of the data for the PHEV were obtained from the manufacturer specifications [91,92] and, the remaining data were based on available literature [59,93]. According to the Toyota motor corporation, the vehicle comprises a 8.8 kWh (120 kg) Li-ion battery sufficient to provide a 40 km driving range (i.e., 100–134 km/h) [91]. The vehicle uses a dual motor generator (53 kW and 23 kW) drive system. The PHEV also has a 43 litre fuel tank (14% less volume than the gasoline tank) that allows the vehicle run on a pure hybrid mode (0.044 L gasoline/km) [91]. The gasoline engine mass of the PHEV was assumed to be 30% less than that of the GV engine [91]. The electricity consumption was considered as 155 Wh/km during all-electric mode [94]. Following Ciborowski et al. [95], this study assumes that the vehicle runs on gasoline for 50% of the travel time.

2.4.4. Hydrogen

Hydrogen production through water electrolysis using a proton exchange membrane (PEM) electrolyser was considered due to its higher efficiency and operational pressure (around at 165 bar) compared to the alkaline electrolysis (AE) process [96]. PEM electrolysis uses 54 kWh of electricity to produce 1 kg of hydrogen [96]. Table 8 provides a summary of the life cycle impact (LCI) for hydrogen fuel production. The input values for hydrogen compression at different stages was based on Mehrdad et al. [97] and existing literature [10,41].

Desalinated water in WA, was considered for H_2 production. The inventory data for seawater desalination (Table 8), was sourced from Shahabi et al. [98] and Biswas et al. [99]. The study considered solar and wind energy as the sources of electricity for the desalination plants in WA [98,100].

Hydrogen distribution through tube tankers using trucks was considered. The transport of 0.3 tonne of hydrogen amounts to approximately 30 tonne freight due to the additional weight of the tubes and accessories [101]. The additional weight associated with the tube tankers of this alternative fuel was also considered for accurately estimating the emission. Around 80% of gasoline in WA is consumed in the Perth metropolitan region [102]. The mean delivery distance of hydrogen was calculated for WA as 138.39 km based on BP locations [10] and gasoline consumption within and outside the Perth metropolitan region. The delivery distance was considered the same for other fuel options (such as gasoline and E65) from the KIA to retailers.

In order to compare GV, with HFCV, the same vehicle brand (i.e., Toyota Mirai 2017) that delivers identical power (max113 kW), was considered. The vehicle comprises a 114 kW fuel cell, a 113 kW motor and a 5 kg hydrogen tank (mass of total tank 87.5 kg) to provide a driving range of around 500 km [103]. The inventory data for an 80 kW polymer electrolyte fuel cell and powertrain of 100 kW HFCV were collected from Miotti et al. [58] and then customized for both the114 kW fuel cell and 113 kW HFCV for this study. Inventory for the HFCV is summarized in Table 4. The vehicle fuel consumption was considered as 0.01 kg/km [103].

Table 8. Summary of inventory for hydrogen production (FU = per VKT; water desalination inventory for 1 L).

Process		Unit	Amount
Fuel Production	Electricity	kWh	5.40×10^{-1}
	Desalinated water from sea	L	9.00×10^{-2}
	Hydrogen Compression	kWh	9.42×10^{-3}
Distribution to Retailer		tkm	1.5×10^{-1}
Water Desalination (1 L)	Electricity	kWh	3.00×10^{-3}
	Sodium hypochlorite	g	3.57×10^{-3}
	sulphuric acid	g	6.90×10^{-4}
	sodium metabisulphite	g	7.00×10^{-5}
	Detergent	g	2.72×10^{-3}
	Citric acid	g	9.30×10^{-4}
	Caustic soda	g	4.00×10^{-4}
	Biocide	g	9.86×10^{-3}
	Polypropylene	g	5.00×10^{-5}
	Polyethylene	g	5.00×10^{-4}
	Polyurethane	g	1.40×10^{-4}
	Acrylonitrile butadiene styrene	g	1.27×10^{-3}
	Polyamide	g	1.40×10^{-4}
	Transportation		
	Local (chemicals)	tkm	8.72×10^{-4}
	International (membranes from USA)	tkm	5.48×10^{-4}
	Waste to landfill	tkm	1.10×10^{-2}

2.5. Life Cycle Impact Assessment

Life cycle environmental impact assessment was conducted to determine the indicators using Simapro 8.4 software [40]. The Australian indicator method was used to determine these indicators including GWP, WC and land use (Table 9). Besides, the FFD indicator was measured based on the energy content of fuel by using the CML method, which is aligned with the Australian best practice impact assessment guide [45].

Table 9. Impact assessment methods to estimate the environmental impacts.

Indicators	Impact Assessment Method	Unit
Global warming Potential (GWP)	IPCC GWP 100 based on IPCC 2013 [104]	$kgCO_{2\text{-eq}}$/VKT
Fossil fuel depletion (FD)	CML-IA baseline V3.03 / World 2000. Based on lower heating value. Does not include renewable energy and energy from waste.	MJ/VKT
Water Consumption (WC)	Australian indicator set v2.01	cm^3 H_2O/VKT
Land Use	Australian indicator set v2.01	cm^2.a/VKT

The considerations in selecting/developing emissions from fuel inputs for estimating corresponding environmental impacts included:

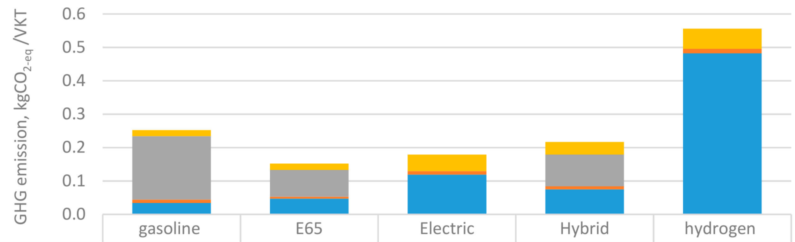
- Australian life cycle inventory emission database (AusLCI) libraries [105] developed by Australian Life Cycle Assessment Society (ALCAS) were employed to calculate the emissions corresponding to inputs used during the life cycle stages.
- For the transportation of chemicals and feedstocks, the widely used 30 tonne articulated truck in rural Australia was considered [69,72].
- Emission factors for international freight were considered to estimate the emissions for foreign transportation of chemicals and materials from overseas (e.g., urea fertilizers and membrane).
- Eco-inventory emission factors, AusLCI libraries and Western Australian electricity mix were used to estimate emissions from the Li-ion battery, charger, controller, inverter and converter for the electric vehicle.
- US input-output database was used to calculate the environmental impacts from farm machinery production during the agriculture of feedstock for ethanol fuel [69].
- The environmental impact of producing USD $1 (1998 price) equivalent farm machinery was available in the software database. In order to use this database, the current price of farm machinery was deflated to the 1998 price (average 2.45%) and converted to USD using the 1998 conversion factor [US$ 1=AU$ 1.5875] [106].
- Emission databases, such as Flexi-N fertilizer were developed based on the composition of Flexi N (40% urea, 40% ammonium nitrate and 20% water) [107].
- The process for enzyme production and water desalination were developed by using AusLCI libraries.
- The libraries for sodium metabisulphite and detergent for desalination were not available in the Simparo databases, so two main ingredients of sodium metabisulphite (sulphur oxide and caustic soda) were used to develop the emission databases for sodium metabisulphite [99]. In the case of detergent products, sodium silicate and sodium metasilicate pentahydrate were used [108].
- Although there are emission databases for the Western Australian electricity mix, this was slightly revised using the current electricity mix (Table 2).

