

Article

Life Cycle Sustainability Assessment of Alternative Energy Sources for the Western Australian Transport Sector

Najmul Hoque¹, Wahidul Biswas^{2,*} , Ilyas Mazhar¹ and Ian Howard¹

¹ School of Civil and Mechanical Engineering, Curtin University, Perth, WA 6102, Australia; smnajmul.hoque@postgrad.curtin.edu.au (N.H.); I.Mazhar@curtin.edu.au (I.M.); i.howard@curtin.edu.au (I.H.)

² Sustainability Engineering Group, Curtin University, Perth, WA 6102, Australia

* Correspondence: w.biswas@curtin.edu.au

Received: 29 May 2020; Accepted: 6 July 2020; Published: 10 July 2020



Abstract: Environmental obligation, fuel security, and human health issues have fuelled the search for locally produced sustainable transport fuels as an alternative to liquid petroleum. This study evaluates the sustainability performance of various alternative energy sources, namely, ethanol, electricity, electricity-gasoline hybrid, and hydrogen, for Western Australian road transport using a life cycle sustainability assessment (LCSA) framework. The framework employs 11 triple bottom line (TBL) sustainability indicators and uses threshold values for benchmarking sustainability practices. A number of improvement strategies were devised based on the hotspots once the alternative energy sources failed to meet the sustainability threshold for the determined indicators. The proposed framework effectively addresses the issue of interdependencies between the three pillars of sustainability, which was an inherent weakness of previous frameworks. The results show that the environment-friendly and socially sustainable energy options, namely, ethanol-gasoline blend E55, electricity, electricity-E10 hybrid, and hydrogen, would need around 0.02, 0.14, 0.10, and 0.71 AUD/VKT of financial support, respectively, to be comparable to gasoline. Among the four assessed options, hydrogen shows the best performance for the environmental and social bottom line when renewable electricity is employed for hydrogen production. The economic sustainability of hydrogen fuel is, however, uncertain at this stage due to the high cost of hydrogen fuel cell vehicles (HFCVs). The robustness of the proposed framework warrants its application in a wide range of alternative fuel assessment scenarios locally as well as globally.

Keywords: alternative transport fuel; triple bottom line; sustainability assessment; life cycle approach; threshold value; improvement strategies; sustainable development

1. Introduction

Concerns regarding climate change along with related health issues, increasing expenses of non-renewable energy sources, and the geopolitical vulnerability related to fossil fuel supplies have propelled countries to look for clean and renewable substitutes [1–3]. Engineers need to search for region-specific alternative fuel sources to improve the environmental, economic, and social situation [1,4,5].

In Australia, the transport sector consumes the highest share of energy (1589.2 PJ, 27.3%) compared to all other sectors in the country [6]. The sector is mainly dependent on fossil fuels and accounts for 16% of total Australian greenhouse gas (GHG) emissions. The Australian transport sector could face serious energy security issues if there is a substantial fluctuation in price and/or geopolitical

conflicts due to the fact that 90% of its transport fuel is imported through different conflict zones [7]. The strategic petroleum reserve of Australia is quite low compared to other International Energy Agency countries. The country, for example, currently holds only 18 and 22 days of cover for petrol and diesel fuel requirements, respectively [8].

Reference [2] reveals that the transportation system in Western Australia (WA) is unsustainable. Mining, which is the life blood of WA's economy, has the same energy consumption (239.7 PJ, 22.36%) as the transport sector (230.7 PJ, 21.5%) [9]. This is because people are heavily dependent on passenger cars, and the use of public transport is not popular due to the dispersed locations within WA and long distances between population centres [10]. Even within Perth, which is the capital of WA, a 20 min journey by car often takes more than an hour by public transport, which usually requires bus and/or train changes [11]. About 72% of WA's vehicles are passenger cars, of which 87% use imported gasoline. WA's transport fuel contributes quite a large share (14%) of the state's GHG emissions [10,12]. Low-elevation vehicle exhaust emissions in the atmosphere have the potential to cause significant human health problems [13]. The UK and France have already declared a ban on the sale of gasoline and diesel cars from 2040 to combat air pollution and health problems [14,15]. The use of locally available alternative fuels needs to be explored for the passenger vehicles in WA to overcome the aforementioned socio-economic and environmental issues [16]. Life cycle sustainability assessment (LCSA), which considers all three aspects of sustainability during the entire life cycle of fuel, is a very useful tool for making realistic decisions [5].

A review of the sustainability assessment of alternative fuels showed that 62% of the published studies considered only the environmental life cycle assessment (ELCA), whereas 25% considered ELCA and life cycle costing (LCC) [17]. The literature on social life cycle assessment (SLCA) and LCSA of alternative fuels is still very limited [17]. The assessment of alternative fuels using the triple bottom line (TBL) sustainability indicators has not been done rigorously [5]. The decision to choose sustainable alternative fuels is primarily dependent on the sources of locally available feedstocks and their long-term availability [2]. Besides, sustainability indicators need to be selected based on local requirements [17–19]. A few studies [20–24] in different sectors, such as fuel, electricity, bio-refineries, and application of solar energy, applied multi-criteria decision-making techniques to combine the three objectives of sustainability based on different weighting approaches, but a scenario analysis with regard to interdependencies between the TBL indicators was absent [17]. Practical case studies that incorporate the three dimensions of sustainability with life cycle approaches to operationalizing the concept of LCSA are required [25]. A comprehensive framework was presented in one [5] of the previous studies by the authors. The framework includes all the relevant phases of a product's life cycle as well as regional scale fuel selection and indicator development. The framework also accommodates scenario analysis, incorporating interdependencies among the three pillars of sustainability in order to overcome the abovementioned weaknesses in other studies.

The first stage of implementing the analysis was to conduct the environmental component of the framework, which has already been published [2]. The second step is the full execution of the framework by integrating SLCA and LCC with ELCA of alternative fuel sources, which is presented in this paper. In addition, the paper presents threshold values for sustainability indicators, which were developed to identify hotspots and incorporate improvement strategies into the framework for identifying sustainable fuel options. The study presents a novel approach to evaluating alternative fuels using Hoque et al.'s framework [5], which proposed incorporating the TBL of sustainability, threshold values, and a life cycle approach.

2. Implementation of the Framework

This section discusses various aspects of the framework such as fuel selection, indicator selection, process for data collection and evaluation, and the development of threshold values for sustainability decisions to present the implementation process of the framework under the goal and scope of the study.

2.1. The Framework

The LCSA framework, as shown in Figure 1, has been used to assess the triple bottom line sustainability performance of alternative fuels. ELCA, SLCA, and LCC tools are integrated into the framework to measure the environmental, social, and economic indicators of the selected fuel options. The selection of appropriate TBL indicators, data collection, sustainability assessment, determination of threshold values, hotspot analysis, and selection of proper improvement strategies are the main constituents of the framework. In order to aid the decision making for sustainable fuel selection, the framework employs a threshold value approach for estimating the level of sustainability performance achieved. Once the TBL metrics have been determined, the findings are compared with the applicable threshold values to verify that the sustainability requirements have been met. The possible causes for not meeting the sustainability performance are then investigated through hotspot analysis. Accordingly, TBL improvement strategies are incorporated into the framework to meet the threshold value.

Fuel options are considered for social assessment only if all the ELCA indicators satisfy the threshold values. This is followed by economic assessment, which is the third phase of the sustainability assessment of the selected fuel options. A similar process is applied to the economic assessment, as social sustainability has to be met prior to considering the economic analysis. Follow-up ELCA, SLCA, and LCC analyses are conducted after incorporating environmental, social, and economic improvement strategies to ascertain and address the interdependencies between TBL indicators. Application of renewable energy during the production of alternative fuel, utilization of cleaner electricity for electric vehicle (EV) charging, local production of alternative fuel vehicle components, etc., are some examples of environmental and social strategies that have been employed in this study. Other than that, different policy instruments, such as rebates, capital subsidy, research and development, soft loans, etc., are examples of incorporated economic strategies.

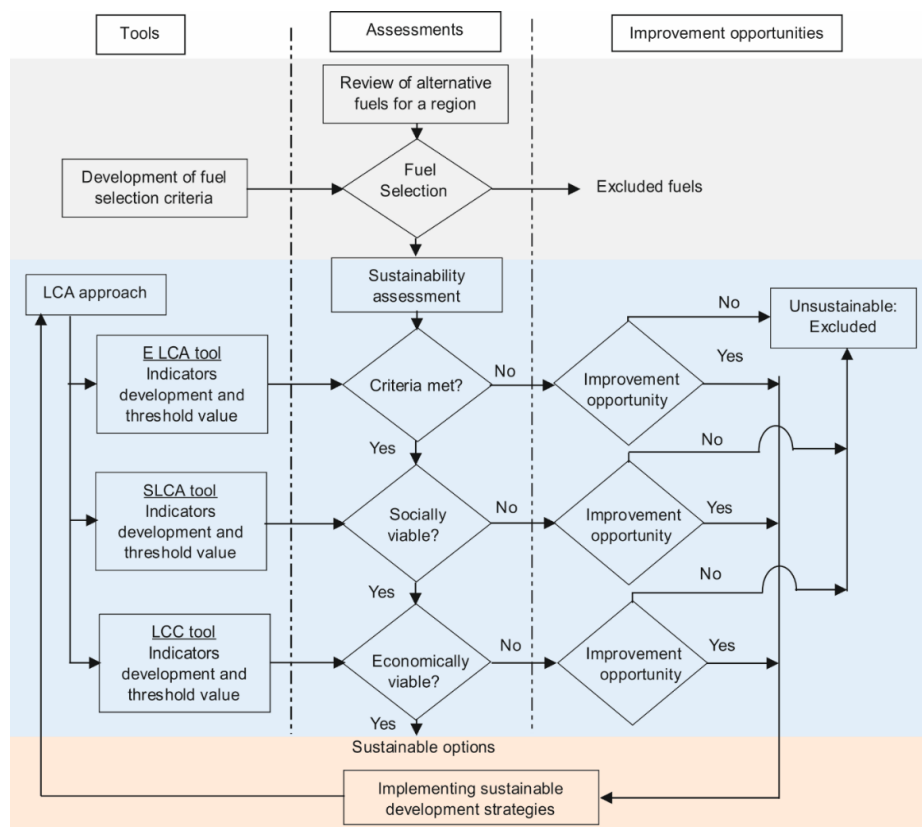


Figure 1. Holistic life cycle sustainability assessment (LCSA) framework to assess alternative transport fuels [5].

2.2. Goal and Scope of the Study

The goal of this LCSA study is to determine the sustainability performance of alternative fuels for the Western Australian transport sector. The functional unit of the study is vehicle kilometre travel (VKT), and the system boundary includes all stages of the fuel life cycle from resource extraction to use in the vehicle (i.e., well to wheel). Furthermore, any modifications in the internal combustion engine and powertrain for enabling the use of alternative fuel are included in the TBL assessment. The gliders of all vehicle types are considered the same [2,26–28]. The end-of-life stage of the vehicle was not considered as the study focused on the fuel life cycle only. The vehicle maintenance phase was also excluded due to its insignificant (1–2%) contribution to the life cycle impacts [2,27,29].

2.3. Fuel Selection

Fuel selection for the region, which is the first step in the framework, entirely depends on the availability of the relevant feedstocks. There would be additional environmental impacts and costs if the feedstocks were to be imported from other places. Keeping in mind the availability of feedstocks in WA, alternative fuel options, such as E65 (ethanol-gasoline blend: 65% ethanol), electricity for EV, electricity-gasoline for plug-in hybrid electric vehicle (PHEV), and hydrogen, have been selected for the base case analysis as an alternative to gasoline for WA's gasoline-driven passenger vehicles [2]. For the ethanol fuel (E65), three potential feedstocks, namely, wheat (10%), cereal straw (53%), and mallee (2%), were considered. The calculation regarding E65 and reasons for selecting these fuel options are presented in Section A of the attached Supplementary Materials.

2.4. Selection of Indicators

The development of region-specific TBL indicators is required for conducting a more reliable sustainability assessment [30,31]. For this study, initially, 13 indicators were selected based on a critical review of the local data and literature. Local reports from related government and semi-government organizations, such as the Australian Renewable Energy Agency [32], Australian Life Cycle Assessment Society [13], Department of Agriculture [33], Commonwealth Scientific and Industrial Research Organization, etc., and published studies were reviewed. Some of the environmental indicators, for example, human toxicity, ozone depletion potential, acidification, and biodiversity, were excluded due to their rather low impact in WA [2,13]. Vehicle exhaust emission, however, as a measure of human health has been considered an important indicator for the social sustainability assessment of alternative fuel in this study, as direct exposure to low-elevation vehicle emissions can cause serious harm to human health [2]. Three exhaust emissions from the vehicle, namely, CO, PM, and NO_x, were considered on the basis of the main air contaminants in WA, their sources from vehicles, and possible health impacts [9]. Besides, local job creation was considered as an important measure for any alternative fuel in Australia [34]. There are ties between social and economic impacts as social development also increases economic activity [34]. The 'local job creation' indicator has been considered under the social dimension of sustainability in the current study, following the existing literature [20,22,35–38] and guidelines such as the social hotspot database [35], guideline for social life cycle assessment, Organization for Economic Co-operation and Development indicators [39], and Global Bioenergy Partnership sustainability indicators [40].

To establish the indicators for this study, expert opinion was gathered through a survey. Obligatory ethics approval had to be obtained from Curtin University (approval number: HRE 2019-0101) before launching the survey. The survey was conducted over 6 months from March 2019 to August 2019 by using an online questionnaire. In total, 30 responses were collected from three stakeholder categories, namely, academia, industry, and government, where each category provided an equal number of responses (i.e., 10 responses were collected from each category). The indicators that were considered important by 50% or more of the experts were selected for assessment. Experts were also given an

option of suggesting new indicators. Finally, four environmental, four social, and three economic indicators were selected through consensus conference, as shown in Table 1.

Table 1. Selected triple bottom line (TBL) indicators for the study.

Sustainability Dimension	Indicator	Unit	Percentage of Respondents that Considered it Important
Environmental	Global warming potential (GWP)	Kg CO ₂ /VKT	87%
	Fossil fuel depletion (FFD)	MJ/VKT	67%
	Water consumption (WC)	m ³ /VKT	63%
	Land use (LU)	Ha.a/VKT	53%
Social	Local job creation *	man.hour/VKT	67%
	Conservation of fossil fuel (CFF)	MJ/VKT	50%
	Occupational health and safety (OHAS)	Qualitative	50%
	Human health based on vehicle exhaust emission (HH _{VEE}) **	gm/VKT	86%
Economic	Life cycle costing (LCC)	AUD/VKT	83%
	Carbon reduction credit (CRC)	AUD/VKT	57%
	Net benefit	AUD/VKT	70%

* Direct job creation locally in WA due to local activities within the system boundary. ** Only vehicle exhaust emission is considered due to its direct impact on human health and its requirement for local policy formation in WA [34].

