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Research Article

Sustainability Implications of Using Hydrogen as an Automotive Fuel in Western Australia

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Abstract

Hydrogen is regarded as a potential solution to address future energy demands and environmental protection challenges. This study assesses the triple bottom line (TBL) sustainability performance of hydrogen as an automotive fuel for Western Australia (WA) using a life cycle approach. Hydrogen is considered to be produced through water electrolysis. Two scenarios, current grid electricity and future renewable-based hydrogen, were compared with gasoline as a base case. The results show that locally produced grid electricity-based hydrogen is good for local jobs but exhibits higher environmental impacts and negative economic benefits for consumers when compared to gasoline. After incorporating wind-generated electricity, reductions of around 69% and 65% in global warming potential (GWP) and fossil fuel depletion (FFD), respectively were achieved compared to the base case gasoline. The land utilization for the production of hydrogen is not a problem as Western Australia has plenty of land to accommodate renewable energy projects. Water for hydrogen feedstock could be sourced through seawater desalination or from wastewater treatment plants in WA. Hydrogen also performed better than gasoline in terms of human health and conservation of fossil fuel indicators under the renewable energy scenario. Local job creation potential of hydrogen was estimated to be 1.29E-03 man-hours/VKT. It has also been found that the cost of hydrogen fuel cell vehicles (HFCV) needs to be similar to that of gasoline vehicles (GV) in order to be comparable with the gasoline life cycle cost per vehicle kilometre travel (VKT).

Keywords
Hydrogen; transportation fuel; life cycle assessment; triple bottom line.

1. Introduction

With the improved standard of living and increased human desires, secure and reliable energy supply has become an essential requirement for modern society [1]. The global primary energy demand is expected to be increased by 1.6% each year until 2030 [2]. In 2018, however, the world had experienced the fastest growth rate of 2.9% since 2010, which was almost double compared to the previous ten years' average [3]. More than 80% of the current primary energy supply originates from fossil fuels of which the transport sector alone accounts for 58% [4]. The research and application pertaining to alternative fuels have increased in recent years due to the fear of the serious consequence of climate change from carbon emissions resulting from fossil fuel combustion. Besides, countries around the world have witnessed more interest in alternative transport fuels due to limited resources, health issues from vehicle exhaust emissions and fluctuation of fossil fuel prices [5]. The utilization of renewable energy sources is one of the proven ways of ensuring the low carbon future of the World while simultaneously meeting the increasing demand for human desire [6]. Due to the abundance of its feedstock and clean-burning quality, hydrogen is considered as a future solution to address renewable energy challenges.

Western Australia holds an excellent position to be a leader in the hydrogen economy, owing to its reputation and skills in managing pressured gas in the LNG export industries over many years [7]. The transport sector of WA at the same time is unsustainable as the state's passenger vehicle dominated transportation system is fully depended on imported liquid fossil fuels [1]. Around 78% of vehicles in WA are passenger cars, and 87.14% of those vehicles use gasoline as fuel [8]. There are also approximately 17% light commercial vehicles in the state, and 37% of those also depend on gasoline [8]. The WA government is, however, committed to obtaining a significant portion of the state's energy demand from renewable energy by 2031, as the transport sector is one of the energy intensive sectors in the state [9]. In 2016-17, 1179.5 PJ of energy was consumed in WA. The transport sector alone consumed 230.7 PJ of energy (21.5%), which is the 2nd most energy consuming sector in WA after mining [10]. With petrol as a dominant transport fuel, around 14% of GHG emissions are from the transport sectors of WA [11, 12]. Direct exposure to vehicle exhaust emissions, such as carbon monoxide, nitrous oxides, and particulate matter can cause serious human health issues like lung diseases, cancers and respiratory problems [13]. The use of alternative fuels can alleviate such issues up to a significant level depending upon the nature of the fuel. For example, the use of hydrogen in vehicles produces only water vapour as exhaust, which is non-toxic.