Once all the input and output data were linked to the relevant libraries, Simapro calculated the relevant indicators according to the selected impact assessment method. A Monte Carlo simulation (MCS) involving 1000 iterations for a 95% confidence level was conducted to determine the uncertainties of the LCA results associated with the quality of inventory data [109].

3. Results and Discussions

3.1. Global Warming Potential (GWP)

E65 has the highest GHG emission reduction potential (40%) due to the replacement of gasoline (Figure 3). Less fertilizer and chemical requirements to grow straw and Mallee plus the lower N_2O emission during on-farm/feedstock production could be the main reasons for the high GHG reduction potential of ethanol (E65). Since N_2O is a powerful GHG (i.e., 268 times more powerful than CO_2), any reduction of this emission significantly reduces the overall GHG emission. The lack of microbial activity in soil in WA's semi-arid climate, in fact, releases 50-times lower N_2O emissions from the fertilizer application than the IPCC value. Figure 4 shows the breakdown of the GHG emission to identify the hotspot of ethanol production. The conversion of straw to ethanol contributes 54% of the production emissions mainly due to the large amount of GHG emission from enzyme production (50% of total conversion emission).



	gasoline	E65	Electric	Hybrid	hydrogen
Vehicle	0.018	0.019	0.049	0.038	0.061
Tailpipe	0.190	0.080	0.000	0.095	0.000
Distribution & transportation	0.010	0.005	0.010	0.009	0.013
Fuel Production	0.034	0.047	0.119	0.075	0.482

Figure 3. Life cycle GWP ($kgCO_{2\text{-}eq}$/VKT) for different fuel options.

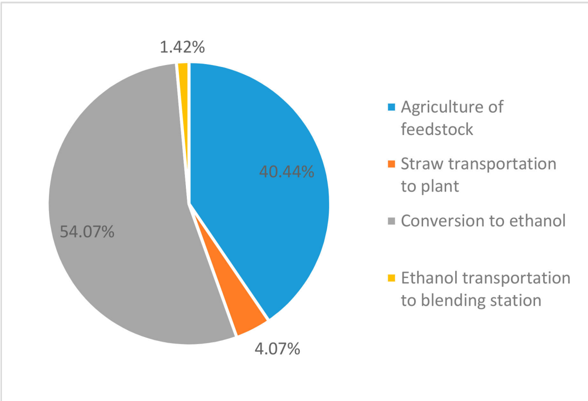


Figure 4. Breakdown of greenhouse gas (GHG) emissions in terms of ethanol (C_2H_5OH) production.

Tailpipe emissions were the main dominant factor for GHG emission for gasoline (75% of life cycle emissions) which could be almost eliminated by the use of bio-ethanol. Any emissions associated with the combustion of plant-based fuel were considered to be sequestered by plants [25]. About 29% and 14% of GHGs can be reduced by switching from gasoline to EVs and PHEVs, respectively, mainly because of the reduction in the tailpipe emission. Like gasoline, tailpipe GHG emission was found to be the hot spot for PHEVs (i.e., 44% of the total life cycle emission). The tailpipe emission was not completely eliminated as gasoline was used 50% of the total travel time. With the zero scope-1 emission (i.e., tailpipe GHG emission for this case) associated with the electric vehicle, EVs showed 21% less emission than the PHEVs.

However, GHG emissions from hydrogen fuel (0.556 $kgCO_{2\text{-}eq}$/VKT) were more than double of gasoline which is due to the large amount of electricity consumption during the water electrolysis (i.e., 83% of overall life cycle emission). The emissions during distribution of H_2 were also higher than the other fuels due to the use of heavy tube tankers to carry gaseous fuel. In the case of HFCV, the hydrogen tank (15% GHG emission of HFCV materials) and fuel cell catalysts (18.5% of GHG emission of HFCV materials) were found to be the two main contributors of GHG emissions. The usage of carbon fibre, which is the material of the hydrogen tank could alone contribute to 83% of emissions associated with the manufacture of the hydrogen tank. Besides, the use of platinum in the fuel cell catalyst accounted for around 90% emission from the total fuel cell materials emissions. Besides, for the EV, the battery alone contributed approximately 43.6% emissions of all EV materials.

GHG emission results of this LCA were comparable with the existing literature.

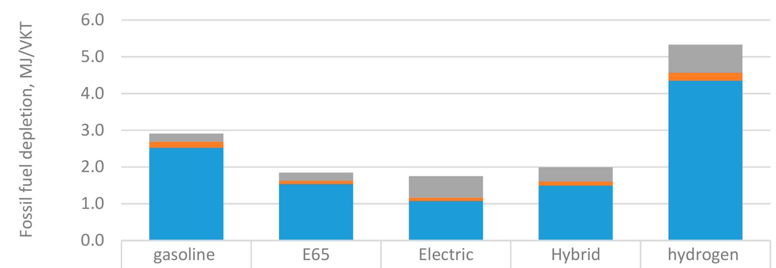
- For example, the GHG emissions for hydrogen fuel production and use in Western Australia for the current study (0.5 $kgCO_{2\text{-}eq}$) is comparable with Biswas et al. (0.67 $kgCO_{2\text{-}eq}$) in 2013 [10]. The GHG emissions of this study were lower due to the fact that it considered the recent WA's electricity mix where the percentage of renewable was higher than that considered previously. Also, it considered the use of a more efficient electrolysis process.

- Emission from GV without taking into account glider emissions (.0184 $kgCO_{2\text{-eq}}$ /VKT i.e., total 2071 $kgCO_{2\text{-eq}}$) and HFCV (.060 $kgCO_{2\text{-eq}}$ /VKT) were comparable to Stasinopoulos et al. (total 2137 $kgCO_{2\text{-eq}}$ without glider) [61] and Miotti et al. (around 0.085 $kgCO_{2\text{-eq}}$/VKT with glider) [58] respectively. The GHG emissions for HFCV were higher for the previous study due to the consideration of glider materials.
- The reduction potential of GHG emissions associated with the replacement of an internal combustion (IC) engine with an EV powertrain of this study (29%) is slightly better than a previous study (22%) [22] in WA. This small difference mainly resulted from the use of updated energy mix and improved fuel efficiency.
- Like Van Mierlo et al. in Belgium [110] and Sen et al. in the USA [111], the current study also found that the PHEV produced higher GHG emissions than the EV. The GHG emissions from ethanol were also comparable to Wang et al. [112] and Zucaro et al. [75].

3.2. Fossil Fuel Depletion (FFD)

Fossil fuel depletion varied from 1.75 to 5.33 per VKT for different fuel options in Western Australia (Figure 5). Similar to GHG emissions, the fuel production stage was found to be the 'hotspot' for FFD. The overall reductions in fossil fuel depletion due to the use of E65, EV and PHEV as a replacement for the gasoline engine were 36%, 40% and, 32%, respectively. For E65, the fuel production and distribution accounted for 89% of the total FFD, mainly because of the additional heat required for dehydration of the wheat-based ethanol conversion and enzyme production during lignocellulosic conversion (i.e., straw and Mallee to ethanol). Hydrogen fuel, however, showed 83% higher fossil fuel depletion compared to gasoline. Hydrogen production and distribution alone contributed 85.5% of the FFD (among which 94% was from the electricity requirement for water electrolysis and 5% from hydrogen distribution). Since, the desalination plant water supply for electrolysis is 100% run by renewable electricity, this input is not contributing FFD. Like GHG emissions, the use of carbon fibre in the hydrogen tank (27% of HFCV) and platinum in the fuel cell catalyst (16% of HFCV) were mainly responsible for the FFD for the HFCV as those were manufactured by using conventional fuel.