Even though social acceptability was included in the beginning as a social indicator based on some previous studies [41,42], it was later excluded based on the respondents' suggestions. The survey respondents commented that the cost competitiveness of alternative fuels (e.g., life cycle costing, LCC) was the critical factor in fuel selection in WA rather than social acceptability. Social implications may arise due to grain-based ethanol production but the main ingredient of ethanol in this study was cereal straw, which remained as an unused by-product [43]. Mallee trees, on the other hand, are an inedible source that was proposed to be grown on the terrace of the agriculture field without disturbing the existing agricultural practices [43]. Only a small portion of wheat that would be enough to produce an E10 requirement for WA (Supplementary Materials: Section A) has been conservatively considered to prevent food scarcity issues [2]. The amount of wheat needed for E10 production is trivial as only the starch part of the wheat, which accounts for around 20% of the wheat, is used for ethanol production and the remaining 80% returns to the food supply chain as a distiller grain [44]. Similarly, eutrophication was removed because it was not considered relevant by the local experts due to its minimal effect on the alternative fuel supply chain in WA [2]. Using the same rationale, the impact of the use of feedstocks for ethanol fuel production was ignored even though it was suggested as an indicator by some of the survey respondents.

2.5. Data Collection and Assessment Procedures

This section presents how the data were collected and used in the ELCA, SLCA, and LCC analyses to calculate TBL indicators.

2.5.1. Environmental Indicators

The detailed data regarding the selected ELCA indicators have already been published in the authors' recent article in *Atmosphere* [2]. Environmental life cycle assessment was conducted by using Simapro 8.4 software and the Australian life cycle inventory. For the unavailable processes in the Australian life cycle inventory, eco-invent databases were modified with the Australian unit process and Western Australian electricity. The calculation of ELCA indicators is governed by Equations (4)–(7) in Section B of the Supplementary Materials. Necessary assumptions for estimating the inputs and outputs pertaining to different life cycle stages of alternative fuels are summarized as follows:

- Based on the average wheat yield in the state, a medium yield of 1.9 tonnes/ha in a farm in WA was considered for the production of wheat [45]. The ethanol conversion plant was considered to be located in the Kwinana Industrial Area (KIA) adjacent to the BP refinery. Local emission factors for WA soil were sourced from Hoque et al. [2].
- The ethanol production plant from straw was considered to be situated in the Northam area as it was one of the eight promising locations for straw-based ethanol production in WA. As wheat was the dominant cereal (around 70%) in WA, wheat-based straw was assumed as an input in the analysis. The estimated amount of straw that remained on the paddock after providing 1.5 tonnes per ha retention was 1.92 tonnes/ha [2]. As cereal was produced in WA solely for food production purposes, and the current straw mostly remains unused, no environmental burden was attributed to straw production [46]. The straw was considered to be transported to the plant from within a 70 km radius of the plant [47].
- Katanning, a mallee-rich area of WA, was chosen for mallee-based ethanol. Mallee biomass was estimated to be transported 100 km to a processing farm [48]. The total life of the mallee tree was considered to be 30 years. The first harvest was considered to be after six years, and the following 6 harvests were done at 4-year intervals (16 metric tonne/harvest/ha) [48]. All ethanol was considered to be transported to the BP refinery, KIA, for blending with gasoline.
- Water electrolysis has been considered for this study for hydrogen production. It employs the proton exchange membrane (PEM) electrolyzer, which requires 54 kWh per kg of hydrogen [2,49]. The hydrogen production plant at KIA was assumed to receive water from a renewable-based desalination plant. This option was chosen because these plants supply around 50% of WA water [50]. The Perth desalination plant in WA [51] is currently completely powered by wind electricity.
- The ethanol and hydrogen were estimated to be transported an average distance of 138.39 km [2] from the final processing plants to the end user. This was calculated based on the mean distance of BP refueling stations from the Kwinana refinery in WA.
- EVs and PHEVs were assumed to be charged overnight at home using grid electricity due to the suitability of home charging in WA [2].
- A Toyota Corolla was chosen as the base vehicle for gasoline as it was one of the popular passenger cars in Australia (Table 2). The Japanese electricity grid [52] was used for the vehicle production component as the vehicle was imported to Australia from Japan [29].

Table 2. Vehicles used for different fuel options.

Options	Equivalent Vehicle	Description	Vehicle Inventory
Gasoline	Toyota Corolla	0.06 L/km	Hoque et al. [2]
HFCV	Toyota Mirai	0.01 kg/km 114 kW polymer electrolyte fuel cell 5 kg hydrogen tank	
EV	Nissan Leaf (2nd generation)	40 kWh Li-ion battery 270 km per single charge	
PHEV	Toyota Prius Prime	8.8 kWh Li-ion battery 155 Wh/km first 40 km 0.044 L gasoline/km in charge sustaining mode	
E 65	Ethanol flex fuel vehicle	0.075 L/km (modified fuel and injection system for the Toyota Corolla)	

2.5.2. Social Indicators

Alternative fuels have the potential to create jobs locally [34]. Direct local job creation due to the manufacturing and activities related to the input and output processes required over the life cycle of the

alternative fuel was measured (Equation (8) in Supplementary Materials: Section B) in this study as job creation/VKT. By considering WA's current vehicle industry competence [53,54] and following the case of WA's neighboring state South Australia [55], the assembly of alternative vehicles that use alternative fuels was assumed to take place locally in Western Australia. Other assumptions for estimating the local job creation were as follows:

- Person-hours required per unit of inputs (e.g., production of herbicides, fertilizers, etc.) were calculated by collecting data from local plants/organizations. For example, fertilizer was required during the cultivation of ethanol feedstocks. The number of staff required to produce each unit of fertilizer was collected from Perdaman Industries located in Karratha, WA. To produce 2 million tonnes of fertilizer per annum, the producer would require around 200 permanent staff [56]. Therefore, the calculated man-hours for this input were 1.79×10^{-4} for per kg of fertilizer by considering standard working hours of 34.4 per week for Australia [57]. Job creations through plant construction (e.g., plants to produce fertilizers, electricity, etc.) were not considered as these plants were not solely constructed to produce inputs for alternative fuels.
- Job creation related to other activities, such as seeding, spraying, and harvesting during the farming stage of ethanol (Supplementary Materials Section C: Table S1), were calculated based on local data published in various studies [42,43,58,59] and information received from the Department of Primary Industries and Regional Development [60]. Staff requirements for the ethanol production plant (e.g., 1.17×10^{-3} man-hours/L for cellulosic ethanol) were taken from AECOM Australia [61], whereas the data for the hydrogen production plant (e.g., 4.48×10^{-3} man-hours/kg H_2) were based on American industries [62] due to the unavailability of local data.
- The measurement of job creation per kWh of electricity generation is quite complex because the electricity is produced from a number of fuel sources. For locally inaccessible information, Equation (9) in the Supplementary Materials: Section B [20,63] was used to generate the data by using the electricity mix of WA. Job creation during the fuel extraction and plant operation phases were taken into account because of the direct influences of these phases on the local job market. The job creation per kWh was calculated as 1.90×10^{-4} man-hours/kWh. Distribution phases of all fuels were assumed to create the same number of jobs based on the estimation by Garrett-Peltier et al. [64].
- The Altona vehicle assembly plant in Australia employed 4000 staff for the assembly of 61,000 cars per year [65]. Based on this information and the average life of 112,567 km for a passenger vehicle in WA [2], the job creation through vehicle assembly per km has been calculated. Assembly of an EV would require 30% less time compared to gasoline due to there being less moving parts in the drive train [66]. A hydrogen fuel cell vehicle (HFCV), on the other hand, requires more time to assemble due to the use of complex technologies (i.e., fuel cells and safety devices). However, the assembly time is expected to reduce with mass production and improvements in automation, as has occurred with the gasoline engine [67,68]. The time required for assembly also varies with the size of the plant, number of cars produced per year, and vehicle model [69]. The job creation through vehicle assembly was thus assumed to be the same for all vehicles to provide a fair comparison.

The conservation of fossil fuel (CFF) by using an alternative fuel was measured using Equation (10) in the Supplementary Materials: Section B. Human health, on the other hand, was assessed based on the difference in the exhaust emissions of gasoline and alternative fuel vehicles per VKT as mentioned during the indicator selection section. For the qualitative indicator (i.e., occupational health and safety, OHAS), a 5-point Likert scale was used to collect scores from the respondents in the supply chains of alternative fuels, where 1 indicated the least satisfaction and 5 indicated 100% satisfaction [5,31]. If any respondent scored less than 5, the reason was asked (or what would make them score 5) [5]. Approval regarding the survey from Curtin University Human Research Ethics Committee (approval number:

HRE 2019-0642) was received in September 2019. The survey was conducted over a period of eight months from September 2019 to April 2020 to collect the responses.

2.5.3. Economic Indicators

The cost data are summarized in Section C of the Supplementary Materials (Table S2). The base year for economic analysis was 2018, and the costs for other years were either inflated or deflated to 2018 AUD. The following considerations were made during the calculation of economic indicators:

- Assumptions regarding the cost per unit of corresponding traditional fuel is one of the deciding factors for the sustainability assessment of alternative fuels. The gasoline price was close to 150 cents/L in 2013 and decreased afterwards but started to increase again in 2018 [70]. To capture this variation, the average gasoline price (135.42 cents/L) for the last 7 years was considered [70].
- Zero economic allocation was provided to cereal straw during the environmental assessment [2]. This was done because the cereals were solely cultivated for food production in WA and, therefore, no cost was allocated for straw production. However, costs associated with straw harvesting, handling, nutrient replacement, and transportation of straw to the processing plant were considered. Additionally, a nominal profit margin of around 11 AUD/tonne of straw was considered for the farmers for their contribution to bioenergy [43].
- The cost relating to different activities for growing mallee in WA was based on the studies by Wu et al. [58] and Stucley et al. [43]. This is shown in Section C of the Supplementary Materials (Table S2). The estimated cost of mallee production was around 53.45 AUD/green metric tonne.
- The capital cost of ethanol plants was calculated based on a 100 ML/year capacity facility with a project life of 20 years [61]. The capital cost for starch and cellulosic (i.e., straw in this study) ethanol plants in Australia was assumed to be AUD 97 M and AUD 194 M, respectively [61].
- A 50,000 kg/day hydrogen production plant (approximately equivalent to ethanol plant capacity) with a project life of 35 years was considered [62,71]. An initial capital cost of around 144 M AUD for the hydrogen plant was assumed based on an estimation by the Commonwealth Scientific and Industrial Research Organization Australia [71]. With the initial investment, a 15% replacement cost was assumed every 7 years due to the fuel cell stack [62]. All the capital costs were based on 100% debt with 7% interest rate over the life cycle of the project [71].
- The costs of utilities, such as electricity, water, and gas, for different purposes are shown in Table 3. Water price for non-residential customers varies in WA due to the associated cost of supplying water in different regional locations [72]. The electricity costs of hydrogen and ethanol plants were based on the price for industrial customers received from a local supplier, Synergy [73].
- Hydrogen delivery through tube tankers was modelled by calculating the costs associated with the price of the truck, tube tankers, the required amount of diesel, and the driver's wage [76]. The calculated cost was found to be 2.30 AUD/kg. This cost of hydrogen distribution was found to be very close to 2.24 AUD/kg, which was the estimate received from a local transportation and logistics company [77].
- All the cost values were inflated by 3% every year [78] until the end of the project life (e.g., 20 years for ethanol and 35 years for hydrogen). The discounted cash flow analysis was used to determine the present value of the future costs associated with fuel production using Equation (11) [78]. LCC per VKT of fuel was then calculated using a capital recovery [79] factor as shown in Equations (12)–(14) in Supplementary Materials: Section B.
- The producer margin of locally produced liquid fuel (i.e., ethanol in this study) was considered to be 0.10 AUD/L [80], which was around 10% of the production cost. A similar profit margin (i.e., 10% of production cost) was also assumed for hydrogen fuel.
- An excise rate of 26.21% for ethanol in Australia was incorporated in the analysis. It has been assumed that there would not be any excise on hydrogen as both the Australian federal government and WA state governments were ready to support the penetration of hydrogen in different settings

within the country [81]. A GST (goods and service tax) of 10%, however, was applied to both the fuels for base case analysis as it was usually added to fuel costs in Australia [82].

- The cost of an ethanol-blended gasoline vehicle was assumed to be the same as for the gasoline vehicle [73,83]. Costs of AUD 44,037, 39,326 and 70,650 were calculated for EV, PHEV, and hydrogen fuel cell vehicles, respectively, based on a study by Miotti et al. [26]. The price of the gasoline vehicle (i.e., AUD 26,709) was based on the market price in WA [84]. The additional vehicle cost for alternative fuel vehicles compared to the gasoline vehicle due to the changes in powertrain was considered to be paid upfront during the vehicle purchase and subjected to discounted cash flow analysis with the same inflation and discount rate as like fuel [85]. The life of a new passenger vehicle in WA was 10.23 years [2].
- For carbon reduction credits (Equation (15) in Supplementary Materials: Section B), an average value of 40 AUD/tonne of GHG emission was assumed based on Wang et al. [86]. The assumed value was consistent with the guidelines from the International Monetary Fund and the United States Environmental Protection Agency [87]. The indicator net benefit was calculated based on the difference between the costs per km of using gasoline and an alternative fuel option.

Table 3. Cost of utilities for different activities.

Items	Unit	Cost/Unit	Purpose	Reference
Electricity	AUD/kWh	0.2011 * (of which the first 10 unit/month is free)	EV and PHEV home charging	[74]
Electricity		0.5274 (peak) 0.1584 (off-peak)	Ethanol and hydrogen production plant	[74]
Desalinated water	AUD/kL	1.17	Hydrogen plant at KIA	[51]
Water for business utility at Northam		7.221	Ethanol from cereal plant	[72]
Water for business utility at Katanning		8.562	Ethanol from mallee plant	[72]
Water for business utility at KIA		3.653	Ethanol from wheat	[72]
Natural gas	AUD/GJ	9.81	Ethanol from wheat	[75]

* Usual home tariff price without subsidy: 0.29 AUD/kWh [74].

2.6. Determination of Threshold Value

The threshold value for each TBL indicator was incorporated into the framework to assess whether the sustainability performance measures had been met [88]. By considering the potential vulnerability of liquid fuel security and the current utilization level of alternative fuels, which is almost zero in the WA transport sector [7,89,90], threshold values were determined in such a way so that it would be possible to incorporate and assess further improvement strategies by identifying social, economic, and environmental hotspots [5].

A 33% reduction in GHG emission was chosen for global warming potential (GWP), as this reduction was required in the transport sector during 2020–2030 to maintain Australia's Paris agreement commitment of reducing the GHS emissions to 26–28% below 2005 levels by 2030 [89]. The minimum reduction target for EU countries is 35% [91]. Due to having no specific targets regarding the future reduction in the use of fossil fuels in WA [90], the threshold values of this TBL indicator for alternative fuels were obtained from other developed countries that experience similar socio-economic situations, for example, EU countries and the USA, as shown in Table 4. The median value of fossil fuel reduction associated with the use of ethanol, electric vehicles, and hydrogen in passenger cars was found to be 34%. For water consumption (WC), the median values of WC for similar regions in terms of water stress and socio-economics, such as the nine European countries including UK, Italy, and Germany,

and almost half of the USA (Table 4) that maintain standard practices during the production and use of alternative fuels, were considered for ascertaining the threshold value. Similarly, for land use (LU), alike regions in terms of land availability, such as Canada and the USA, were chosen to develop the threshold values.