By considering the current situations, hydrogen is considered as one of the potential fuels for the WA's transport sector to improve energy security and lessen the environmental burden [1]. Locally produced alternative fuels can also increase the region's socioeconomic status, such as the creation of long-term job opportunities [7, 14]. However, there could be potential economic and environmental implications associated with the conversion of feedstock to hydrogen fuels [15]. Triple bottom line assessment is thus required to realize the environmental, social and economic influence of the fuel locally [6, 14]. The consideration of the life cycle approach in sustainability assessment is also essential as it considers the entire life cycle of the fuel [14]. The review of the life cycle sustainability assessments of alternative fuels suggests that there is very limited research that considers all the three dimensions of sustainability [6]. The current study concentrates on the triple bottom line of sustainability aspects of hydrogen fuel using the life cycle approach. The focus of the study is the sustainability assessment of hydrogen as an automotive fuel in WA. The study investigates the social and economic dimensions of sustainability as well as environmental impact assessment in an integrated manner. Since renewable based hydrogen has already been proven more environmentally friendly than the conventional method [11], this paper compares the future renewable-based hydrogen production with the current gasoline counterparts.

2. Methodology

The goal of this study is to compare the sustainability performance of hydrogen fuel with gasoline in Western Australia. The study follows the concept of life cycle sustainability assessment (LCSA) that comprises of environmental life cycle assessment (ELCA), social life cycle assessment (SLCA) and life cycle costing (LCC) tools. The functional unit of this life cycle assessment (LCA) is VKT.

ELCA follows the guidelines of ISO 14040:2006 and ISO 14044:2006 LCA guidelines [16, 17]. Different stages of the hydrogen fuel life cycle are considered under the study as shown in Figure 1a. The study evaluates the whole life cycle of fuel that includes hydrogen production, distribution, and vehicle use. The analysis also includes modifications of the power train of the conventional vehicle to use hydrogen fuel. The gliders for both vehicles are considered to be the same [1]. ELCA, SLCA and LCC follow the similar system boundary. LCC follows the discounted cash flow analysis using the discount factor of 7% [18], inflation rate of 3% [19] and a project life of 35 years [18]. As shown in Figure 1b, four environmental, four social and three economic indicators were considered in the LCSA analysis. These TBL indicators were selected using the rigorous literature review and experts' opinion on the three broad categories, such as academia, industry, and government. The calculation procedures [20] of the selected indicators are provided in Appendix- A.

Data required for the analysis were collected from literature and local organizations. The Proton Exchange Membrane (PEM) electrolysis method was considered to produce hydrogen fuel. Sustainability of hydrogen fuel largely depends on the electricity required during the hydrogen production as a large amount of electricity (54 kWh/kg H_2) is usually required for the electrolysis [20, 21]. Data for the local electricity mix of WA was used in this assessment [1]. Water that was used for hydrogen production was considered to be sourced from the Perth desalination plant powered by wind generators [1]. To generate 1 m^3 of water, 3 kWh of electricity was required in different stages of desalination process. The detailed inventory for 1 m^3 of water desalination has been presented in Table A1 in Appendix-B. The hydrogen production plant was considered to be located in the Kwinana Industrial Area. The mean distance of WA's gasoline refuelling stations from Kwinana petroleum refinery was thus used as the hydrogen delivery distance (i.e. around 139 km).