In contrast to the hydrogen fuel, FFD was the lowest for the EV due to the use of a cleaner electricity mix (only 28% from low efficient coal, around 7.5% renewable, 53% from natural gas) as fuel. Fuel production and distribution for the EV accounted for 67% of the FFD compared to 33% for the EV materials. The battery was found to be the highest FFD consumer (46% of the EV materials) mainly due to the production of the Li-ion battery cell. The FFD associated with the use of the PHEV, on the other hand, were found to be 14% higher than the EV as the latter relies on gasoline for 50% of the travel time.



	gasoline	E65	Electric	Hybrid	hydrogen
Vehicle	0.22	0.22	0.58	0.38	0.76
Distribution & transportation	0.17	0.09	0.09	0.11	0.21
Fuel Production	2.53	1.54	1.08	1.50	4.36

Figure 5. Fossil fuel depletion for different fuel options (tailpipe emissions are omitted as there were no FFD associated with tailpipe emissions).

In the absence of studies that considered FFD as an indicator for assessing alternative fuels, it is quite complex to compare the LCA results of products derived from a biological system for one particular region in comparison with another. This is primarily due to the difference in climate conditions and resource use [16]. Despite this, some comparisons with the existing literature have been made as follows:

- Cavalett et al. [113] showed that E100 (100% ethanol) from sugarcane in Brazil produced 5 times lower FFD than the gasoline, while E65 containing 35% fossil fuel (i.e., gasoline) in this study produced almost 1.54 times lower FFD than the gasoline.
- In addition, the electric vehicle in different European countries reduced FFD impact between 25% to 36% depending on the electricity grid [23] which was comparable with the current study (i.e., 40% for the EV and 31% for PHEV).

3.3. Water Consumption (WC)

Life cycle water consumption was calculated based on the water use for different activities over the life cycle of the fuel. Among the analysed fuel options, E65 emerged as the highest water consumer (1440 cm^3 /VKT), being 2.3 times higher than that consumed by a gasoline engine. As shown in Figure 6, the production stage alone consumed 87% of the life cycle water use. This higher water consumption was due to the direct water requirement during the conversion of ethanol from lignocellulosic feedstocks. Ethanol conversion from Straw and Mallee wood contributed around 79% and 93% of water consumption during the production stages. Besides, the manufacture of fertilizers in the pre-farm stage accounted for 92% of water consumption of production stage for wheat-based ethanol.

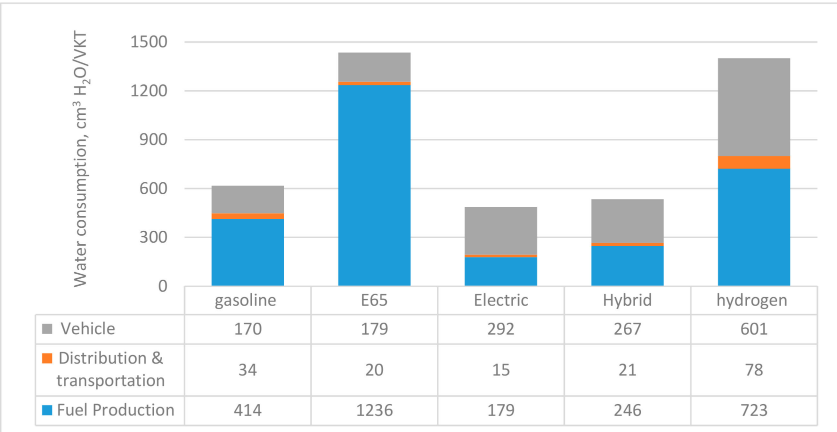


Figure 6. Water consumption impact for different fuel options (tailpipe emissions are omitted as there are no WC associated with the tailpipe emission).

WC for hydrogen fuel (1401 cm^3 /VKT) was lower than E65 mainly due to the use of seawater for electrolysis. Hydrogen production and distribution accounted for 57% of the total life cycle water consumption and the remaining 43% were from HFCV. The reason for high water consumption during hydrogen production was the large amount of electricity (54 kWh/kg of H_2; i.e., 1310 cm^3 H_2O/kWh) requirement during water electrolysis. Besides, higher WC for HFCV primarily due to the use of Nickel metal hydride battery (22% of HFCV WC) and platinum catalyst (22% HFCV WC) in the fuel cell. However, after adjusting the production stage water consumption (i.e., 9 kg/kg H_2) of hydrogen fuel by including seawater in the impact assessment, the total WC of hydrogen fuel (1490 cm^3/VKT) was slightly higher than E65.

Unlike E65 and hydrogen fuel, WC per VKT for gasoline (618 cm^3), EV (487 cm^3) and PHEV (534 cm^3) were found to be closer. The vehicle materials account for 60% WC for the EV compared to 40% in fuel production mainly due to the high water requirement during the production of the battery and other electronic components such as the inverter, converter and electric motor. The life cycle water consumption of PHEV was slightly higher than EV as the production and distribution of the gasoline (i.e., gasoline was used 50% of the total travel time of PHEV) required more water than that used to generate electricity in WA.

The WC for gasoline production for this study was similar to the findings of Sun et al. [114]. Besides, Wu et al. [115] showed that WC for ethanol production from corn was 1.6 to 57 times higher than gasoline depending on irrigation requirements. The water consumption of E65 of this study was 2.82 times higher than gasoline because the percentage of C_2H_5OH in the blend was low which means that a small amount of water was required for irrigation for growing C_2H_5OH feedstock. In addition, farmers in WA rely on rainfed agriculture [72]. Sharma and Strezov [116] showed that production of hydrogen consumed 1.5 times more water than gasoline (without considering vehicle) per km. Therefore, the finding of 2.27 times higher WC than gasoline for this study is comparable due to the consideration of WC for distribution of hydrogen and vehicle materials.

3.4. Land Use

Land use impact (cm^2.a/VKT) was measured as a total use of the land for a given period of time for occupation by the built environment, forestry production and agricultural production processes [117]. As shown in Figure 7, the fuel production phase dominated the land use impact for E65 and for hydrogen fuel. E65 showed the highest land use impact (i.e., 1092 cm^2.a/VKT) due to the requirement of land to grow feedstocks. For example, the production of wheat, straw and Mallee accounted for 99%, 83% and 93% land use, respectively, during the farming stage. Similarly, hydrogen production and distribution contributed to 87% of land use impact, which is due to the use of land to generate electricity during water electrolysis.

For the EV, however, 41% of land use occurred from vehicle materials as well as 61% from fuel production. The higher land use from fuel production was due to land use in the upstream processes of electricity generation. On the other hand, the land requirement for EV battery accounts for 49.32% of the land used for all materials. This is due to the use of land for mining, processing and manufacturing of materials for batteries. The PHEV requires almost half of the land compared to the EV, which would be due to the use of gasoline fuel to complete 50% of the journey. It should be noted that electricity production requires more land than gasoline production and supply due to the infrastructural requirements.