Table 4. Threshold values for TBL indicators.

Indicators	Thresholds	Source of Information	Description
GWP	Reduction $\geq 33\%$	Climate Council, Australia [89]	Alternative fuels should reduce at least 33% of GWP impact compared to gasoline in Australia.
FFD	Reduction $\geq 34\%$	Studies from regions socio-economically similar to WA [92–100].	At least a 34% FFD reduction is required to meet the criteria compared to base case gasoline.
WC	$\leq 1.48 \times 10^{-3} \text{ m}^3/\text{VKT}$	Studies from similar regions to WA in terms of water stress and socio-economics [96,101–103].	Water consumption of alternative fuel cannot exceed $1.48 \times 10^{-3} \text{ m}^3/\text{VKT}$
LU	$\leq 1.73 \times 10^{-6} \text{ ha.a/VKT}$	Studies from similar regions to WA in terms of land availability and socio-economics [2,95–97,100,104].	Land use of alternative fuels should be less than or equal to $1.73 \times 10^{-6} \text{ ha.a/VKT}$
local job creation	$\geq 1.09 \times 10^{-3} \text{ man-hours/km}$	O’Connell et al. [34]	The total job creation has to be $\geq 1.09 \times 10^{-3} \text{ man-hours/km}$.
CFF	$\geq 1.00 \times 10^0 \text{ MJ/VKT}$	Median value of studies from regions socio-economically similar to WA [92–100].	Alternative fuels in WA should conserve equal to or more than $1.00 \times 10^0 \text{ MJ/VKT}$ of fossil fuel.
OHAS	5 (100% agreement from the respondents)	Based on the methodology of Hoque et al. [5]	Acceptance levels were measured based on a 5-point Likert scale where 5 is the required level of acceptance.
HH _{VEE}	alternative fuel vehicle’s emission < gasoline vehicle’s emission	Based on O’Connell et al. [34]	One of the reasons for choosing alternative fuel is to reduce tail pipe emissions, which should be lower than the existing option (gasoline in this instance).
LCC	$\leq 8.13 \times 10^{-2} \text{ AUD/VKT}$	Based on the cost of local gasoline use [34]	The cost of alternative fuel should be compared with the existing option (gasoline in this study) to determine its financial viability.
CRC	$\geq 3.30 \times 10^{-3} \text{ AUD/km}$	Based on Climate Council, Australia [89] and 40 AUD/tonne carbon price [86].	With the CRC of 40 AUD/tonne, the credit should be at least $3.30 \times 10^{-3} \text{ AUD/km}$ based on the Climate Council of Australia.
Net benefit	Cost of using gasoline per VKT - Cost of using alternative fuel per VKT ≥ 0	O’Connell et al. [34]	The cost of alternative fuel should be compared with the existing option (gasoline in this study) to determine its financial viability.

The indicator OHAS met the sustainability criteria when all the respondents scored 5 (i.e., 100%) [5,31]. Based on 40 AUD/tonne of GHG emission as the cost and a 33% GHG emission reduction target for Australia [89], a carbon reduction credit (CRC) of $3.30 \times 10^{-3} \text{ AUD/km}$ was selected as the minimum criterion for the alternative fuels to be sustainable. Job creation should increase due to the implementation of alternative fuels in a region [64]. The threshold value for job creation (job creation $\geq 1.07 \times 10^{-3} \text{ man-hours/km}$) was considered for this study based on a study by O’Connell et al. [34]. As vehicle assembly was considered to happen locally in WA, job creation potential through fuel life cycle and vehicle assembly was added to determine the threshold value. The cost of using gasoline (AUD/VKT) in WA was used as the threshold for the LCC of alternative fuels [34,105–109]. Similarly, the difference between the costs of using gasoline and alternative fuel per VKT was used as the threshold for the net benefit indicator, as shown in Table 4.

3. Interpretation of Base Case Results

The base case results of the environmental and social life cycle assessments and the life cycle costing analysis are discussed in the forthcoming sections. In addition, a comparison of results with the threshold values has also been made to realize the sustainability performance.

3.1. Environmental Life Cycle Assessment

The environmental life cycle assessment method as recommended in the International Organization for Standardization (ISO) 14040-44 [110,111] standard was used to determine the environmental indicators for the study. Australian indicators set allowed us to calculate all environmental indicators except for FFD. Besides, the CML method was used to calculate the FFD [13].

Table 5 shows the base case environmental results and the performance of different fuels based on threshold values. Hydrogen did not meet the environmental target mainly due to its high electricity requirements during the production stage (54 kWh/kg H₂) [2]. E65 met the criteria in regard to GWP, FFD, and WC indicators because of its low resource requirements to grow ethanol feedstocks, especially cereal straw (53% contribution in the blend), which was a by-product of cereal production. E65, however, did not meet the land use criterion due to its land requirements to grow ethanol feedstocks. The farming of ethanol feedstocks (all three feedstocks in this study) in WA is rainfed, which reduces a large amount of the irrigation requirements compared to EU nations and the USA [2,112]. Besides, around 60% of electricity in WA was produced from natural gas and renewable sources [2], which require less water than nuclear plants predominantly used in EU nations and coal-based electricity used in Victoria and New South Wales [113]. EV and PHEV also met the criterion for WC because of their low requirements for water to generate electricity in WA. EV failed to meet the GWP threshold (i.e., 29% lower than gasoline, as it needs to reduce a further 4% to meet the criterion). The electricity that was used for EV charging was the main hotspot (1.21×10^{-1} kg CO₂/VKT) as it contributes 67% of the total GWP. The reason for PHEV having a higher impact than EV in the GWP and FFD indicators was the phased use of gasoline (i.e., PHEV used 50% electricity and 50% gasoline in WA [2]) as local electricity was found to use cleaner fuel than gasoline. As a result, PHEV failed to meet the GWP and FFD criteria. The combustion of gasoline (44%) and the use of electricity (31%) during the vehicle use stage were the main hotspots for the GHG emission. The usage phase, which consumes fuel (gasoline: 49% and electricity: 31%), was also the main reason for higher FFD emissions for PHEV.

Table 5. Environmental performances of different alternative fuel options.

Indicators	Options	Results	Remarks
GWP	Hydrogen	5.57×10^{-1} CO ₂ /VKT	120.00% higher than gasoline; fails to meet the criterion
	E65	1.49×10^{-1} CO ₂ /VKT	41.03% lower than gasoline; meets the criterion
	EV	1.80×10^{-1} CO ₂ /VKT	28.92% lower than gasoline; fails to meet the criterion
	PHEV	2.17×10^{-1} CO ₂ /VKT	14.10% lower than gasoline fails to meet the criterion
FFD	Hydrogen	5.34 MJ/VKT	83% higher than gasoline; fails to meet the criterion
	E65	1.74 MJ/VKT	40% lower than gasoline; meets the criterion
	EV	1.77 MJ/VKT	39.40% lower than gasoline; meets the criterion
	PHEV	2 MJ/VKT	31.36% lower than gasoline, fails to meet the criterion
WC	Hydrogen	1.49×10^{-3} m ³ /VKT	Fails to meet the criterion
	E65	1.12×10^{-3} m ³ /VKT	meets the criterion
	EV	4.89×10^{-4} m ³ /VKT	meets the criterion
	PHEV	5.35×10^{-4} m ³ /VKT	meets the criterion
LU	Hydrogen	2.83×10^{-6} ha.a/VKT	Fails to meet the criterion
	E65	5.72×10^{-6} ha.a/VKT	Fails to meet the criterion
	EV	1.07×10^{-6} ha.a/VKT	meets the criterion
	PHEV	6.23×10^{-7} ha.a/VKT	meets the criterion

3.2. Social Life Cycle Assessment

Social performances of alternative fuels are shown in Table 6. Ethanol was found to be the best-performing fuel with regards to job creation due to having labour-intensive upstream activities including farming, feedstock processing, and ethanol production. Figure 2 shows that around 60% of the jobs could be created (1.35×10^{-3} man-hours/L ethanol) during the conversion of feedstocks to ethanol and the remaining 40% were created from establishment (1.26×10^{-4} man-hours/L ethanol), harvest (4.49×10^{-4} man-hours/L ethanol), post-harvest management (4.46×10^{-5} man-hours/L ethanol), wood transportation to the plant (2.32×10^{-4} man-hours/L ethanol), and ethanol transportation to the blending station (5.39×10^{-5} man-hours/L ethanol). Job creation potential for E65 in this study (1.13×10^{-3} man-hours/VKT) is, however, 4.2% lower than hydrogen due to the 65% replacement of imported gasoline in WA. Generating the electricity that is required for hydrogen production and storage (1.04×10^{-4} man-hours/VKT) and the hydrogen production plant (4.48×10^{-5} man-hours/VKT) were the two main job creation avenues for hydrogen fuel. Additionally, 1.15×10^{-7} job man-hours can be created from the water desalination that is required to supply water to the hydrogen production plant. Moreover, 1.042×10^{-3} man-hours working opportunity per VKT can also be created locally by the vehicle assembly plant for all fuel options. EV failed to meet the criterion in terms of job creation by a small margin due to less labour-intensive electricity for charging. The PHEV also failed to meet the criterion for local job creation mainly due to the use of imported gasoline replacing 50% of the locally generated electricity.

Table 6. Social performances of different alternative fuel options.

Indicators	Options	Results	Remarks
local job creation	Hydrogen	1.19×10^{-3} man-hours/VKT	Meets the criterion
	E65	1.13×10^{-3} man-hours/VKT	Meets the criterion
	EV	1.07×10^{-3} man-hours/VKT	Fails to meet the criterion
	PHEV	1.06×10^{-3} man-hours/VKT	Fails to meet the criterion
CFF	Hydrogen	-2.43×10^0 MJ/VKT	Fails to meet the criterion
	E65	1.17×10^0 MJ/VKT	Meets the criterion
	EV	1.15×10^0 MJ/VKT	Meets the criterion
	PHEV	9.1×10^{-1} MJ/VKT	Fails to meet the criterion
OHAS	Hydrogen	5	Meets the criterion
	E65	5	Meets the criterion
	EV	5	Meets the criterion
	PHEV	5	Meets the criterion
HH _{VEE}	Hydrogen	There is no tail pipe CO, PM, or NO _x emission	Meets the criterion
	E65	CO $\approx 1.77 \times 10^{-1}$ gm/VKT	Lower than gasoline (2.75×10^{-1} gm/VKT); meets the criterion
		NO _x $\approx 3.57 \times 10^{-3}$ gm/VKT	Higher than gasoline (2.00×10^{-3} gm/VKT); fails to meet the criterion
		PM $\approx 6.58 \times 10^{-4}$ gm/VKT	Lower than gasoline (1.85×10^{-3} gm/VKT); meets the criterion
	EV	There is no tail pipe CO, PM, or NO _x emission	Meets the criterion
	PHEV	At least a 50% reduction * of tail pipe CO, PM, and NO _x emissions compared with gasoline	Meets the criterion Meets the criterion Meets the criterion

* Electricity is used during 50% of the travel time. The fuel consumption of PHEV (0.04 L/km) is also lower than gasoline (0.06 L/km) during battery sustaining mode. Therefore, CO, PM, and NO_x reduction could be at least 50% compared with gasoline.

All the fuel options were found to meet the OHAS threshold. In total, 112 responses in terms of OHAS were collected from the stakeholders of the supply chains for the four alternative fuels (i.e., 28 responses for each fuel). All the respondents for E65 provided 100% satisfaction (i.e., 5) and explained that the farming and conversion of feedstock to ethanol were safer than the production of gasoline. In the United States, for example, the worker fatality rate in oil and gas industries (2007 to 2016) was six times higher than the industry average [114]. Contact with equipment, exposure to harmful environments such as silica, fires and explosions, and falls from elevated areas are some of the possible fatal events reported in the oil and gas industry, though significant improvements have already been achieved in many areas [114]. Like E65, EV also met the OHAS threshold. For the usage stage of the EV life cycle, two of the respondents recommended improvements in the battery cooling system to improve the battery performance during hot summer days, enabling the prevention of quicker degradation of the battery, but they still provided the required safety score. Research has shown that there are some concerns about the safety of EV batteries from fire due to some recent EV fire events, although it is unclear if the fire susceptibility of the vehicle is due to the EV battery issues [115,116]. The results from the EU Everyday Safety Project (EVERSAFE) revealed that the safety of EV was quite high and almost close to the levels of conventional vehicles [117]. EV manufacturers, however, have acknowledged the issue and have significantly improved the battery safety through the revision of charging, battery management systems (BMSs), thermal management, and mechanical crash protection [117]. Additionally, “cut loop” systems that deactivate all the high-voltage connections during emergencies have also been incorporated into EVs [115]. More development pertaining to battery safety (e.g., non-flammable electrolytes, better thermal management, innovative BMSs, integrated fire extinguishing capability, etc.) is also being researched for the next generation of batteries [115–117].

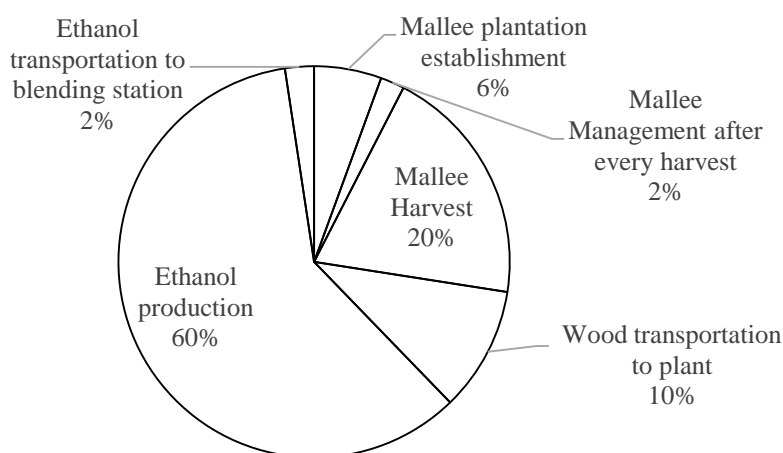


Figure 2. Job creation for 1 L ethanol supply to terminal gate from mallee.