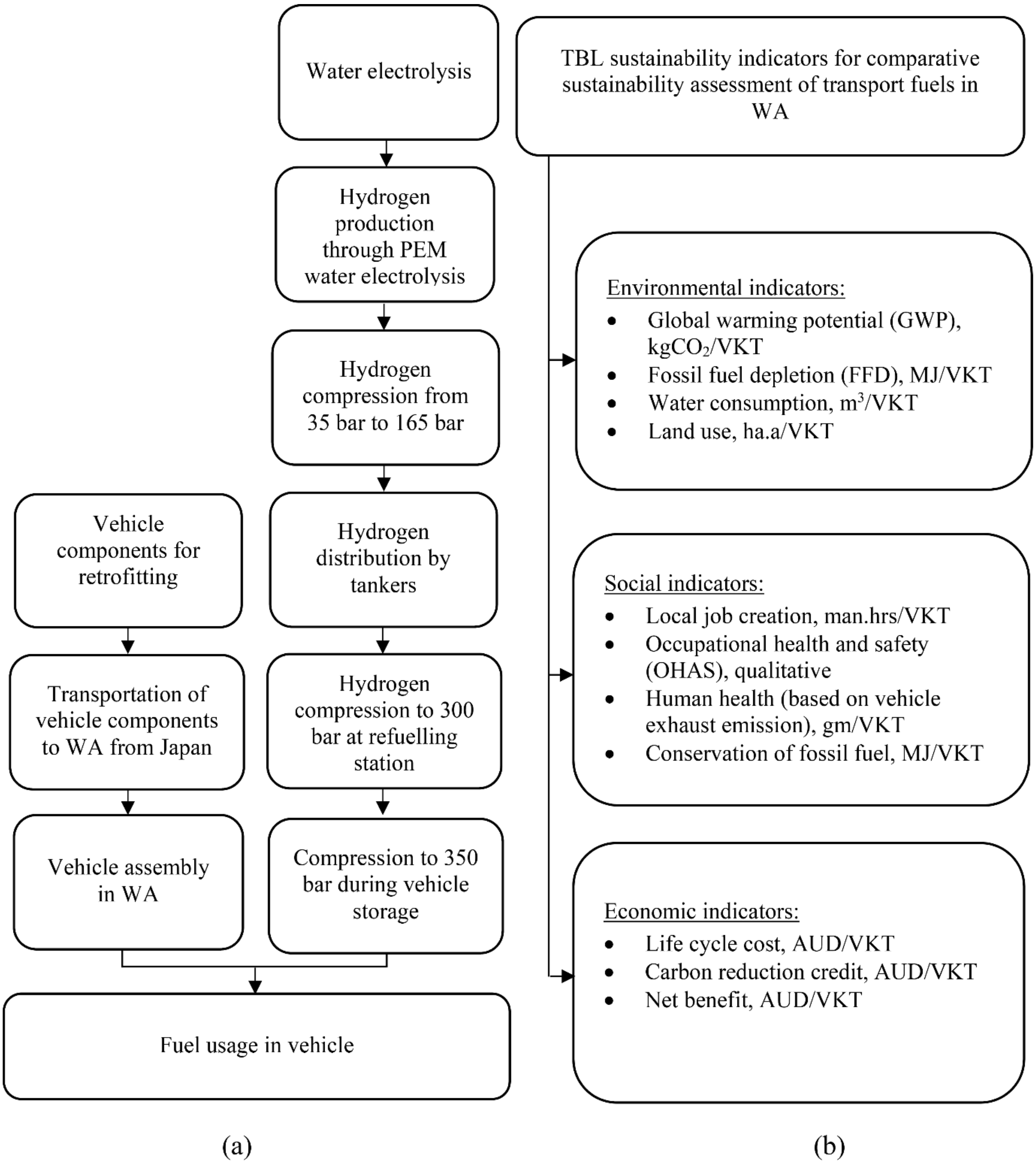

Figure 1 (a) Simplified block diagram of the stages considered in the life cycle assessment of hydrogen fuel, (b) development of sustainability indicators used for the study [1].

Electricity requirement for hydrogen compression in different stages was calculated using Eq. **1** [22]. The calculated value was verified by comparing it with the data in a study by Bruce et al. [18].

$$E_{compression} = \frac{\gamma mRT}{(\gamma - 1)W_h}\left[\left(\frac{P}{P_0}\right)^{\frac{(\gamma-1)}{\gamma}} - 1\right] \quad (1)$$

Where, m =mass of hydrogen in kg, γ = ratio of specific heat which is 1.4, P = pressure of hydrogen, P_0 =atmospheric pressure, T = Average room temperature 298 K, W_h = molecular weight of hydrogen (2.016gm/mole), R = Gas constant (8.31 J/mole K).