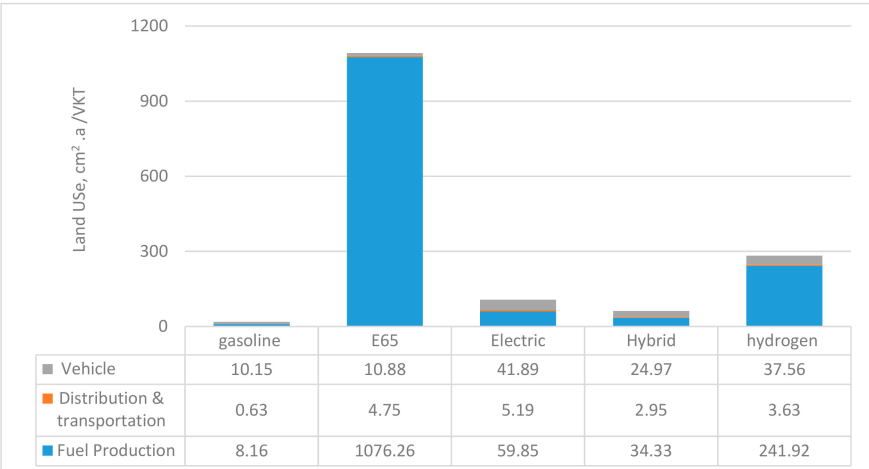


Figure 7. Land use impact for different fuel options (tailpipe emission is omitted as there is no land use impact associated with tailpipe emission).

Compared to gasoline, E65, hydrogen, EV and PHEV required 57.62, 14.94, 5.64, 3.28 times more land, respectively, being comparable to the results published in other studies. As there was no study on the land use impact for different fuel options in WA, the results were compared with the studies on other regions. For example, Sharma and Strezov [116], found that E85 and hydrogen require 350 and 1.24 times more land than that of gasoline per VKT. In this study, the land use of E65 was low, because it considers a lower blended ethanol (i.e., 65% ethanol compared 85% in the previous study). Land use impact for hydrogen, however, is higher for this study due to the consideration of land required for mining, process and manufacturing of vehicle materials. Besides, land use for EV was lower than hydrogen due to having less electricity requirement per VKT and the lower materials requirements compared to HFCV.

4. Scenario Analysis

The scenario analysis was conducted to investigate as to how the changes or modifications of input influence the overall performance of alternative fuels. Thus, this analysis involved the use of improvement strategies based on hotspots (key reasons for higher environmental impacts). Table 10 shows the modifications or strategies considered to further reduce GHG emissions. Firstly, "hotspots" for each alternative fuels were identified to determine the appropriate GHG mitigation strategies. The reason for higher environmental impact of hydrogen was the electricity generation. Wind is considered as an alternative to fossil fuels to generate electricity due to its enormous potential [118–121] and uses [35,98,100] in WA. As shown in Table 10, wind energy based hydrogen production has the potential to reduce life cycle GHG emissions as low as 70% compared to gasoline.

The use phase electricity consumption was also found to be the hotspot for EV in all impact categories including GHG emission. The projected energy mix that has the largest share of renewable energy (i.e., 37% by 2030) [35] was considered for scenario analysis. This will result in further GHG savings potential (from 29% to 50%) due to the replacement of the IC engine with an EV. For the PHEV, E10 was considered a replacement for gasoline for a clean energy mix (i.e., 37% RE) to treat the hotspots. In addition, the travel time during which electricity was used in the PHEV increased from 50% to 60% of the total mileage of the car. Based on these strategies and assumptions, GHG emission reduction potential of the PHEV increased from 14% to 33%.

Table 10. Improvement of GHG emission by applying scenario analysis.

Fuel	Basis	Strategy Considered	Improvement
Hydrogen	Hot spots	Hydrogen production by Wind energy	-Base case result: 120% higher than gasoline. -After implementing the strategy: 70% lower than gasoline.
EV	Hot spots	Cleaner grid electricity for charging	-Base case result: 29% lower than gasoline. -After implementing the strategy: 50% lower than gasoline.
PHEV	Hot spots	Use of E10 in place of gasoline	-Base case result: 14% lower than gasoline.
	Hot spots	Cleaner grid electricity for charging	-After implementing the strategies and alternative scenario: 33% lower than gasoline. Additional reduction of 3% for E10, 11% for cleaner electricity and 5% for considering the alternative scenario was achieved from the base case.
	Alternative scenario	Vehicle runs on electricity for 60% of the travel time.	
Ethanol (E65)	Hot spots	Renewable energy is used for enzyme production	-Base case result: 40% lower compared to gasoline. -After implementing the strategy: 5% additional reduction per L of fuel. Overall reduction of 41% per km compared to gasoline.

GHG emission reduction due to the replacement of gasoline with E65 was the highest during the base case analysis. Renewable energy is, however, considered for enzyme production for further improvement as this was the main contributor of emission during ethanol production. By applying this scenario, an additional 5% GHG emission reduction was possible from the production stage per litre of E65, which was around 1% per km. GHG emission reduction per km was lower due to the dominance of tailpipe GHG emissions.

Using these improvement scenarios not only reduced the direct environmental impacts but also could reduce the external cost associated with land intake, GHG consequences to climate change, water consumption and related health issues [16,122,123]. For example, the air pollution from fossil fuel based motor vehicles reduces the quality of life and causes morbidity and mortality effects. The overall life expectancy lost due to this premature mortality could be from a few months up to 10 years [124]. The internalization of these factors may help to increase the competitiveness of alternative fuels in the market. A stringent policy formulation towards climate change is, however, essential for a rapid transition to alternative fuels [123].

5. Uncertainty Analysis

Uncertainty analysis was based on 1000 iterations for a 95% confidence level. The calculated value, mean and coefficient of variance (CV) of each indicator are shown in Table 11. The CV values ranged between 1.36 and 25.95. The relatively smaller CV was obtained for the global warming potential (1.36 to 2.98), which was indicative of a lower degree of uncertainty as there was no direct effect from the land use change, vegetation and topography [109]. Nonetheless, higher variations in the CV values were observed for the land use category (0.43 to 25.92) due to the aforementioned factors. The difference between the calculated value and mean for all impact categories was also found to be quite small, which varied between 0.4% and 5.82%.

Table 11. Uncertainty analysis (based on FU per VKT).

Indicators	Parameters	Gasoline	E65	EV	PHEV	Hydrogen
GWP ($kgCO_2$)	Calculated Value	0.253	0.152	0.179	0.217	0.556
	Mean	0.252	0.149	0.173	0.211	0.549
	CV	1.47	1.6	2.99	1.36	2.98
FFD (MJ)	Calculated Value	2.91	1.85	1.75	1.99	5.33
	Mean	2.87	1.81	1.69	1.92	5.26
	CV	2.24	1.82	2.69	1.71	2.44
WC (cm^3 H_2O)	Calculated Value	618	1435	487	534	1402
	Mean	609	1433	477	521	1400
	CV	6.15	4.3	5.45	3.74	6.76
Land Use (cm^2.a)	Calculated Value	18.95	1092	107	62	283
	Mean	17.80	1092	106	61	282
	CV	20.19	0.43	19.5	18.43	25.92

6. Conclusions

This study has investigated the environmental performance of potential fuel options for Western Australia using the life cycle assessment framework. Alternative fuel options, such as E65, EV, PHEV and hydrogen were selected based on local resource availability. The study has compared these fuels with the fossil fuel gasoline as a reference case. Four indicators, namely GWP, FFD, WC and land use were considered based on their necessity that was established through the literature review and expert surveys. Monte Carlo simulation statistical analysis was conducted to ascertain the reliability of the results.