There is some fear regarding the safety of hydrogen vehicles across Australia. Hydrogen is a highly inflammable gas that is stored in a high-pressure tank inside the vehicle [118]. This safety fear is mainly due to people’s unfamiliarity with hydrogen fuel, unlike gasoline [119]. Hydrogen has been used for oil refining and fertilizer production for many decades with an exemplary safety record [119]. All the respondents for hydrogen fuel were 100% satisfied with the safety procedures. Furthermore, there are examples showing that hydrogen is already suitably implemented as a transport fuel in several countries with the execution of safety protocols [120]. There are already millions of hydrogen vehicles on the roads in the USA, Japan, South Korea, and China [120]. WA’s local governments are liaising with the federal government and the countries with hydrogen experiences to devise safety protocols for hydrogen production and use [81]. Sørensen [67] found that the occupational health and safety scores with respect to death, severe injury, and stress/inconvenience during driving were the same for both HFCVs and gasoline vehicles. Government campaigns, demonstration projects,

promotional activities, and training are required to increase awareness among the community [118,119]. Three hydrogen buses were included in the WA public transport service trial during the years 2004 to 2007. There were no health and safety issues reported during this trial. People were familiarized with hydrogen, and public acceptance of hydrogen use was increased after the trial [121]. Conservation of fossil fuels, on the other hand, was found to be negative for hydrogen fuel (-2.42 MJ/VKT) due to the large amount of energy required during its production stage. Similarly, PHEV also failed to meet the criteria for conservation of fossil fuel, amounting to 0.9 MJ/VKT, due to the use of gasoline during 50% of the travel time as mentioned earlier.

There are no tailpipe CO, PM, or NO_x emissions from EV and HFCV, which fulfils the social sustainability objective of HH_{VEE} . PHEV also met the threshold in regard to HH_{VEE} by reducing the gasoline consumption through the use of electricity during 50% (base case scenario) of its travel time. Different results related to emissions from ethanol-blended gasoline were found in the literature, which was mainly due to differences in the test procedures, vehicle models, and engine parameters. Secondly, most of these studies did not investigate the complete fuel range from E0 to E85. Due to these reasons, the data used in this study were taken from a recent investigation conducted by Jin et al. (2017) [122] for a passenger car, which took into account the complete fuel range and all possible emissions for fair comparison. Moreover, engines were also calibrated to match the different ethanol blends from E0 to E85 during the test. The test vehicle was also comprised of a three-way catalytic converter as an after-treatment device like existing gasoline cars on the road. NO_x emissions for E65 failed to meet the criterion as NO_x was found to increase compared to gasoline. Further investigations are, however, required regarding the NO_x emission, as both increasing and decreasing trends of NO_x relative to gasoline have been found in the literature when the percentage of ethanol is increased in the gasoline-ethanol blend [122,123].

3.3. Life Cycle Costing

Life cycle costings of E65, EV, PHEV, and hydrogen and their comparisons with gasoline are shown in Figure 3. Based on the current scenario, E65 fuel was found to be the best option (0.096 AUD/VKT) but was still 1.5 cents higher than gasoline per VKT due to the higher fuel consumption of E65 compared to gasoline. There was no additional cost for E65 from the vehicle as the costs of both gasoline and E65 were assumed to be similar [73]. The costs of ethanol production from wheat, cereal straw, and mallee were around 0.71 , 1.01 , and 1.10 AUD/L, respectively, without the producer profit margin. The findings of this study were similar to a previous study, which found that the ethanol production from wheat and wood could be around 0.70 AUD/L and 1.07 AUD/L, respectively, in Australia [61]. The fuel costs for EV and PHEV were even lower than that of gasoline mainly due to the availability of subsidized electricity tariffs for electric vehicle (EV and PHEV) owners in WA, as shown in Table 3. After the inclusion of additional vehicle cost, however, the LCCs of EV and PHEV were estimated to be 0.22 and 0.18 AUD/VKT, respectively.

Hydrogen, on the other hand, was the worst-performing fuel with regards to the LCC indicator, being around 9.5 times higher than gasoline. The base case hydrogen fuel cost for this study was calculated as 31 AUD/kg (i.e., 0.31 AUD/VKT), compared with around 21 AUD/kg in refueling stations in the USA [124]. This higher cost in WA was expected due to the 30% higher manufacturing cost in Australia compared to the USA [125]. The electricity required (54 kWh/kg H_2) during the production of hydrogen was the main contributor (82%) to its cost. Other than this, around 12.4% of the cost was from the distribution of hydrogen.

None of the fuels met the economic sustainability criteria as they failed to compete with gasoline. The fuel option E65, however, met the criterion with regard to CRC. The low levels of fertilizers and resources required to grow the ethanol feedstocks were the main reason for attaining a higher carbon reduction credit for the use of E65 in WA. As shown in Table 7, all the fuel options also failed to meet the criterion for net benefit, even after the incorporation of carbon reduction credit.

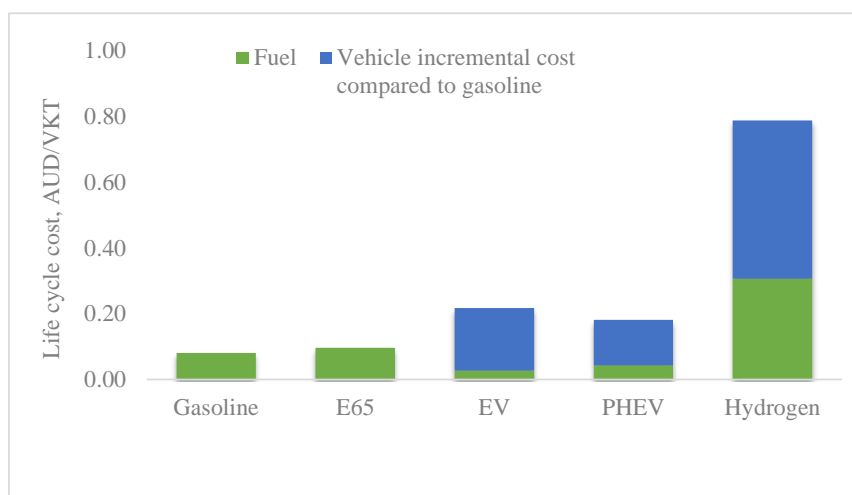


Figure 3. Life cycle costing (LCC) of different fuel options.

Table 7. Performances of different alternative fuel options in terms of carbon reduction credit (CRC) and net benefit indicators.

Indicators	Options	Results, AUD/VKT	Remarks
CRC	Hydrogen	-1.21×10^{-2}	Fails to meet the criterion
	E65	4.22×10^{-3}	Meets the criterion
	EV	2.94×10^{-3}	Fails to meet the criterion
	PHEV	1.43×10^{-3}	Fails to meet the criterion
Net benefit	Hydrogen	Without CRC -7.06×10^{-1}	Fails to meet the criterion
		With CRC -7.18×10^{-1}	Fails to meet the criterion
	E65	Without CRC -1.51×10^{-2}	Fails to meet the criterion
		With CRC -1.08×10^{-2}	Fails to meet the criterion
	EV	Without CRC -1.36×10^{-1}	Fails to meet the criterion
		With CRC -1.33×10^{-1}	Fails to meet the criterion
	PHEV	Without CRC -1.00×10^{-1}	Fails to meet the criterion
		With CRC -9.87×10^{-2}	Fails to meet the criterion

4. Improvement Strategies

Improvement strategies related to TBL sustainability were incorporated into the framework in such a way as to make them applicable in the near future in WA. Improvement strategies have been suggested in the impending sections when any indicators failed to meet the required sustainability objectives. Following the interdependencies in the framework, revised ELCA, SLCA, and LCC results are also presented.

4.1. Environmental Strategies

Hydrogen fuel did not meet the threshold of any environmental indicators. Therefore, a “hotspot” analysis was conducted based on the LCA results. This helped to identify and incorporate improvement strategies to be able to achieve the required level of environmental performance. The electricity consumption during the production of hydrogen was found to be the main environmental hotspot during the life cycle of hydrogen. Electricity generation from clean energy sources, such as renewables, was considered to treat the hotspot. WA has huge potential to produce most of its electricity (90% to 100%) from wind and solar [126,127]. The Perth desalination plant in WA, for example, uses wind-generated electricity from the 80 MW Emu Downs Wind Farm [51]. Based on WA’s future renewable hydrogen production strategy [81], a scenario with a combination of wind and solar energy (50% wind and 50% solar) was considered for electricity generation for hydrogen production.

After incorporating the strategy into the framework, as shown in Table 8, all the environmental criteria were found to be met when compared to the threshold values. The calculations related to the improvement strategies are summarized in Section D of the Supplementary Materials.

EV failed to meet the criteria with regard to the GWP indicator, and the electricity required for charging the battery was identified as the main hotspot. According to the renewable energy penetration forecast, there could be around 37% renewable energy in the WA electricity mix in the next 10 years [128]. This cleaner electricity production strategy could potentially be able to meet all the criteria for EV. In the case of PHEV, three possible strategies, namely, E10 as a replacement for gasoline, cleaner electricity for charging (as used for the EV), and a solar rooftop photovoltaic panel (180 W_p) equipped with the vehicle, were considered to treat the hotspots. E10 was proposed as no vehicle modification was required due to this fuel change [34]. The 180 W_p solar cell was proposed as this had already been applied in the Toyota Prius Prime in Japan without causing any inconvenience to users [129] and WA has an enormous solar radiation potential to charge EVs with integrated solar systems [130]. The average solar irradiation in WA was considered to be 5.30 kWh/m².day [131] to calculate the electricity generated by photovoltaic cells. The car was assumed to be exposed to the sun for at least for 2.5 h/day, which is realistic given the long sunshine hours (7.92 h/day) in WA [131]. The efficiency of the photovoltaic system was assumed to be 14% due to its low cost like rooftop photovoltaic (PV) panels [132].

Table 8. Strategies to improve the environmental sustainability performance.

Options	Strategies	Effect on Sustainability Performance
Hydrogen	Renewable electricity (wind and solar) [2,10]	GWP: 69.37% < gasoline; FFD: 65.28% < gasoline WC: 3.55×10^{-4} m ³ /km; LU: 1.64×10^{-7} ha.a/km
EV	Cleaner electricity for charging [2]	GWP: 49.86% < gasoline; FFD: 49.70% < gasoline WC: 4.80×10^{-4} m ³ /km; LU: 1.07×10^{-6} ha.a/km
PHEV	Use of E10 in place of gasoline [2] Cleaner electricity for charging [2] 180 W _p solar cells installed on the car [129]	GWP: 34.70% < gasoline; FFD: 43.57% < gasoline WC: 5.27×10^{-4} m ³ /km; LU: 6.67×10^{-7} ha.a/km
Ethanol	Ethanol blend E55 considered in place of E65	GWP: 34.51% < gasoline; FFD: 34.01% < gasoline WC: 1.06×10^{-3} m ³ /km; LU: 1.69×10^{-6} ha.a/km

E65 failed to meet the land use criterion due to the use of large amounts of land for wheat feedstock production. Of these feedstocks, grain contributing 10% of the blend (i.e., 10% ethanol from wheat) is responsible for utilizing 71% of land (5.29×10^{-4} ha.a/L), while straw contributing 53% of the blend occupies only 19% of the land (2.67×10^{-5} ha.a/L). The land use for mallee-based ethanol (3.56×10^{-4} ha.a/L) was not significant due to the small portion (2%) of ethanol in the blend. In WA, the yield of rainfed cereal (especially wheat, which accounts for 70% of cereal production) mainly depends on the amount of rainfall [133,134]. Research studies and investigations suggest that a yield gap of 3 tonne/ha [133] in WA's water-stressed wheat belt can be mitigated through different improvement strategies, such as genetic improvement, utilization of nitrogen input as required, application of bio-mineral fertilizer, prevention of damage to the grains from frost and heat by timely sowing, soil surface and residue management, crop rotation, and integrated weed control [133–136]. Yield improvement with the aforementioned strategies, however, was found to be uncertain due to the potential cost and benefit constraints in large-scale grain production [134]. The land use impact of E65 was found to be still 2 times higher than the threshold, even after the cereal yield in WA was increased from 1.9 tonnes/ha (base case) to 4.9 tonnes/ha by overcoming the yield gap of 3 tonne/ha. The E55 blend (E2 from mallee and E53 from cereal straw), however, met all other environmental criteria. It has been found that farmers are willing to plant more mallee trees in WA if there is a demand for it [137]. Therefore, it could be possible to produce an environmentally sustainable ethanol blend of more than E55 in the future in WA by utilizing a mix of mallee and straw. There could be sustainability issues from the land use impact again due to the increase of mallee in the ethanol blend. This issue, however,

can be alleviated if marginal and under-utilized land, such as the narrow belt around the current agricultural field, is utilized for biofuel feedstock production [104,138,139].

4.2. Social Strategies

All fuel scenarios that are found to be environmentally friendly are considered for social assessment. Any social changes that take place due to the environmental improvement strategies are taken into account in the following SLCA (Table 9). Job creation potential decreased by 1.12% due to the replacement of E65 with E55. This was because of the reduction in labour-intensive ethanol in the blend. The job creation potential for hydrogen, EV, and PHEV, however, increased by around 20%, 3%, and 4%, respectively, from the base case after incorporating the environmental strategies, such as renewable electricity, E10 in place of gasoline, etc. The increase in net jobs with the uptake of renewable-based electricity was similar to the findings of the Climate Council of Australia [140].

The PHEV still failed to meet the threshold value in regards to job creation potential even though Western Australia holds substantial reserves of all the required minerals for battery production for PHEV to further increase jobs [141]. Two world famous lithium processing companies, Tianqi and Albemarle, are already investing in WA for lithium processing. Three lithium processing plants were in the development phase in 2019 [141]. With its unique advantages and the growth of the EV all over the world, the WA state government has already investigated the value chain of the battery industry and is currently examining the opportunity more closely in conjunction with the federal government in order to become the world leader in the sustainable battery industry [53]. Three locations, Kwinana, Kalgoorlie, and Bunbury, had already been selected as suitable locations [141]. If the batteries were considered to be produced locally in WA, the job creation potential for EV and PHEV was increased to 1.19×10^{-3} man-hours/VKT and 1.10×10^{-3} man-hours/VKT, respectively. The PHEV met the threshold value after incorporating this strategy into the framework. The increase in job creation with this approach for hydrogen was found to be quite small (1.84×10^{-10} man-hours/VKT) due to the small battery capacity (only 1.6 kWh) compared to EV and PHEV. The indicator CFF was also increased for all the fuel options except E55 after incorporating the environmental strategies. The CFF was found to decrease with E55 mainly due to the increase of gasoline in the blend compared to E65, but it still met the sustainability criterion.

Table 9. Revised environmental and social performances of alternative fuels.

Options	Social Performance after Incorporating Environmental Strategies	Revised Results after Incorporating Social Strategies	
		Environmental	Social
Hydrogen	local job creation: 1.43×10^{-3} man-hours/VKT	GWP: 69.38% < gasoline	local job creation: 1.43×10^{-3} man-hours/VKT
	CFF: 1.90×10^0 MJ/VKT	FFD: 65.30% < gasoline	CFF: 1.91×10^0 MJ/VKT
	OHAS: 5	WC: 3.55×10^{-4} m ³ /km	OHAS: 5
	HH _{VEE} : Same as base case	LU: 1.64×10^{-7} ha.a/km	HH _{VEE} : Same as base case
EV	local job creation: 1.10×10^{-3} man-hours/VKT	GWP: 50.10% < gasoline	local job creation: 1.19×10^{-3} man-hours/VKT
	CFF: 1.45×10^0 MJ/VKT	FFD: 50.04% < gasoline	CFF: 1.46×10^0 MJ/VKT
	OHAS: 5	WC: 4.78×10^{-4} m ³ /km	OHAS: 5
	HH _{VEE} : Same as base case	LU: 1.07×10^{-6} ha.a/km	HH _{VEE} : Same as base case
PHEV	local job creation: 1.07×10^{-3} man-hours/VKT	GWP: 34.78% < gasoline	local job creation: 1.10×10^{-3} man-hours/VKT
	CFF: 1.31×10^0 MJ/VKT	FFD: 43.68% < gasoline	CFF: 1.31×10^0 MJ/VKT
	OHAS: 5	WC: 5.26×10^{-4} m ³ /km	OHAS: 5
	HH _{VEE} : Further reduction * of tail pipe emission. Minimum reduction could be around 56.6% compared to gasoline.	LU: 6.67×10^{-7} ha.a/km	HH _{VEE} : Social strategies have no effect on exhaust emission.
Ethanol (E55)	local job creation: 1.11×10^{-3} man-hours/VKT	GWP: 35.61% < gasoline	local job creation: 1.11×10^{-3} man-hours/VKT
	CFF: 1.00×10^0 MJ/VKT	FFD: 34% < gasoline	CFF: 1.00×10^0 MJ/VKT
	OHAS: 5	WC: 1.07×10^{-3} m ³ /km	OHAS: 5
	HH _{VEE} : CO $\approx 1.92 \times 10^{-1}$ gm/VKT; PM $\approx 8.18 \times 10^{-4}$ gm/VKT; NO _x emission (3.86×10^{-3} gm/km) still fails to meet the criterion due to the higher value compared to gasoline per km.	LU: 1.72×10^{-6} ha.a/km	HH _{VEE} : To make this criterion sustainable, further engine calibration and/or after-treatment devices are required for the consistent reduction of NO _x compared to gasoline.

* Electricity was used during 56.6% of the travel time after implementing the strategies (it was 50% in the base case).

The incorporated environmental strategies were not found to affect the OHAS consensus. Respondents in the electricity generating stage, for example, were consulted again regarding cleaner electricity production (environmental strategy for EV, PHEV, and hydrogen) in WA to further improve the OHAS. The respondents indicated that the OHAS would slightly increase from the base case due to the replacement of fossil fuel-based electricity. The reason for this was the reduction of the upstream fuel extraction phase (i.e., mining of coal/oil/gas). Furthermore, renewable electricity production through wind and solar reduces the risk of accidents and hazardous environments compared to thermal power plants. Similarly, OHAS for E55 also remained the same as E65 because both of these fuel options required the same supply chain during the production and use stages (i.e., using the same vehicle).

The fuel option E55 also did not meet the NO_x emission reduction target. Other studies suggest that the NO_x emission could increase or decrease with higher ethanol blends [122,123,142–145]. It can reduce by up to 30% or increase by 93% due to the replacement of gasoline with E55 [122,123,142,143]. This is mainly due to the inter-vehicle variability and test procedures [123,146]. These results clearly indicate that the reduction of NO_x with the higher ethanol blend is not consistent. For addressing this sustainability issue, the following strategies have been recommended [122,143]:

- Sophisticated engine calibration: Previous studies explain that the higher ethanol blends lean out the air-fuel mixture, which results in an increase in NO_x emission [143]. Thus, the engine control module of the vehicle needs to be able to adjust the air-fuel ratio with the amount of ethanol content in the blend [143].
- After-treatment devices: The use of exhaust gas recirculation (EGR) as an after-treatment device can also help to meet the vehicle exhaust emission standard [147,148]. It has been found that clean and cooled EGR in the gasoline engine with the aid of gasoline particulate filters (GPFs) could reduce HC, CO, NO_x, and PM without compromising fuel economy [148]. The cooled clean EGR technique decreases knocking, which enables a higher compression ratio for fuel economy although some engine power is required for cooling [148].

The social strategy regarding the local production of batteries for job creation potential also changes the environmental performances and social indicators, such as CFF, due to the interdependencies of these sustainability objectives. These relative changes, however, do not affect the sustainability decision-making process as further environmental burdens could be reduced due to avoidance of the transport of batteries from overseas. The potential reductions in transportation in terms of tonne-kilometres (tkm) for EV, PHEV, and hydrogen were 2.76×10^{-2} tkm/VKT, 8.75×10^{-3} tkm/VKT, and 1.67×10^{-3} tkm/VKT, respectively, for this strategy. The revised environmental and social performances are shown in Table 9. No further environmental changes are considered for the minor change in engine calibration for E55 fuel due to its minimal effect on life cycle emissions. A slight increase in fuel consumption (around 2%) was, however, considered based on a study by Wei et al. [147] due to the after-treatment techniques to control NO_x. After incorporating this into the framework, the fuel option E55 failed to meet the FFD and CFF indicators. Based on the hotspots in ethanol production, one more additional strategy was considered through the use of renewable electricity for enzyme production [2] in order to satisfy all the social sustainability criteria.

4.3. Economic Strategies

The costs associated with environmentally and socially sustainable scenarios (Table 9) are incorporated into the framework. The recalculated cost for E55 (0.102 AUD/VKT) was around 2.1 cents higher than the threshold (0.081 AUD/km). The cost increased slightly after switching to E55 due to the replacement of cheap wheat-based ethanol with costly lignocellulosic ethanol in the blend. Plant cost was identified as one of the economic hotspots during ethanol production. The fuel option E55 met the threshold value in regard to all economic indicators after incorporating the following three strategies:

- Long-term soft loan for the capital cost at the rate of 3% interest rate over the project life;

- Renewable energy projects received capital subsidy in Australia [80]. It has been proposed that 10% of the capital cost (around AUD 19.5 M) of the ethanol project would be funded by the government grant [149];
- Removal of excise rate on ethanol [80] and GST on E55, which would reduce 10% of the fuel cost for the end consumer [150].

The economic hotspot for hydrogen fuel was due to the large amount of electricity consumption during its production. Oxygen that was produced from the hydrogen plant as a by-product was utilized as an economic improvement strategy to increase the revenue. This O₂ can be used locally in aquaculture, waste treatment plants, and industrial furnaces [71,151]. Around 5% of the hydrogen production plant cost was eliminated with this strategy [151,152]. Solar and wind-based electricity was used as an improvement strategy, as shown in Section 4.1, to satisfy the environmental criteria. As indicated in a study by Bruce et al. [71], wind and solar-based low-carbon renewable electricity for hydrogen production plants could be possible in Australia, as shown in Table 10.

Table 10. Possible low-cost renewable electricity for hydrogen production plants in Australia.

Options	Description	Expected cost [71]
1	Hydrogen plants use electricity from the network, but low-emission electricity is still possible through power purchase agreements (PPAs). PPAs help buyers to secure low-priced renewable electricity from remote area power supply systems that are usually operated by wind and solar plants in Australia through long-term contracts [153,154]. The agreed price may vary up to a certain level based on the spot price in the national electricity market [153].	Depending on the contract and government support, the average electricity price in Australia could be as low as 6 cents/kWh for generating electricity from renewable wind and solar.
2	Electricity is considered to be supplied from a renewable energy farm in the vicinity of hydrogen plants.	The estimated cost could be the same as option 1 (i.e., 6 cents/kWh).
3	Due to the increasing trend of renewable electricity, surplus renewable electricity from the grid will be available as “curtailed renewable energy” in the grid.	The price is estimated to be low (2 cents/kWh) for this curtailed electricity due to the low demand for this surplus electricity.

For the continuous production of hydrogen, option 1 from Table 10 was considered for this study due to its high capacity factor. Additionally, the hydrogen plant can gain competitive advantages by using option 3 when it is available. With a 10% capital subsidy, a soft loan scheme of 3% over the life of the project, as well as the removal of GST and the utilization of the by-product oxygen, it was shown that the hydrogen fuel cost was similar to gasoline per VKT, provided that the hydrogen production plant received electricity at the rate of 8.3 cents/kWh. This assumption of electricity cost was also consistent with the latest wholesale electricity spot price in the Australian national electricity market [155]. The estimated costs after the implementation of each strategy are provided in Section D of the Supplementary Materials. The strategy related to utilization of oxygen during hydrogen production as a by-product had interdependencies with environmental and social sustainability in the framework. This small amount of change, however, did not influence the ELCA and SLCA indicators significantly. For example, less than 1% reduction was observed for the overall life cycle environmental emission. The electricity cost at the domestic user level was assumed to be the same, even after the penetration of 37% renewables into the grid as the base case [156,157]. Thus, the fuel cost of the EV remained the same as the base case. After incorporating the environmental and social strategies, the fuel cost of the PHEV was, however, decreased from 0.043 AUD/VKT to 0.040 AUD/VKT due to the reduction of gasoline use per km.

The EV, PHEV, and HFCV, however, did not meet any of the economic criteria due to their high vehicle cost. To meet all the economic criteria for EV, PHEV, and HFCV, around 13.58, 9.67, and 48.05 cents/VKT of financial subsidies are still required. The subsidies are essential for a few years at the initial stages to enable market penetration [158,159]. For example, Norway was the first country that

introduced incentives on electric and hybrid electric vehicle acquisition back in the 1990s, and the country is currently the world leader based on market share of EV sales [160]. Germany, Sweden, France, China, and the USA are also among the most EV-using countries. The initial subsidies on EVs provided by these countries were between AUD 5000 and AUD 16,000 in 2019 [161]. The following strategies in WA are expected to ease the penetration of EV and PHEV:

- The removal of GST on vehicle purchases would provide savings of around AUD 4000 on EV and AUD 3575 on PHEV.
- A fifty percent subsidy on vehicle registration can generate around AUD 4000 benefit over the life of the vehicle. This subsidy comprises the license fee, recording fee, insurance duty, and GST but will not include insurance because injury cover is required for driver and passenger wellbeing [162].
- Currently, there is no import duty on passenger vehicles in Australia from some countries, including Japan and the USA, under the free trade agreement. Inclusion of an import duty of around 10% on gasoline vehicles can reduce the difference in cost between gasoline and alternative fuel vehicles to AUD 1000.
- The remaining amount of around AUD 4200 for EV and AUD 1100 for PHEV can be covered either by direct subsidy and/or tax benefits for the EV owner.
- Some in-kind benefits, such as access to bus lanes, priority parking in shopping centres, and reserved public parking locations, may popularize EVs and PHEVs in WA [163–165].

Hydrogen, on the other hand, was the more environmentally friendly transport fuel compared with electricity when hydrogen was produced by renewable electricity. After incorporating all the economic strategies, the hydrogen fuel cost was found to be similar to that of gasoline as well. Hydrogen as a transport fuel, however, may not be sustainable at this stage in WA due to the high vehicle cost. Supply chain improvement, mass production, and further research could bring the cost of HFCV close to gasoline in 2030 [71]. During the breakdown of cost, it appeared that just two components of HFCV (fuel cell and hydrogen tank) contribute around 70% of the cost of the vehicle [26]. More research and development on HFCV are required to reduce the cost of these two components. Constructing hydrogen infrastructures is another barrier to hydrogen-based transportation, which the WA government needs to build from scratch unlike EV infrastructures. To kick start hydrogen transportation in WA, hydrogen vehicles could be included in the government fleets and governments need to start establishing infrastructures, such as hydrogen refueling stations.

4.4. Summary Results of the LCSA Framework for Western Australian Transport Fuel

The LCSA framework has been used successfully to assess alternative transport fuels for Western Australia. The framework includes fuel selection; indicator selection according to local needs; data collection; ELCA, LCC, and SLCA assessments; determination of threshold values for sustainability decisions; and cleaner production strategies to achieve TBL sustainability. The framework enables an investigation into the base case sustainability implications of potential fuel options for the state and finding suitable strategies to meet the sustainability objectives. The framework reveals that three options, namely, ethanol-gasoline blend E55, EV, and PHEV, would be sustainable in WA with the recommended cleaner production strategies and financial assistance, as shown in Table 11. Hydrogen fuel showed better environmental and social performance when hydrogen was produced from renewable energy. The hydrogen fuel option, however, was found to be unsustainable due to the high cost of HFCV.

Table 11. Final outcome of Hoque et al.'s framework for transport fuel in Western Australia (WA).

Options	Base Case Sustainability Issues	Sustainability Improvement Strategies	Implications of Improvement Strategies			Final Status of Sustainability
			Environmental	Social	Economic	
Hydrogen +	Fails to meet all environmental, one social (CFF), and all economic indicators.	<ul style="list-style-type: none"> Renewable electricity (solar and wind) for hydrogen production Utilization of oxygen by-product from hydrogen production plant Soft loan for the plant capital cost (3% interest rate over the life of the project) Electricity for the hydrogen production plant at the rate of 8.3 cents/kWh through PPA Removal of GST on hydrogen purchase for the public user No economic strategies were considered for HFCV due to its high cost 	Meets all the criteria GWP: $69.38\% < \text{gasoline}$ FFD: $65.30\% < \text{gasoline}$ WC: $3.55 \times 10^{-4} \text{ m}^3/\text{km}$ LU: $1.64 \times 10^{-7} \text{ ha.a/km}$	Meets all the criteria local job creation: 1.43×10^{-3} man-hours/VKT CFF: $1.91 \times 10^0 \text{ MJ/VKT}$ OHAS: 5 HH _{VEE} : No tail pipe CO, PM, or NO _x emission	Fails to meet LCC and net benefit criteria LCC: $5.62 \times 10^{-1} \text{ AUD/VKT}$ CRC: $7.02 \times 10^{-3} \text{ AUD/VKT}$ Net benefit without CRC: $-4.80 \times 10^{-1} \text{ AUD/VKT}$ Net benefit with CRC: $-4.73 \times 10^{-1} \text{ AUD/VKT}$	Economic sustainability was not achieved due to the high cost of HFCV.
EV	Fails to meet one environmental (GWP), one social (local job creation criteria), and all economic indicators.	<ul style="list-style-type: none"> Cleaner electricity (grid with 37% renewable electricity) for charging EV The removal of GST on EV purchase 50% subsidy on EV registration Inclusion of import duty on gasoline vehicle Around 4200 AUD of direct subsidy and/or tax benefits for EV owner 	Meets all the criteria GWP: $50.10\% < \text{gasoline}$ FFD: $50.04\% < \text{gasoline}$ WC: $4.78 \times 10^{-4} \text{ m}^3/\text{km}$ LU: $1.07 \times 10^{-6} \text{ ha.a/km}$	Meets all the criteria local job creation: 1.19×10^{-3} man-hours/VKT CFF: 1.46 MJ/VKT OHAS: 5 HH _{VEE} : No tail pipe CO, PM, or NO _x emission	Meets all the criteria LCC: $8.13 \times 10^{-2} \text{ AUD/VKT}$ CRC: $5.07 \times 10^{-3} \text{ AUD/VKT}$ Net benefit without CRC: $0.00 \times 10^0 \text{ AUD/VKT}$ Net benefit with CRC: $5.07 \times 10^{-3} \text{ AUD/VKT}$	All three dimensions of sustainability were achieved.
PHEV	Fails to meet two environmental (GWP and FFD), two social (local job creation and CFF), and all economic indicators.	<ul style="list-style-type: none"> Use of E10 in place of gasoline Cleaner electricity for charging as with EV 180 Wp solar PV panel attached on the vehicle to reduce use of liquid fuel Local production of battery in WA The removal of GST on PHEV purchase 50% subsidy on PHEV registration Inclusion of import duty on gasoline vehicle Around 1100 AUD direct subsidy and/or tax benefits for PHEV owner 	Meets all the criteria GWP: $34.78\% < \text{gasoline}$ FFD: $43.68\% < \text{gasoline}$ WC: $5.26 \times 10^{-4} \text{ m}^3/\text{km}$ LU: $6.67 \times 10^{-7} \text{ ha.a/km}$	Meets all the criteria local job creation: 1.10×10^{-3} man-hours/VKT CFF: $1.31 \times 10^0 \text{ MJ/VKT}$ OHAS: 5 HH _{VEE} : Vehicle exhaust emission (CO, PM, and NO _x) lower than gasoline. Vehicle runs on electricity during 56.6% of its travel time after implementing the strategies.	Meets all the criteria LCC: $8.13 \times 10^{-2} \text{ AUD/VKT}$ CRC: $3.52 \times 10^{-3} \text{ AUD/VKT}$ Net benefit without CCR: $0.00 \times 10^0 \text{ AUD/VKT}$ Net benefit with CCR: $3.52 \times 10^{-3} \text{ AUD/VKT}$	All three dimensions of sustainability were achieved.