The results indicated that the EV and PHEV have the potential to reduce the GHG emission, FFD and WC impact when compared to gasoline. That was mainly due to the reduction of tailpipe emissions and the use of cleaner electricity. Since hydrogen production is reliant on large amounts of electricity, it has a higher environmental impact in all the impact categories compared to that of gasoline. The requirement of heavy tube tankers for hydrogen distribution, and use of carbon fibre in the hydrogen tank and platinum in the fuel cell in the HFCV are also responsible for the higher impacts from hydrogen. Ethanol (E65), however, outperformed all other fuel options in terms of GWP impacts due to its low environmental burden during feedstock production but produced higher WC impacts similar to the ones from hydrogen. Land use impact was also the highest for E65 followed by hydrogen, EV, PHEV and gasoline. The highest land use impact associated with E65 was due to the land requirement during the agricultural production of feedstocks. In terms of vehicle materials, the EV (41% of total life-cycle land use) had the highest land use impact that is predominantly due to the battery production. A sensitivity analysis that has been carried out shows that the GHG emissions can be further reduced by between 14% and 70% by simply substituting grid electricity with renewable power generation in the production of H_2 and electricity for hydrogen and electric vehicles.

Feedstocks for the study were selected in such a way that their use in the production of fuel(s) had minimal or no effect on the food supply chain in WA. The state also has an enormous amount of land which is capable of supporting renewable power production and alternative fuel activities. Adoption of renewable resources would reduce the environmental burden due to extensive fuel use, especially with hydrogen and electric vehicles in the state. However, future research regarding sustainability evaluation of these fuel options may need to incorporate social and economic aspects.

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Abbreviations

- AVM Additional vehicle materials
- BP British Petroleum
- CSIRO The Commonwealth Scientific and Industrial Research Organisation
- CV Coefficient of variance
- E65 Ethanol-gasoline blend (65% ethanol and 35% gasoline)
- E85 Ethanol-gasoline blend (85% ethanol and 15% gasoline)
- ELCA Environmental Life cycle assessment
- EV Electric vehicle
- FFD Fossil Fuel Depletion
- FU Functional unit

- GHG Greenhouse gas
- g Gram
- gmt Green Metric tonne
- GV Gasoline vehicle
- GWP Global warming potential
- ha Hectare
- HFCV Hydrogen fuel cell vehicle
- ISO International standard organization
- kg Kilogram
- KIA Kwinana Industrial Area
- L Litre
- LCA Life cycle assessment
- LCI Life cycle inventory
- ML Million Litre
- Mt Million tonne
- PEM Proton exchange membrane electrolysis
- PHEV Plug-in hybrid electric vehicle
- PJ Peta joule
- tkm Tonne-kilometer
- VKT Vehicle kilometre
- WA Western Australia
- WC Water Consumption

References

1. Xing, Y.; Song, H.; Yu, M.; Wang, C.; Zhou, Y.; Liu, G.; Du, L. The characteristics of greenhouse gas emissions from heavy-duty trucks in the Beijing-Tianjin-Hebei (BTH) region in China. *Atmosphere* **2016**, *7*, 121. [CrossRef]
2. Moghaddam, E.A.; Ahlgren, S.; Hulteberg, C.; Nordberg, Å. Energy balance and global warming potential of biogas-based fuels from a life cycle perspective. *Fuel Process. Technol.* **2015**, *132*, 74–82. [CrossRef]
3. UNEP. Global Green House Gas Emission Data. 2017. Available online: https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data (accessed on 18 September 2017).
4. Brondani, M.; Hoffmann, R.; Mayer, F.D.; Kleinert, J.S. Environmental and energy analysis of biodiesel production in Rio Grande do Sul, Brazil. *Clean Technol. Environ. Policy* **2015**, *17*, 129–143. [CrossRef]
5. Western Australian Planning Commission. *State Planning Strategy 2050*; Western Australian Planning Commossion, Government of Western Australia: Perth, Australia, 2014.
6. Department of the Environment and Energy. *Australian Energy Update 2017*; Commonwealth of Australia: Cabberra, Australia, 2017.
7. Department of the Environment and Energy. Australian Energy Update 2018 (Table K). Commonwealth of Australia, Cabberra, Australia; 2018. Available online: https://www.energy.gov.au/publications/australian-energy-update-2018 (accessed on 12 July 2019).
8. Australian Bureau of Statistics. *9208.0—Survey of Motor Vehicle Use, Australia*; Government of Australia: Cabberra, Australia, 2017.
9. Department of Finance Public Utilities Office. *Strategic Energy Initiative Energy 2031: Building the Pathways for Western Australia's Energy Future*; Department of Finance Public Utilities Office: Perth, Australia, 2012.
10. Biswas, W.K.; Thompson, B.C.; Islam, M.N. Environmental life cycle feasibility assessment of hydrogen as an automotive fuel in Western Australia. *Int. J. Hydrog. Energy* **2013**, *38*, 246–254. [CrossRef]
11. Australian Bureau of Statistics. *9309.0—Motor Vehicle Census, Australia*; Government of Australia: Canberra, Australia, 2017.
12. Department of Resources Energy and Tourism. *National Energy Security Assessment 2011*; Commonwealth of Australia: Canberra, Australia, 2011.
13. John, B.A.O. *Australia's Liquid Fuel Security Part-2*; A Report for NRMA Motoring & Services; National Road and Motorists' Association: Sydney, Australia, 2014.
14. Biswas, W.K.; Barton, L.; Carter, D. Biodiesel production in a semiarid environment: A life cycle assessment approach. *Environ. Sci. Technol.* **2011**, *45*, 3069–3074. [CrossRef] [PubMed]
15. Hoque, N.; Biswas, W.; Mazhar, I.; Howard, I. LCSA Framewrok for Assessing Sustainability of Alternative Fuel for Transport Sector. *Chem. Eng. Trans.* **2019**, 72. [CrossRef]
16. Hoque, N.; Mazhar, I.; Biswas, W. Application of Life Cycle Assessment for Sustainability Evaluation of Transportation Fuels. In *Reference Module in Materials Science and Materials Engineering*; Elsevier: Amsterdam, The Netherlands, 2018.
17. Requia, W.J.; Adams, M.D.; Arain, A.; Koutrakis, P.; Ferguson, M. Carbon dioxide emissions of plug-in hybrid electric vehicles: A life-cycle analysis in eight Canadian cities. *Renew. Sustain. Energy Rev.* **2017**, *78*, 1390–1396. [CrossRef]
18. Balat, M.; Balat, H. Recent trends in global production and utilization of bio-ethanol fuel. *Appl. Energy* **2009**, *86*, 2273–2282. [CrossRef]
19. Farine, D.R.; O'Connell, D.A.; John Raison, R.; May, B.M.; O'Connor, M.H.; Crawford, D.F.; Herr, A.; Taylor, J.A.; Jovanovic, T.; Campbell, P.K. An assessment of biomass for bioelectricity and biofuel, and for greenhouse gas emission reduction in Australia. *GCB Bioenergy* **2012**, *4*, 148–175. [CrossRef]
20. Lim, C.I.; Biswas, W.K. Development of triple bottom line indicators for sustainability assessment framework of Malaysian palm oil industry. *Clean Technol. Environ. Policy* **2018**, *20*, 539–560. [CrossRef]
21. Lim, C.I.; Biswas, W. An evaluation of holistic sustainability assessment framework for palm oil production in Malaysia. *Sustainability* **2015**, *7*, 16561–16587. [CrossRef]
22. Biswas, W.; Kabir, A.; Islam, N.; Rosano, M. Life Cycle Environmental Benefits from the Use of Retrofit Electric Vehicles in Western Australia. In Proceedings of the 8th Australian Life Cycle Assessment Society (ALCAS) Conference: Pathways to greening global markets, Sydney, Australia, 15–18 July 2013.