Table 11. Cont.

Options	Base Case Sustainability Issues	Sustainability Improvement Strategies	Implications of Improvement Strategies			Final Status of Sustainability
			Environmental	Social	Economic	
E65 *	Fails to meet one environmental (land use), one social (HH_{VE} : NO_x emission for E65 was found to be higher than gasoline), and two economic (LCC and net benefit) indicators.	<ul style="list-style-type: none"> E55 to be considered in place of E65 by excluding land-intensive wheat-based ethanol Renewable electricity for enzyme production Engine control strategy and after-treatment device to reduce the NO_x emission compared to gasoline Soft loan (3% interest rate) for the capital cost over the period of project life 10% subsidy on plant capital cost Removal of excise duty on ethanol Removal of GST on E65 for the user 	Meets all the criteria GWP: $35.61\% < \text{gasoline}$ FFD: $34.00\% < \text{gasoline}$ WC: $1.07 \times 10^{-3} \text{ m}^3/\text{km}$ LU: $1.72 \times 10^{-6} \text{ ha.a/km}$	Meets all the criteria local job creation: $1.11 \times 10^{-3} \text{ man-hours/VKT}$ CFF: $1.00 \times 10^0 \text{ MJ/VKT}$ OHAS: 5 HH_{VEE} : Tail pipe CO and PM emissions are lower than gasoline. Consistent NO_x emission reduction compared to gasoline is also possible with engine control strategies and after-treatment devices.	Meets all the criteria LCC: $8.13 \times 10^{-2} \text{ AUD/VKT}$ CRC: $3.61 \times 10^{-3} \text{ AUD/VKT}$ Net benefit without CCR: $0.00 \times 10^0 \text{ AUD/VKT}$ Net benefit with CCR: $3.61 \times 10^{-3} \text{ AUD/VKT}$	E55 * meets all three dimensions of sustainability.

⁺ Hydrogen fuel meets the OHAS indicators, but a standard safety protocol for hydrogen production and use needs to be devised. Moreover, training and a promotional campaign by the government are also required. * Considering E55 in place of E65 to meet the environmental criteria. Further investigation is required regarding tail pipe NO_x emission when the vehicle runs on E55. Consistent reduction of NO_x compared to gasoline needs to be ascertained with the sophisticated engine control and after-treatment strategies as mentioned in the improvement strategy column to meet the human health criterion.

The suggested strategies, for example, the production of alternative fuels with environmentally friendly cleaner alternatives, financial incentives for alternative fuel production and alternative vehicle purchase, etc., are common and have been incorporated in such a way so that their objectives are achievable in the near future locally in WA. For example, using renewable energy for hydrogen production and cleaner grid electricity (i.e., with 37% renewables) for EV charging could help to meet all the environmental and social criteria for the fuels. The implementation of these strategies is viable in WA due to having a large amount of wind and solar energy potential [81,140]. The strategy of local battery production is suggested for the PHEV to meet the local job creation criterion, as WA is in a unique position for sustainable battery production [53]. The strategy of local battery production also helps other fuel options, especially EV due to its larger battery, to generate more jobs locally in WA. Furthermore, the financial incentives that are already in place in several countries have been suggested for electric vehicles to make them economically competitive in relation to gasoline [161]. Similarly, economic support for biofuel production and use is also common in various countries in the world [166]. Improvement strategies are determined in this study to materialize the basis of the framework as this could assist policymakers to implement alternative fuels in Western Australia. The framework is highly flexible as it allows fuel selection and accommodates scenario analysis to address the region-specific needs and preferences.

5. Conclusions

The LCSA framework has been practically implemented successfully for alternative transport fuels in WA. Four alternative energy sources, namely, ethanol (E65), hydrogen, electricity, and electricity-gasoline hybrid, were selected based on the availability of local resources. The framework reveals that none of the fuels are sustainable in the base case as all of them failed to meet the criteria for one or more TBL indicators. Ethanol E65 was unsuccessful in meeting the land use criterion due to the higher land requirement during the production of feedstock compared to other fuel options. EV and PHEV failed to meet the GWP criterion by a margin of 4% and 19% when compared to the threshold value. Both the electric vehicle options also failed to meet the job creation indicator. Except for local job creation, human health, and OHAS, hydrogen fuel failed to meet the TBL indicators mainly due to the consumption of a large amount of electricity during the production of hydrogen.

The framework has been successful in incorporating cleaner production strategies and strengthening the inter-relationship between the three pillars of sustainability. Three improvement strategies, namely, use of E10 in place of gasoline, placement of 180 W_p solar PV panels on vehicles, and cleaner electricity for charging, were required to make the PHEV environmentally sustainable. Similarly, renewable energy for hydrogen production and cleaner electricity for EV charging were considered for the hydrogen and EV, respectively, to meet the sustainability thresholds in regard to environmental indicators. The fuel option E65 failed to meet the land use criterion. Thus, E55, which met all the environmental criteria, was proposed. After incorporating the environmental improvement strategies, the use of hydrogen as a fuel option was found to be the best-performing fuel in regard to the GWP. It resulted in around a 69% reduction in GWP and about a 65% reduction in the FFD indicator when compared to gasoline due to the replacement of current fossil-based electricity with wind and solar energy. The reductions of GHG emission for EV and PHEV were found to be around 50% and 35%, respectively, after incorporating the strategies. For PHEV, local battery production was required to meet the job creation criterion. The strategy of local battery production was considered due to WA's anticipated leading role in sustainable battery production within 5 to 10 years. Research suggests that NO_x emissions from the vehicle exhaust might increase or remain similar compared to gasoline for a higher ethanol blend (E55 in this study). It is also recommended that engine control strategies and after-treatment devices are required to maintain a consistent NO_x reduction compared to gasoline during the use of a higher ethanol blend.

The LCC of environmentally and socially sustainable E55, EV, PHEV, and hydrogen fuels was found to be 0.10, 0.22, 0.18, and 0.79 AUD/VKT, respectively. For economic sustainability, E55 required

a lesser subsidy (2.1 cents/VKT) compared to other fuel options. The fuel costs of EV and PHEV were found to be 66% and 50% lower than gasoline per VKT due to the subsidized electricity for electric vehicles in WA. Financial aid (around AUD 4200 for EV and AUD 1100 for PHEV) along with a 50% reduction in the alternative vehicle registration cost, the removal of GST on alternative vehicle sales, and the enforcement of import duty on gasoline vehicles were, however, required to meet the economic criteria for EV and PHEV due to high cost of the vehicles. Subsidies would be required for the first few years as alternative fuels are expected to become more sustainable with the improvement of the supply chain and mass production of alternative fuel vehicles. Hydrogen fuel is, however, considered unsustainable for public use at this stage in WA due to the high cost of HFCV. To kick start WA's hydrogen economy, the WA government could consider the use of hydrogen-fuelled vehicles in its government fleets.

Sustainable alternative fuel production, which is one of the key requirements for WA to alleviate the fuel security problem, combat climate change, and safeguard human health, is possible in WA with the incorporation of the recommended cleaner production strategies, government support, and initiatives. The proposed framework has the capacity and flexibility to accommodate the sustainability assessment needs of other regions of the world.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2071-1050/12/14/5565/s1>, Section A: Fuel selection, Section B: Governing equations of indicators, Section C: Data summary for job creation and economic indicators, Section D: Sample calculations for improvement strategies.

Author Contributions: Conceptualization and Methodology, N.H., W.B., and I.M.; Analysis, N.H.; investigation, N.H.; Data curation, N.H.; Writing original draft, N.H.; Visualization, N.H.; Writing review and editing, N.H., W.B., I.M., I.H.; Supervision, W.B., I.M., I.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors are grateful to the 'Australian Government Research Training Program Scholarship' for supporting Najmul Hoque's study at Curtin University, Australia. The authors also express their gratitude to the respondents for their participation in the surveys and for their valuable comments and suggestions. The authors would also like to thank the local industries and organizations, especially the Department of Primary Industries and Regional Development, BP Kwinana Refinery, Public Transport Authority of Western Australia, RAC Western Australia, 4farmers Australia, CSBP Fertilizer, Syngenta Australia, Nufarm Australia, and Dow Chemical Australia Ltd., for their support during the data collection phase of the study.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

AUD	Australian Dollar
BP	British Petroleum
CFF	Conservation of fossil fuel
CRC	Carbon reduction credit
E2	Ethanol-blended gasoline (2% ethanol and 98% gasoline)
E55	Ethanol-blended gasoline (55% ethanol and 45% gasoline)
E65	Ethanol-blended gasoline (65% ethanol and 35% gasoline)
ELCA	Environmental life cycle assessment
EU	European Union
EV	Electric vehicle
FFD	Fossil fuel depletion
GHG	Greenhouse gas
GST	Goods and service tax
GV	Gasoline vehicle
GWP	Global warming potential
ha	Hectare
HFCV	Hydrogen fuel cell vehicle
HH _{VEE}	Human health based on vehicle exhaust emission
ISO	International Organization for Standardization
kg	Kilogram

KIA	Kwinana Industrial Area
L	Litre
LCA	Life cycle assessment
LCC	Life cycle costing
LCSA	Life cycle sustainability assessment
MJ	Megajoule
ML	Megalitre
Mt	Megatonne
OHAS	Occupational health and safety
PEM	Proton exchange membrane
PHEV	Plug-in hybrid electric vehicle
PJ	Petajoule
PPA	Power purchase agreement
SLCA	Social life cycle assessment
TBL	Triple bottom line
tkm	Tonne-kilometre
VKT	Vehicle kilometre travel
WA	Western Australia
WC	Water consumption

References

- Roy, P.; Dutta, A. Life cycle assessment of ethanol derived from sawdust. *Bioresour. Technol.* **2013**, *150*, 407–411. [CrossRef] [PubMed]
- Hoque, N.; Biswas, W.; Mazhar, I.; Howard, I. Environmental Life Cycle Assessment of Alternative Fuels for Western Australia's Transport Sector. *Atmosphere* **2019**, *10*, 398. [CrossRef]
- Roy, P.; Orikasa, T.; Tokuyasu, K.; Nakamura, N.; Shiina, T. Evaluation of the life cycle of bioethanol produced from rice straws. *Bioresour. Technol.* **2012**, *110*, 239–244. [CrossRef] [PubMed]
- Tucki, K.; Orynycz, O.; Murk, R.; Świć, A.; Botwińska, K. Modeling of Biofuel's Emissivity for Fuel Choice Management. *Sustainability* **2019**, *11*, 6842. [CrossRef]
- Hoque, N.; Biswas, W.; Mazhar, I.; Howard, I. LCSA Framework for Assessing Sustainability of Alternative Fuel for Transport Sector. *Chem. Eng. Trans.* **2019**, *72*, 103–108.
- Department of Industry and Science. *Australian Energy Update 2015*; Department of Industry and Science, Commonwealth of Australia: Canberra, Australia, 2015.
- John, B.A. *Australia's Liquid Fuel Security Part-2 2014. A Report for NRMA Motoring & Services*; National Road and Motorists' Association: Sydney, Australia, 2014.
- Commonwealth of Australia. *Liquid Fuel Security Rev.*; Department of the Environment and Energy: Canberra, Australia, 2019.
- Government of Western Australia. *Perth Air Emissions Study 2011–2012*; Government of Western Australia: Perth, Australia, 2018.
- 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]
- Wynne, E. Perth Public Transport Use Falls for Fifth Year in a row, with Many Preferring Traffic to Trains. 2017. Available online: <https://www.abc.net.au/news/2017-09-12/why-are-people-avoiding-public-transport-in-perth/8893648> (accessed on 21 February 2020).
- Chapple, R. *Western Australian Greenhouse Gas Estimates 2012*; Government of Western Australia: Perth, WA, Australia, 2012.
- Renouf, M. Best Practice Guide for Life Cycle Impact Assessment (LCIA) in Australia. In *Australian Life Cycle Assessment Society*; Life Cycle Assessment Society: Melbourne, Australia, 2015.
- Roger, H. New Diesel and Petrol Vehicles to be Banned from 2040 in UK. *BBC News*. 2017. Available online: <https://www.bbc.com/news/uk-40723581> (accessed on 12 September 2019).
- Chrisafis, A.; Vaughan, A. France to ban sales of petrol and diesel cars by 2040. *The Guardian*. 2017. Available online: <https://www.theguardian.com/business/2017/jul/06/france-ban-petrol-diesel-cars-2040-emmanuel-macron-volvo> (accessed on 12 February 2020).

16. 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.
17. 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.
18. Lim, C.I.; Biswas, W. Sustainability assessment for crude palm oil production in Malaysia using the palm oil sustainability assessment framework. *Sustain. Dev.* **2019**, *27*, 253–269. [[CrossRef](#)]
19. Hasan, U.; Whyte, A.; Al Jassmi, H. Life cycle assessment of roadworks in United Arab Emirates: Recycled construction waste, reclaimed asphalt pavement, warm-mix asphalt and blast furnace slag use against traditional approach. *J. Clean. Prod.* **2020**, *257*, 120531. [[CrossRef](#)]
20. Akber, M.Z.; Thaheem, M.J.; Arshad, H. Life cycle sustainability assessment of electricity generation in Pakistan: Policy regime for a sustainable energy mix. *Energy Policy* **2017**, *111*, 111–126. [[CrossRef](#)]
21. Santoyo-Castelazo, E.; Azapagic, A. Sustainability assessment of energy systems: Integrating environmental, economic and social aspects. *J. Clean. Prod.* **2014**, *80*, 119–138. [[CrossRef](#)]
22. Osorio-Tejada, J.L.; Llera-Sastresa, E.; Scarpellini, S. A multi-criteria sustainability assessment for biodiesel and liquefied natural gas as alternative fuels in transport systems. *J. Nat. Gas Sci. Eng.* **2017**, *42*, 169–186. [[CrossRef](#)]
23. Li, T.; Roskilly, A.P.; Wang, Y. A Regional Life Cycle Sustainability Assessment Approach and its Application on Solar Photovoltaic. *Energy Procedia* **2017**, *105* (Suppl. C), 3320–3325. [[CrossRef](#)]
24. Keller, H.; Rettenmaier, N.; Reinhardt, G.A. Integrated life cycle sustainability assessment—A practical approach applied to biorefineries. *Appl. Energy* **2015**, *154*, 1072–1081. [[CrossRef](#)]
25. Guinée, J. Life Cycle Sustainability Assessment: What Is It and What Are Its Challenges? In *Taking Stock of Industrial Ecology*; Clift, R., Druckman, A., Eds.; Springer International Publishing: Cham, Switzerland, 2016; pp. 45–68.
26. 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](#)]
27. Sharma, R.; Manzie, C.; Bessedé, M.; Crawford, R.H.; Bear, M.J. Conventional, hybrid and electric vehicles for Australian driving conditions. Part 2: Life cycle CO₂-e emissions. *Transp. Res. Part C Emerg. Technol.* **2013**, *28*, 63–73. [[CrossRef](#)]
28. 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 Publ.* **2010**, *44*, 6550–6556.
29. Stasinopoulos, P.; Shiwakoti, N.; McDonald, S. Life-cycle greenhouse gas emissions of electric and conventional vehicles in Australia. In *ITS-Enhancing Liveable Cities and Communities*; Intelligent Transport Systems Australia (ITS Australia): Melbourne, Australia, 2016; pp. 1–10.
30. Lim, C.I.; Biswas, W. An evaluation of holistic sustainability assessment framework for palm oil production in Malaysia. *Sustainability* **2015**, *7*, 16561–16587. [[CrossRef](#)]
31. 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](#)]
32. Australian Renewable Energy Agency. *Life Cycle Assessment (LCA) of Bioenergy Products and Projects*; Australian Government: Canberra, Australia, 2016.
33. Carre, A. *A Comparative Life Cycle Assessment of Alternative Constructions of a Typical Australian House Design*; Forest and Wood Products Australia: Melbourne, Australia, 2011; p. 147-0809.
34. O'Connell, D.; Batten, D.; O'Connor, M.H.; May, B.; Raison, R.J.; Keating, B.A.; Beer, T.; Braid, A.L.; 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.
35. Ekener-Petersen, E.; Höglund, J.; Finnveden, G. Screening potential social impacts of fossil fuels and biofuels for vehicles. *Energy Policy* **2014**, *73* (Suppl. C), 416–426. [[CrossRef](#)]
36. Onat, N.C.; Kucukvar, M.; Tatari, O. Towards life cycle sustainability assessment of alternative passenger vehicles. *Sustainability* **2014**, *6*, 9305–9342. [[CrossRef](#)]
37. Souza, A.; Watanabe, M.D.B.; Cavalett, O.; Ugaya, C.M.L.; Bonomi, A. Social life cycle assessment of first and second-generation ethanol production technologies in Brazil. *Int. J. Life Cycle Assess.* **2018**, *23*, 617–628. [[CrossRef](#)]

38. Yu, M.; Halog, A. Solar photovoltaic development in Australia—A life cycle sustainability assessment study. *Sustainability* **2015**, *7*, 1213–1247. [CrossRef]
39. OECD. *Society at a Glance 2016: OECD Social Indicators*; OECD Publishing: Paris, France, 2016.
40. Food and Agriculture Organization of the United Nations (FAO). *The Global Bioenergy Partnership Sustainability Indicators for Bioenergy*; FAO: Rome, Italy, 2011.
41. Osorio-Tejada, J.L.; Llera-Sastresa, E.; Scarpellini, S. Liquefied natural gas: Could it be a reliable option for road freight transport in the EU? *Renew. Sustain. Energy Rev.* **2017**, *71*, 785–795. [CrossRef]
42. Weldegiorgis, F.S.; Franks, D.M. Social dimensions of energy supply alternatives in steelmaking: Comparison of biomass and coal production scenarios in Australia. *J. Clean. Prod.* **2014**, *84*, 281–288. [CrossRef]
43. 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.
44. United Petroleum. Ethanol Production. 2018. Available online: <https://www.unitedpetroleum.com.au/about/ethanol-production/> (accessed on 3 May 2018).
45. 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).
46. Grant, T.F. *Greenhouse Gas and Sustainability Footprints of Emerging Biofuels for Queensland*; Department of Environment and Science: Queensland, Australia, 2018.
47. Brooksbank, K.; Lever, M.; Paterson, H.; Weybury, M. *Biomass Scoping Study: Opportunities for Agriculture in Western Australia*; Department of Agriculture and Food: Perth, WA, Australia, 2014.
48. Crossin, E. Life cycle assessment of a mallee eucalypt jet fuel. *Biomass Bioenergy* **2017**, *96*, 162–171. [CrossRef]
49. Hinkley, J.; Hayward, J.; McNaughton, R.; Gillespie, R.; Matsumoto, A.; Watt, M.; Lovegrove, K. *Cost Assessment of Hydrogen Production from PV and Electrolysis*; Commonwealth Scientific and Industrial Research Organization: Canberra, Australia, 2016.
50. Water Corporation. Desalination. 2019. Available online: <https://www.watercorporation.com.au/water-supply/our-water-sources/desalination> (accessed on 11 January 2011).
51. Water Technology. Perth Seawater Desalination Plant. 2019. Available online: <https://www.water-technology.net/projects/perth/> (accessed on 16 May 2019).
52. Japan Electric Power Corporation Center. *The Electric Power Industry in Japan 2019*; Japan Electric Power Corporation Center: Tokyo, Japan, 2019.
53. Government of Western Australia. *Future Battery Industry Strategy Western Australia*; Government of Western Australia: Perth, WA, Australia, 2019.
54. Hastie, H. Train Builds Return to Midland after Historic Railcar ‘Super-Contract’ Signing. *WA Today*. 2019. Available online: <https://www.watoday.com.au/national/western-australia/train-builds-return-to-midland-after-historic-railcar-super-contract-signing-20191210-p53im7.html> (accessed on 7 January 2020).
55. Energy Matters. Australian Electric Vehicle Maker ACE-EV Could Produce 15,000 Cars by 2025. 2019. Available online: <https://www.energymatters.com.au/renewable-news/electric-vehicle-maker-plans-15000-evs/> (accessed on 7 January 2020).
56. Perdaman Industries (Chemical and Fertilizers). Job Creation by Perdaman Industries (Chemical and Fertilizers) at Karratha, Western Australia. 2017. Available online: <https://perdaman.com.au/perdaman-industries-chemicals-fertilisers/> (accessed on 22 November 2019).
57. Rustandi, F.; Wu, H. Biodiesel production from canola in Western Australia: Energy and carbon footprints and land, water, and labour requirements. *Ind. Eng. Chem. Res.* **2010**, *49*, 11785–11796. [CrossRef]
58. 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]
59. 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]
60. Pathan, S.; (Department of Primary Industries and Regional Development, Perth, Western Australia). Personal Communication, 2018.
61. AECOM Australia. *Efficient Costs of New Entrant Ethanol Producers*; AECOM Australia: Perth, WA, Australia, 2016.
62. Miller, M.; Raju, A.S.; Roy, P.S. The Development of Lifecycle Data for Hydrogen Fuel Production and Delivery. UC Davis National Center for Sustainable Transportation. Available online: <https://escholarship.org/uc/item/3pn8s961> (accessed on 19 December 2019).

63. Rutovitz, J.; Dominish, E.; Downes, J. *Calculating Global Energy Sector Jobs: 2015 Methodology*; Institute for Sustainable Futures: Sydney, Australia, 2015.
64. Garrett-Peltier, H. *The Employment Impacts of a Low-Carbon Fuel Standard for Minnesota*; University of Massachusetts: Amherst, MA, USA, 2012.
65. ABC News. Toyota Workers out of Jobs as Car Manufacturer Closes Altona Plant. 2017. Available online: <https://www.abc.net.au/news/2017-10-03/toyota-car-production-ends-altona-after-50-years-manufacturing/9007624> (accessed on 24 November 2019).
66. Gustafson, S. Shift to Electric Vehicles Weighs Heavy on UAW-GM Talks. 2019. Available online: <https://www.autoblog.com/2019/09/27/uaw-gm-strike-ev-job-fears/> (accessed on 17 December 2019).
67. Sørensen, B. Social Implications. In *Hydrogen and Fuel Cells*, 2nd ed.; Academic Press: Boston, MA, USA, 2012; Chapter 6; pp. 361–402.
68. Harding, R.; Inagaki, K. Japan Gambles on Toyota's Hydrogen Powered Car. 2017. Available online: <https://www.ft.com/content/328df346-10cb-11e7-a88c-50ba212dce4d> (accessed on 17 December 2019).
69. Toyota. How Long Does it Actually Take to Make a Car? 2019. Available online: <https://www.toyota.co.jp/en/kids/faq/b/01/06/> (accessed on 17 December 2019).
70. Fuel Watch Western Australia. Fuel Watch Historical Price Search. 2020. Available online: <https://www.fuelwatch.wa.gov.au/fuelwatch/pages/public/historicalPriceSearch.aspx> (accessed on 13 February 2020).
71. Bruce, S.; Temminghoff, M.; Hayward, J.; Schmidt, E.; Munnings, C.; Palfreyman, D.; Hartley, P. *National Hydrogen Roadmap: Pathways to an Economically Sustainable Hydrogen Industry in Australia*; CSIRO Australia: Canberra, Australia, 2018.
72. WA Water Corporation. Regional Non-Residential Water Use Steps. 2019. Available online: <https://www.watercorporation.com.au/home/business/my-account/your-bill-and-charges> (accessed on 12 May 2019).
73. He, Y. *Impacts of Flexible-Fuel Vehicles on Brazil's Fuel Markets*; Rutgers University-Graduate School-New Brunswick: New Brunswick, NJ, USA, 2013.
74. Synergy. *Standard Electricity Prices and Charges*; Synergy: Perth, WA, Australia, 2019.
75. Department of Industry Innovation and Science Australia. *Gas Price Trends Review*; Department of Industry Innovation and Science Australia: Canberra, Australia, 2017.
76. US Department of Energy. *Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan: Planned Program Activities for 2011–2020*; DOE, U.S.: Washington, DC, USA, 2012.
77. Ruhul, A.; (Centurion Logistics & Transport Services, Perth, Western Australia). Personal Communication, 2018.
78. Lawania, K.K.; Biswas, W.K. Cost-effective GHG mitigation strategies for Western Australia's housing sector: A life cycle management approach. *Clean Technol. Environ. Policy* **2016**, *18*, 2419–2428. [CrossRef]
79. Lee, J.-Y.; Yoo, M.; Cha, K.; Lim, T.; Hur, T. Life cycle cost analysis to examine the economical feasibility of hydrogen as an alternative fuel. *Int. J. Hydrog. Energy* **2009**, *34*, 4243–4255. [CrossRef]
80. Department of Agriculture and Food Western Australia. *Ethanol Production from Grain*; Department of Agriculture and Food Western Australia: Perth, WA, Australia, 2006.
81. Government of Western Australia. *Western Australian Renewable Hydrogen Strategy*; Government of Western Australia: Perth, WA, Australia, 2019.
82. United Petroleum. List Pricing (Wholesale). 2017. Available online: <https://www.unitedpetroleum.com.au/wholesale/list-pricing/> (accessed on 10 April 2020).
83. Shirk, M. *History of Significant Vehicle and Fuel Introductions in the United States*; Oak Ridge National Lab. (ORNL): Oak Ridge, TN, USA, 2017.
84. Toyota. Toyota Corolla Hatch Price. 2020. Available online: <https://www.toyota.com.au/corolla/hatch/prices> (accessed on 20 January 2020).
85. NSW Government. *Management Standard for Life Cycle Costing*; NSW Government: Sydney, Australia, 2014.
86. Wang, P.; Deng, X.; Zhou, H.; Yu, S. Estimates of the social cost of carbon: A review based on meta-analysis. *J. Clean. Prod.* **2019**, *209*, 1494–1507. [CrossRef]
87. Kember, O.; Jackson, E.; Connor, J. *Counting All The Costs: Recognising the Carbon Subsidy to Polluting Energy*; Policy Brief; The Climate Institute: Sydney, Australia, 2014.
88. Fatimah, Y.A.; Biswas, W.K. Remanufacturing as a means for achieving low-carbon SMEs in Indonesia. *Clean Technol. Environ. Policy* **2016**, *18*, 2363–2379. [CrossRef]