23. Hawkins, T.R.; Singh, B.; Majeau-Bettez, G.; Strømman, A.H. Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. *J. Ind. Ecol.* **2013**, *17*, 53–64. [CrossRef]
24. Sadeghinezhad, E.; Kazi, S.N.; Sadeghinejad, F.; Badarudin, A.; Mehrali, M.; Sadri, R.; Reza Safaei, M. A comprehensive literature review of bio-fuel performance in internal combustion engine and relevant costs involvement. *Renew. Sustain. Energy Rev.* **2014**, *30*, 29–44. [CrossRef]
25. Stucley, C.; Schuck, S.; Sims, R.; Bland, J.; Marino, B.; Borowitzka, M.; Abadi, A.; Bartle, J.; Giles, R.; Thomas, Q. *Bioenergy in Australia: Status and Opportunities*; Bioenergy Australia: New South Wales, Australia, 2012.
26. Wilkinson, I. Western Australian Wheat Industry. 2018. Available online: https://www.agric.wa.gov.au/grains-research-development/western-australian-wheat-industry (accessed on 1 January 2018).
27. Brooksbank, K.; Lever, M.; Paterson, H.; Weybury, M. *Biomass Scoping Study: Opportunities for Agriculture in Western Australia*; Department of Agriculture and food: Perth, Australia, 2014.
28. Department of the Environment and Energy. *Australian Petroleum Statistics*; Department of the Environment and Energy: Canberra, Australia, 2017.
29. O'Connell, D.; Batten, D.; O'Connor, M.; May, B.; Raison, R.; Keating, B.A.; Beer, T.; Braid, A.; Haritos, V.; Begley, C. *Biofuels in Australia: Issues and Prospects: A Report for the Rural Industries Research and Development Corporation*; Rural Industries Research and Development Corporation: Canberra, Australia, 2007.
30. Mu, D.; Seager, T.; Rao, P.S.; Zhao, F. Comparative life cycle assessment of lignocellulosic ethanol production: Biochemical versus thermochemical conversion. *Environ. Manag.* **2010**, *46*, 565–578. [CrossRef] [PubMed]
31. United Petroleum. Ethanol Production. 2018. Available online: https://www.unitedpetroleum.com.au/about/ethanol-production/ (accessed on 3 May 2018).
32. Wu, H.; Fu, Q.; Giles, R.; Bartle, J. Production of mallee biomass in Western Australia: Energy balance analysis. *Energy Fuels* **2007**, *22*, 190–198. [CrossRef]
33. URS Asutralia. *Oil Mallee Industry Development Plan for Western Australia*; URS Australia Pty Ltd.: Perth, Australia, 2008.
34. John, B.; Amir, A. The Economics of the Industry: Future Drivers and Barriers to the Bioenergy and Mallee Industries. 2019. Available online: https://www.oilmallee.org.au/media-centre.html (accessed on 10 May 2019).
35. The Climate Institute. Clean Energy Jobs in Regional Australia. Available online: http://www.climateinstitute.org.au/verve/_resources/cleanenergyjobssnapshot_westernaustralia.pdf (accessed on 17 September 2018).
36. Mullan, J.; Harries, D.; Bräunl, T.; Whitely, S. Modelling the impacts of electric vehicle recharging on the Western Australian electricity supply system. *Energy Policy* **2011**, *39*, 4349–4359. [CrossRef]
37. OECD/IEA. *Global EV Outlook 2017: Two Million and Counting*; International Energy Agency: Paris, France, 2017.
38. Roger, H. New diesel and petrol vehciles to be banned from 2040 in UK. *BBC News*, 26 July 2017.
39. Chrisafis, A.; Vaughan, A. France to Ban Sales of Petrol and Diesel Cars by 2040. *The Guardian*, 6 July 2017.
40. PRe'-Consultants. *Simapro 8.4 Lca Software*; Pre' Consultants: Amersfoort, The Netherlands, 2016.
41. Hydrogen Strategy Group. *Hydrogen for Australia's Future*; Commonwealth of Australia: Canberra, Australia, 2018.
42. Ally, J.; Pryor, T. Life-cycle assessment of diesel, natural gas and hydrogen fuel cell bus transportation systems. *J. Power Sources* **2007**, *170*, 401–411. [CrossRef]
43. Pickin, J.; Randell, P. *Australian National Waste Report 2016*; Department of the Environment and Energy and Blue Environment Pty Ltd.: Melbourne, Australia, 2017.
44. Zanchi, L.; Delogu, M.; Zamagni, A.; Pierini, M. Analysis of the main elements affecting social LCA applications: Challenges for the automotive sector. *Int. J. Life Cycle Assess.* **2018**, *23*, 519–535. [CrossRef]
45. Renouf, M.; Grant, T.; Sevenster, M.; Logie, J.; Ridoutt, B.; Ximenes, F.; Bengtsson, J.; Cowie, A.; Lane, J. *Best Practice Guide for Life Cycle Impact Assessment (LCIA) in Australia*; Australian Life Cycle Assessment Society: Melbourne, Australia, 2015.
46. Bureau of Meteorology. *Australia's Changing Climate*; Bureau of Meteorology: Melbourne, Australia, 2016.
47. Australian Bureau of Statistics. *4610.0—Water Account, Australia, 2015–2016*; Government of Australia: Canberra, Australia, 2017.
48. Rangelands NRM. What Are the Rangelands? Available online: https://rangelandswa.com.au/who-we-are-2/what-are-the-rangelands/ (accessed on 10 December 2018).
49. Taylor, R. Drinking Water Shortage Forecast for South West WA within a Decade. *ABC News*, 21 July 2015.