89. Climate Council. *Australia's Rising Greenhouse Gas Emissions*; Climate Council of Australia Ltd.: Sydney, Australia, 2018.
90. Clean Energy Council. *Clean Energy Australia: Report 2019*; Clean Energy Council: Melbourne, Australia, 2019.
91. 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](#)]
92. 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](#)]
93. Evangelisti, S.; Tagliaferri, C.; Brett, D.J.L.; Lettieri, P. Life cycle assessment of a polymer electrolyte membrane fuel cell system for passenger vehicles. *J. Clean. Prod.* **2017**, *142*, 4339–4355. [[CrossRef](#)]
94. Tagliaferri, C.; Evangelisti, S.; Acconcia, F.; Domenech, T.; Ekins, P.; Barletta, D.; Lettieri, P. Life cycle assessment of future electric and hybrid vehicles: A cradle-to-grave systems engineering approach. *Chem. Eng. Res. Des.* **2016**, *112*, 298–309. [[CrossRef](#)]
95. 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](#)]
96. Lombardi, L.; Tribioli, L.; Cozzolion, R.; Bella, G. Comparative environmental assessment of conventional, electric, hybrid, and fuel cell powertrains based on LCA. *Int. J. Life Cycle Assess.* **2017**, *22*, 1989–2006. [[CrossRef](#)]
97. Mehmeti, A.; Angelis-Dimakis, A.; Arampatzis, G.; McPhail, S.; Ulgiati, S. Life cycle assessment and water footprint of hydrogen production methods: From conventional to emerging technologies. *Environments* **2018**, *5*, 24. [[CrossRef](#)]
98. Rapier, R. Energy Balance For Ethanol Better Than For Gasoline? 2019. Available online: <http://www.energytrendsinsider.com/2006/04/08/energy-balance-for-ethanol-better-than-for-gasoline/> (accessed on 24 June 2019).
99. Paul, W.; Winnie, C.; Harry, S. *2015 Energy Balance for the Corn-Ethanol Industry*; United States Department of Agriculture Office of the Chief Economist, Office of Energy Policy and New Uses: Washington, DC, USA, 2016.
100. 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](#)]
101. Patyk, A.; Bachmann, T.M.; Brisse, A. Life cycle assessment of H₂ generation with high temperature electrolysis. *Int. J. Hydrog. Energy* **2013**, *38*, 3865–3880. [[CrossRef](#)]
102. Harto, C.; Meyers, R.; Williams, E. Life cycle water use of low-carbon transport fuels. *Energy Policy* **2010**, *38*, 4933–4944. [[CrossRef](#)]
103. Elgowainy, A.; Wu, M.; Lampert, D.; Cai, H.; Han, J.; Wang, M. *Life-Cycle Analysis of Water Consumption for Hydrogen Production: 2016 DOE Hydrogen and Fuel Cells Program Annual Merit Review*; Argonne National Laboratory: Lemont, IL, USA, 2016.
104. Pontau, P.; Hou, Y.; Cai, H.; Zhen, Y.; Jia, X.; Chiu, A.; Xu, M. Assessing land-use impacts by clean vehicle systems. *Resour. Conserv. Recycl.* **2015**, *95*, 112–119. [[CrossRef](#)]
105. Luo, L.; van der Voet, E.; Huppes, G. Life cycle assessment and life cycle costing of bioethanol from sugarcane in Brazil. *Renew. Sustain. Energy Rev.* **2009**, *13*, 1613–1619. [[CrossRef](#)]
106. Sengupta, S.; Cohan, D.S. Fuel cycle emissions and life cycle costs of alternative fuel vehicle policy options for the City of Houston municipal fleet. *Transp. Res. D* **2017**, *54*, 160–171. [[CrossRef](#)]
107. Shahraeeni, M.; Ahmed, S.; Malek, K.; Van Drimmelen, B.; Kjeang, E. Life cycle emissions and cost of transportation systems: Case study on diesel and natural gas for light duty trucks in municipal fleet operations. *J. Nat. Gas Sci. Eng.* **2015**, *24*, 26–34. [[CrossRef](#)]
108. Zhou, T.; Roodra, M.J.; Maclean, H.L.; Luk, J. Life cycle GHG emissions and lifetime costs of medium-duty diesel and battery electric trucks in Toronto, Canada. *Transp. Res. D* **2017**, *55*, 91–98. [[CrossRef](#)]
109. Daylan, B.; Ciliz, N. Life cycle assessment and environmental life cycle costing analysis of lignocellulosic bioethanol as an alternative transportation fuel. *Renew. Energy* **2016**, *89*, 578–587. [[CrossRef](#)]
110. ISO14040. *Environmental Management—Life Cycle Assessment—Principles and Framework*; ISO: Geneva, Switzerland, 2006.

111. International Organization for Standardization. *ISO14044. Environmental Management-Life Cycle Assessments-Requirements and Guidelines*; International Standard Organization (ISO): Geneva, Switzerland, 2006.
112. Barton, L.; Thamo, T.; Engelbrecht, D.; Biswas, W. 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]
113. Mekonnen, M.M.; Gerbens-Leenes, P.; Hoekstra, A.Y. The consumptive water footprint of electricity and heat: A global assessment. *Environ. Sci. Water Res. Technol.* **2015**, *1*, 285–297. [CrossRef]
114. Allison, E.; Mandler, B. *Health and Safety in Oil and Gas Extraction: Reducing the Exposure of Oil and Gas Workers to Health and Safety Hazards*; American Geosciences Institute: Alexandria, VA, USA, 2018.
115. Jansen, J.; Rong, Y.; Markit, I. *Safety Is Paramount*; PV Magazine Australia: Canberra, Australia, 2019.
116. Kong, L.; Li, C.; Jiang, J.; Pecht, M.G. Li-ion battery fire hazards and safety strategies. *Energies* **2018**, *11*, 2191. [CrossRef]
117. Bisschop, R.; Willstrand, O.; Amon, F.; Rosenggren, M. *Fire Safety of Lithium-Ion Batteries in Road Vehicles*; RISE Research Institute of Sweden: Gothenburg, Sweden, 2019.
118. Hydrogen Strategy Group. *Hydrogen for Australia's Future*; Hydrogen for Australia's Future: Canberra, Australia, 2018.
119. DSDMIP Queensland. *Queensland Hydrogen Industry Strategy 2019–2024*; The Department of State Development, Manufacturing, Infrastructure and Planning: City East, QLD, Australia, 2019.
120. COAG Energy Council Hydrogen Working Group. *Australia's National Hydrogen Strategy*; Department of Industry, Science, Energy and Resources: Canberra, Australia, 2019.
121. Government of Western Australia. *Perth Fuel Cell Bus Trial Summary of Achievements 2004–2007*; Department of Planning and Infrastructure, Government of Western Australia: Perth, WA, Australia, 2008.
122. Jin, D.; Choi, K.; Myung, C.; 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]
123. Masum, B.M.; Masjuki, H.H.; Kalam, M.A.; Fattah, I.M.R.; Palash, S.M.; Abedin, M.J. Effect of ethanol–gasoline blend on NO_x emission in SI engine. *Renew. Sustain. Energy Rev.* **2013**, *24*, 209–222. [CrossRef]
124. D'Allegro, J. Powering the Future: Hydrogen Cars May yet Threaten Tesla. CNBC Newsletter. 2019. Available online: <https://www.cnn.com/2019/02/21/musk-calls-hydrogen-fuel-cells-stupid-but-tech-may-threaten-tesla.html> (accessed on 25 December 2019).
125. Elaine. Australia Has the Highest Manufacturing-Cost Structure Among Largest Goods-Exporting Countries: Study. 2014. Available online: <https://www.australianmanufacturing.com.au/15915/australia-has-the-highest-manufacturing-cost-structure-among-largest-goods-exporting-countries-study> (accessed on 23 March 2020).
126. 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]
127. Laslett, D.; Careter, C.; Creagh, C.; Jennigs, 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]
128. The Climate Institute. *Clean Energy Jobs in Regional Australia*. 2009. Available online: http://www.climateinstitute.org.au/verve/_resources/cleanenergyjobssnapshot_westernaustralia.pdf (accessed on 17 September 2018).
129. Dujmovic, J. Toyota's Prius Is Testing a New Solar Look that Could Put it Back in the Lead for Hybrid Cars. 2019. Available online: https://www.marketwatch.com/story/toyotas-prius-is-testing-a-new-solar-look-that-could-put-it-back-in-the-lead-for-hybrid-cars-2019-07-11?fbclid=IwAR1ZAzaEU40I_rYo8pNBrd5Ar66a1HZ72EnKuT7agH9dls2i1adrCWE0RA (accessed on 20 December 2019).
130. Geoscience Australia, BREE. *Australian Energy Resource Assessment*; Australian Government: Canberra, Australia, 2014.
131. Australian Bureau of Meteorology. *Climate Information for Solar Energy*; Commonwealth of Australia: Canberra, Australia, 2019.
132. Hoque, N.; Kumar, S. Performance of photovoltaic micro utility systems. *Energy Sustain. Dev.* **2013**, *17*, 424–430. [CrossRef]

133. Hochman, Z.; Horan, H. Causes of wheat yield gaps and opportunities to advance the water-limited yield frontier in Australia. *Field Crops Res.* **2018**, *228*, 20–30. [CrossRef]
134. Robertson, M.; Kirkegaard, J.; Rebetzke, G.; Llewellyn, R.; Wark, T. Prospects for yield improvement in the Australian wheat industry: A perspective. *Food Energy Secur.* **2016**, *5*, 107–122. [CrossRef]
135. Barton, L.; Hoyle, F.C.; Stefanova, K.T.; Murphy, D.V. Incorporating organic matter alters soil greenhouse gas emissions and increases grain yield in a semi-arid climate. *Agric. Ecosyst. Environ.* **2016**, *231*, 320–330. [CrossRef]
136. Assainar, S.K.; Abbott, L.K.; Mickan, B.S.; Storer, P.J.; Whiteley, A.S.; Siddique, K.H.M.; Solaiman, Z.M. Polymer-coated rock mineral fertilizer has potential to substitute soluble fertilizer for increasing growth, nutrient uptake, and yield of wheat. *Biol. Fertil. Soils* **2020**, *56*, 1–14. [CrossRef]
137. URS Asutralia. Oil mallee industry development plan for Western Australia. In *Forest Products Commission*; URS Australia: Perth, WA, Australia, 2008.
138. RIRDC. *Sustainable Production of Bioenergy: A Review of Global Bioenergy Sustainability Frameworks and Assessment Systems*; RIRDC: Canberra, Australia, 2009.
139. Kelly, G. Avenues to sustainable road transport energy in New Zealand. *Int. J. Sustain. Transp.* **2015**, *10*, 505–516. [CrossRef]
140. Climate Council. *Renewable Energy Jobs: Future Growth in Australia*; The Climate Council of Australia Limited: Sydney, Australia, 2016.
141. Commonwealth of Australia. *The Lithium-Ion Battery Value Chain: New Economy Opportunities for Australia*; Australian Trade and Investment Commission: Canberra, Australia, 2018.
142. Karavalakis, G.; Short, D.; Russell, R.L.; Jung, H.; Johnson, K.C.; Asa-Awuku, A.; Durbin, T.D. Assessing the impacts of ethanol and isobutanol on gaseous and particulate emissions from flexible fuel vehicles. *Environ. Sci. Technol.* **2014**, *48*, 14016–14024. [CrossRef]
143. Karavalakis, G.; Durbin, T.D.; Shrivastava, M.; Zheng, Z.; Villela, M.; Jung, H. Impacts of ethanol fuel level on emissions of regulated and unregulated pollutants from a fleet of gasoline light-duty vehicles. *Fuel* **2012**, *93*, 549–558. [CrossRef]
144. Oh, C.; Cha, G. Impact of fuel, injection type and after-treatment system on particulate emissions of light-duty vehicles using different fuels on FTP-75 and HWFET test cycles. *Int. J. Automot. Technol.* **2015**, *16*, 895–901. [CrossRef]
145. Doğan, B.; Erol, D.; Yaman, H.; Kodani, E. The effect of ethanol-gasoline blends on performance and exhaust emissions of a spark ignition engine through exergy analysis. *Appl. Therm. Eng.* **2017**, *120*, 433–443. [CrossRef]
146. Delavarrafee, M.; Frey, H.C. Real-world fuel use and gaseous emission rates for flex fuel vehicles operated on E85 versus gasoline. *J. Air Waste Manag. Assoc.* **2018**, *68*, 235–254. [CrossRef]
147. Wei, H.; Zhu, T.; Shu, G.; Tan, L.; Wang, Y. Gasoline engine exhaust gas recirculation—A review. *Appl. Energy* **2012**, *99*, 534–544. [CrossRef]
148. Fischer, M.; Kreutziger, P.; Sun, Y.; Kotrba, A. Clean EGR for Gasoline Engines—Innovative Approach to Efficiency Improvement and Emissions Reduction Simultaneously. SAE International, 2017; SAE Technical Paper 2017-01-0683. Available online: <https://saemobilus.sae.org/content/2017-01-0683/> (accessed on 19 December 2019).
149. Lauren, V.; (Australian Renewable Energy Agency, Canberra, Australia). Personal Communication, 2020.
150. Parliament of Australia. Petrol, Excise and GST. 2020. Available online: https://www.aph.gov.au/Parliamentary_Business/Committees/Senate/Economics/Completed_inquiries/2004-07/petrol_price/report/c05 (accessed on 19 April 2020).
151. Kato, T.; Kubota, M.; Kobayashi, N.; Suzuoki, Y. Effective utilization of by-product oxygen from electrolysis hydrogen production. *Energy* **2005**, *30*, 2580–2595. [CrossRef]
152. Harvego, E.A.; O'Brien, J.E.; McKellar, M.G. *System Evaluations and Life-Cycle Cost Analyses for High-Temperature Electrolysis Hydrogen Production Facilities*; Idaho National Laboratory: Idaho Falls, ID, USA, 2012.
153. Energetics; Norton Rose Fulbright; WWF-Australia. *NSW Guide to Corporate Power Purchase Agreement*; WWF-Australia: Sydney, Australia, 2018.
154. WWF-Australia. *Helping Business-Pathways to Purchase Renewable Energy*; WWF-Australia: Sydney, Australia, 2016.

155. Australian Government. Wholesale Statistics. 2020. Available online: <https://www.aer.gov.au/wholesale-markets/wholesale-statistics/annual-volume-weighted-average-spot-prices-regions> (accessed on 15 January 2020).
156. Mzengrab, M. How the ACT's 100% Renewable Electricity Target Is Saving Households Cash. 2019. Available online: https://reneweconomy.com.au/how-the-acts-100-renewable-electricity-target-is-saving-households-cash-22222/?fbclid=IwAR35z3qAV3ZRvAORZsfM03sRPKOG6hmOedPnDq15s1dZSJJe_nZdKyMATWBM (accessed on 11 October 2019).
157. Vorrath, S. City of Adelaide Seals Deal to Go 100% Renewable. July 2020. Available online: <https://reneweconomy.com.au/city-of-adelaide-seals-deal-to-go-100-renewable-starting-july-44123/?fbclid=IwAR2aw9WWR4spwyyqDhUFwZaMxrEbMGQQtsCZaTazsDAX2CI-x8LT0JcyE7Y> (accessed on 6 February 2020).
158. Arslan, R.; Ulusoy, Y.; Tekin, Y.; Sürmen, A. An evaluation of the alternative transport fuel policies for Turkey. *Energy Policy* **2010**, *38*, 3030–3037. [CrossRef]
159. Holtmark, B.; Skonhoft, A. The Norwegian support and subsidy policy of electric cars. Should it be adopted by other countries? *Environ. Sci. Policy* **2014**, *42*, 160–168. [CrossRef]
160. RAC. EV Takeup: We Look at Incentives and EV Take up around the World. 2020. Available online: https://rac.com.au/car-motoring/info/future_ev-incentives (accessed on 20 January 2020).
161. Volkswagen, A.G. How Electric Car Incentives around the World Work. 2019. Available online: <https://www.volkswagenag.com/en/news/stories/2019/05/how-electric-car-incentives-around-the-world-work.html> (accessed on 20 January 2020).
162. The Royal Automobile Club of WA. How Much Does Car Rego Cost in WA? Find Out Why Some Cars' Registration Costs Are Cheaper than Others. 2020. Available online: <https://rac.com.au/car-motoring/info/how-much-does-car-rego-cost-in-wa> (accessed on 10 January 2020).
163. Electric Vehicle Council Australia. *State of Electric Vehicles*; Electric Vehicle Council Australia: Sydney, Australia, 2019.
164. Climate Works. *The State of Electric Vehicles in Australia: Driving Momentum in Electric Mobility*; ClimateWorks, Australia on Behalf of Electric Vehicle Council Australia: Melbourne, Australia, 2018.
165. Parliament of Victoria. *Inquiry into Electric Vehicles*; Government of Australia: Melbourne, Australia, 2018.
166. IEA. *IEA Bioenergy Countries' Report: Bioenergy Policies and Status of Implementation*; IEA: Paris, France, 2016.



© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).