50. Water Corporation. Ground Water. Available online: https://www.watercorporation.com.au/water-supply/our-water-sources/groundwater?pid=res-wss-spw-np-gw (accessed on 17 October 2018).
51. McFarlane, D. Will Perth have enough water for its diverse needs in a drying climate? In *Planning Boomtown and Beyond*; Biermann, S., Olaru, D., Paul, V., Eds.; UWA Publishing: Perth, Australia, 2016; pp. 209–237.
52. Grant, T.; Bontinck, P.; Sharma, B.; Renouf, M. *Greenhouse Gas and Sustainability Footprints of Current and Future Biofuels for Queensland*; Lifecycles: Melbourne, Australia, 2016.
53. Edge Environment and Life Cycle Strategies. *Literature Review for Establishing a National LCA Approach for Australian Bioenergy*; Australian Renewable Energy Agency: Canberra, Australia, 2016.
54. Australian Renewable Energy Agency. *Life Cycle Assessment (LCA) of Bioenergy Products and Projects*; Australian Government: Canberra, Australia, 2016.
55. Australian Institute of Health and Welfare. Australia's Welfare 2017: In Brief. Available online: https://www.aihw.gov.au/reports/australias-welfare/australias-welfare-2017-in-brief/contents/indicators-of-australia-s-welfare (accessed on 14 November 2018).
56. ISO14040. *Environmental Mangament-Life Cycle Assessment-Principles and Frame Work*; ISO: Geneva, Switzerland, 2006.
57. ISO14044. *Environemnental Management-Life Cycle Assessments-Requirements and Guidelines*; International Standard Organization (ISO): Geneva, Switzerland, 2006.
58. Miotti, M.; Hofer, J.; Bauer, C. Integrated environmental and economic assessment of current and future fuel cell vehicles. *Int. J. Life Cycle Assess.* **2017**, *22*, 94–110. [CrossRef]
59. Sharma, R.; Manzie, C.; Bessede, M.; Crawford, R.H.; Brear, M.J. Conventional, hybrid and electric vehicles for Australian driving conditions. Part 2: Life cycle CO_2-e emissions. *Transp. Res. Part C Emerg. Technol.* **2013**, *28*, 63–73. [CrossRef]
60. Notter, D.A.; Gauch, M.; Widmer, R.; Wager, P.; Stamp, A.; Zah, R.; Althaus, H.-J. *Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles*; ACS Publications: New York, NY, USA, 2010.
61. Stasinopoulos, P.; Shiwakoti, N.; McDonald, S. Life-cycle greenhouse gas emissions of electric and conventional vehicles in Australia. In Proceedings of the ITS—Enhancing Liveable Cities and Communities, Melbourne, Australia, 10–14 October 2016; pp. 1–10.
62. Mushalik, M. Almost Half of Australia's Petrol, Diesel and Jet Fuel Imports Come from South Korea and Japan. Available online: http://crudeoilpeak.info/almost-half-of-australias-petrol-diesel-and-jet-fuel-imports-come-from-south-korea-and-japan (accessed on 13 May 2019).
63. Australian Bureau of Statistics. *9208.0—Survey of Motor Vehicle Use, Australia, 12 Months Ended 30 June 2018*; Government of Australia: Canberra, Australia, 2018.
64. Australian Bureau of Statistics. *9309.0—Motor Vehicle Census, Australia, 31 Jan 2018*; Government of Australia: Canberra, Australia, 2018.
65. Motoring Australia. Australian New Car Sales Drop in 2018. Available online: https://www.motoring.com.au/australian-new-car-sales-drop-in-2018-116332/ (accessed on 7 June 2019).
66. Commonwealth of Australia. Green Vehicle Guide. 2018. Available online: https://www.greenvehicleguide.gov.au/ (accessed on 10 January 2019).
67. Toyota Motor Corporation. Toyota Corolla Hatch Specifications. Available online: https://www.toyota.com.au/-/media/toyota/main-site/vehicle-hubs/corolla/files/corolla_hatch_spec_data_apr2019.pdf (accessed on 15 May 2019).
68. Engelbrecht, D. *Integrated Spatial Technology Framework for Greenhouse Gas Mitigation in Grain Production in Western Australia*; Curtin University: Perth, Australia, 2015.
69. Biswas, W.K.; Barton, L.; Carter, D. Global warming potential of wheat production in Western Australia: A life cycle assessment. *Water Environ. J.* **2008**, *22*, 206–216. [CrossRef]
70. National Greenhouse Gas Inventory Committee. *Australian Methodology for the Estimation of Greenhouse Gas Emissions and Sinks 2006*; Agriculture Australian Government Department of Climate Change: Canberra, Australia, 2007.
71. De Klein, C.; Novoa, R.S.; Ogle, S.; Smith, K.A.; Rochette, P.; Wirth, T.C.; McConkey, B.; Mosier, A.; Rypdal, K.; Walsh, M. N_2O emissions from managed soils, and CO_2 emissions from lime and urea application. *IPCC Guidel. Natl. Greenh. Gas Invent.* **2006**, *4*, 1–54.

72. Barton, L.; Thamo, T.; Engelbrecht, D.; Biswas, W.K. Does growing grain legumes or applying lime cost effectively lower greenhouse gas emissions from wheat production in a semi-arid climate? *J. Clean. Prod.* **2014**, *83*, 194–203. [CrossRef]
73. Brock, P.; Madden, P.; Schwenke, G.; Herridge, D. Greenhouse gas emissions profile for 1 tonne of wheat produced in Central Zone (East) New South Wales: A life cycle assessment approach. *Crop Pasture Sci.* **2012**, *63*, 319–329. [CrossRef]
74. Muñoz, I.; Flury, K.; Jungbluth, N.; Rigarlsford, G.; i Canals, L.M.; King, H. Life cycle assessment of bio-based ethanol produced from different agricultural feedstocks. *Int. J. Life Cycle Assess.* **2014**, *19*, 109–119. [CrossRef]
75. Zucaro, A.; Forte, A.; Fierro, A. Life cycle assessment of wheat straw lignocellulosic bio-ethanol fuel in a local biorefinery prospective. *J. Clean. Prod.* **2018**, *194*, 138–149. [CrossRef]
76. Borrion, A.L.; McManus, M.C.; Hammond, G.P. Environmental life cycle assessment of bioethanol production from wheat straw. *Biomass Bioenergy* **2012**, *47*, 9–19. [CrossRef]
77. Wilkinson, I. *Western Australian Grains Industry*; Department of primary Industries and Regional Development: Perth, Asutralia, 2018.
78. Olivera, T.; Agbolab, F.; Stockenhubera, M. *A Collaborative Supply Chain Study of Fertiliser Usage in an Australian Context, with a Focus on Pre-Farm Inputs, Using Life Cycle Assessment*; The University of NewCastle: Newcastle, Australia, 2016.
79. McKenzie, C. (CSBP Fertilizer, K.I.A., Webberton, Australia). Personal communication, 2018.
80. Oil Mallee Association Australia. Oil Malee Research and Development. Available online: https://www.oilmallee.org.au/industry-development.html (accessed on 10 May 2019).
81. Crossin, E. Life cycle assessment of a mallee eucalypt jet fuel. *Biomass Bioenergy* **2017**, *96*, 162–171. [CrossRef]
82. RAC. E 85 Conversion. Available online: https://www.racq.com.au/cars-and-driving/cars/owning-and-maintaining-a-car/facts-about-fuels/e85-conversions (accessed on 25 September 2018).
83. Jones, C. Vehicle Changes for E85 Conversion. DoE/NREL/EPA Clean Cities Webcast. 2007. Available online: https://afdc.energy.gov/files/pdfs/jones_webcast_050307.pdf (accessed on 12 May 2019).
84. Matějovskyý, L.; Macaýk, J.; Pospiýšil, M.; Baroš, P.; Staš, M.; Krausovaý, A. Study of Corrosion of Metallic Materials in Ethanol–Gasoline Blends: Application of Electrochemical Methods. *Energy Fuels* **2017**, *31*, 10880–10889. [CrossRef]
85. Jin, D.; Choi, K.; Myung, C.-L.; Lim, Y.; Lee, J.; Park, S. The impact of various ethanol-gasoline blends on particulates and unregulated gaseous emissions characteristics from a spark ignition direct injection (SIDI) passenger vehicle. *Fuel* **2017**, *209*, 702–712. [CrossRef]
86. Synergy. *Electric Vehicle Home Plan*; Synergy: Perth, Australia, 2019.
87. Climate Works. *The State of Electric Vehicles in Australia*; ClimateWorks; Australia on Behalf of Electric Vehicle Council: Melbourne, Australia, 2017.
88. RAC. The Latest and Greatest Electric Vehicles in Australia. Available online: Availabeonline:https://rac.com.au/car-motoring/info/future_new-electric-vehicles-coming-to-australia-in-2019 (accessed on 14 May 2019).
89. Nissan, A. New Nissan Leaf. 2019. Available online: https://www.nissan.com.au/cars-vehicles/new-leaf/overview (accessed on 14 May 2019).
90. Helmers, E.; Dietz, J.; Hartard, S. Electric car life cycle assessment based on real-world mileage and the electric conversion scenario. *Int. J. Life Cycle Assess.* **2017**, *22*, 15–30. [CrossRef]
91. Toyota Motor Corporation. Prius Prime Specs. Available online: https://www.toyota.com/priusprime/features/mpg/1235/1237/1239 (accessed on 14 May 2019).
92. Wikipedia the Free Encyclopedia. Toyota Prius Plug-in Hybrid. Available online: https://en.wikipedia.org/wiki/Toyota_Prius_Plug-in_Hybrid (accessed on 14 May 2019).
93. US Department of Energy. *Plug in Hybrid Vehicle Vlaue Position Study*; US Department of Energy: Oak Ridge, TN, USA, 2010.
94. US Department of Energy. Vehicle Fuel Economy. Available online: https://www.fueleconomy.gov/feg/Find.do?action=sbs&id=41184 (accessed on 14 May 2019).
95. Ciborowski, P.; Eyoh, I.; Seltz, J.; Wu, C. *Air Emissions Impacts of Plug-In Hybrid Vehicles in Minnesota's Passenger Fleet: Report for Plug-in Hybrid Task Force*; Minnesota Pollution Control Agency: Baxter, MN, USA, 2007.
96. Hinkley, J.; Hayward, J.; McNaughton, R.; Gillespie, R.; Matsumoto, A.; Watt, M.; Lovegrove, K. *Cost Assessment of Hydrogen Production from PV and Electrolysis*; CSIRO Australia: Canberra, Australia, 2016.

97. Ehsani, M.; Gao, Y.; Longo, S.; Ebrahimi, K. *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles*; CRC Press: Boca Raton, FL, USA, 2018.
98. Shahabi, M.P.; McHugh, A.; Anda, M.; Ho, G. Comparative economic and environmental assessments of centralised and decentralised seawater desalination options. *Desalination* **2015**, *376*, 25–34. [CrossRef]
99. Biswas, W.K. Life cycle assessment of seawater desalinization in Western Australia. *World Acad. Sci. Eng. Technol.* **2009**, *56*, 8.
100. Technology, W. Perth Seawater Desalination Plant. Available online: https://www.water-technology.net/projects/perth/ (accessed on 16 May 2019).
101. Simsons, A.; Bauer, C. *Life Cycle Assessment of Hydrogen Production*; Wokaun, A., Wilhelm, E., Eds.; Cambridge University Press: Cambridge, UK, 2011. [CrossRef]
102. Corban, M. (BP Refinery, K.I.A., Perth Australia). Personal communication, 2019.
103. Toyota Motor Corporation. Mirai Product Information. Available online: https://ssl.toyota.com/mirai/assets/core/Docs/Mirai%20Specs.pdf (accessed on 16 May 2019).
104. IPCC. *Climate Change 2013: The Physical Science Basis*; Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Cambridge University Press: Cambridge, UK; New York, NY, USA.
105. AusLCI. *The Australian National Life Cycle Inventory Database (AusLCI)*; Australian Life Cycle Assessment Society (ALCAS): Melbourne, Australia, 2011.
106. Trading Economics. Australian Historical Inflation Rate. Available online: https://tradingeconomics.com/australia/inflation-cpi (accessed on 16 May 2019).
107. CSBP Fertilizer. Safety Data Sheets of Fertilizers. Available online: https://csbp-fertilisers.com.au/safety-data-sheets (accessed on 2 June 2019).
108. DIATOM. Detergents. Available online: http://www.diatom.com.br/en-US/applications/detergentes (accessed on 16 May 2019).
109. Arceo, A.; Biswas, W.K.; John, M. Eco-efficiency improvement of Western Australian remote area power supply. *J. Clean. Prod.* **2019**, *230*, 820–834. [CrossRef]
110. Van Mierlo, J.; Messagie, M.; Rangaraju, S. Comparative environmental assessment of alternative fueled vehicles using a life cycle assessment. *Transp. Res. Procedia* **2017**, *25*, 3435–3445. [CrossRef]
111. Sen, B.; Ercan, T.; Tatari, O. Does a battery-electric truck make a difference?—Life cycle emissions, costs, and externality analysis of alternative fuel-powered Class 8 heavy-duty trucks in the United States. *J. Clean. Prod.* **2017**, *141*, 110–121. [CrossRef]
112. Wang, L.; Littlewood, J.; Murphy, R.J. Environmental sustainability of bioethanol production from wheat straw in the UK. *Renew. Sustain. Energy Rev.* **2013**, *28*, 715–725. [CrossRef]
113. Cavalett, O.; Chagas, M.F.; Seabra, J.E.A.; Bonomi, A. Comparative LCA of ethanol versus gasoline in Brazil using different LCIA methods. *Int. J. Life Cycle Assess.* **2013**, *18*, 647–658. [CrossRef]
114. Sun, P.; Elgowainy, A.; Wang, M.; Han, J.; Henderson, R.J. Estimation of U.S. refinery water consumption and allocation to refinery products. *Fuel* **2018**, *221*, 542–557. [CrossRef]
115. Wu, M.; Xu, H. *Consumptive Water Use in the Production of Ethanol and Petroleum Gasoline—2018 Update*; Argonne National Laboratory (ANL): Lemont, IL, USA, 2018.
116. Sharma, A.; Strezov, V. Life cycle environmental and economic impact assessment of alternative transport fuels and power-train technologies. *Energy* **2017**, *133*, 1132–1141. [CrossRef]
117. Carre, A. *A Comparative Life Cycle Assessment of Alternative Constructions of a Typical Australian House Design*; Project Number PNA 147-0809; Forest and Wood Products Australia: Melbourne, Australia, 2011.
118. Shafiullah, G.; Amanullah, M.; Ali, A.S.; Jarvis, D.; Wolfs, P. Prospects of renewable energy—A feasibility study in the Australian context. *Renew. Energy* **2012**, *39*, 183–197. [CrossRef]
119. Bahadori, A.; Nwaoha, C.; Zendehboudi, S.; Zahedi, G. An overview of renewable energy potential and utilisation inAustralia. *Renew. Sustain. Energy Rev.* **2013**, *21*, 582–589. [CrossRef]
120. Laslett, D.; Carter, C.; Creagh, C.; Jennings, P. A large-scale renewable electricity supply system by 2030: Solar, wind, energy efficiency, storage and inertia for the South West Interconnected System (SWIS) in Western Australia. *Renew. Energy* **2017**, *113*, 713–731. [CrossRef]
121. Lu, B.; Blakers, A.; Stocks, M. 90–100% renewable electricity for the South West Interconnected System of Western Australia. *Energy* **2017**, *122*, 663–674. [CrossRef]

122. Nocera, S.; Cavallaro, F. Economic evaluation of future carbon dioxide impacts from Italian highways. *Procedia-Soc. Behav. Sci.* **2012**, *54*, 1360–1369. [CrossRef]
123. Nocera, S.; Cavallaro, F. The competitiveness of alternative transport fuels for CO_2 emissions. *Transp. Policy* **2016**, *50*, 1–14. [CrossRef]
124. Bureau of Transport and Regional Economics. *Health Impacts of Transport Emissions in Australia: Economic Costs: Working Paper 63*; Department of Transport and Regional Services, Commonwealth of Australia: Canberra, Australia, 2005.