Hydrogen powered vehicles for this investigation would use fuel cell technology. Different material processes for the HFCV, such as fuel cell, motor, inverter, converter, and hydrogen tank were collected from studies by Hoque et al [1] and Miotti et al. [15]. A summary of data for the vehicle materials has been presented in Table A2 in Appendix-B. The hydrogen consumption per km considered was 0.01 kg per km [23] and 0.06 litre per km [24] for gasoline.

3. Base Case Analysis

The outcomes of the sustainability assessment of hydrogen production using the current electricity grid are discussed in this section. The section also presents a comparative analysis of the TBL sustainability results for hydrogen and gasoline in WA.

3.1 Environmental Sustainability

Simapro 8.4 LCA software was used to determine the environmental indicators, including global warming potential (GWP), water consumption, fossil fuel consumption (FFD) and land use, for both the hydrogen and gasoline fuels for passenger car. The environmental impacts of hydrogen fuel and vehicle (i.e. additional impact of HFCV compared to GV) are shown in Figure 2. The GWP impact of hydrogen was estimated to be 5.57E-01 kgCO_2 per VKT that was around 2.20 times higher than that of gasoline. Similarly, FFD of hydrogen fuel was around 1.83 times higher than that of gasoline. The reason for hydrogen having higher GWP and FFD impacts than gasoline was due to the large amount of electricity required during the production of hydrogen. As shown in Table 1, around 85% of the GWP impact was from the electricity used during the production stage. The hydrogen distribution phase was responsible for 2.35% of GWP impacts as around 30 tonnes of freight was required to carry only 0.3 tonnes of hydrogen due to the additional weight of the tube tankers [25].

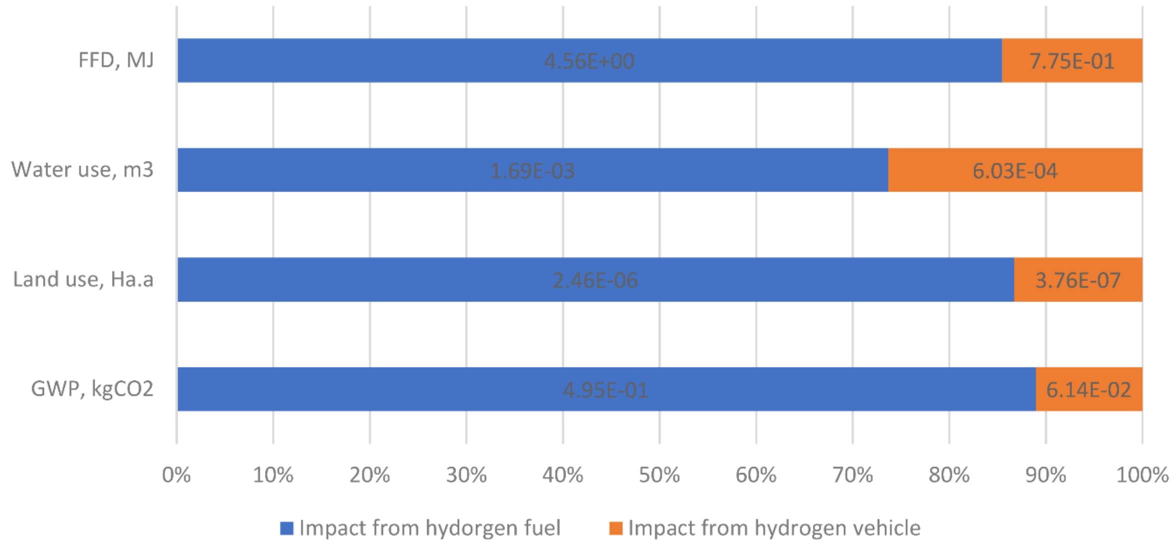

Figure 2 Environmental life cycle impacts of HFCV per VKT.

Around 11% of impact, on the other hand, was due to the changes required in the vehicle from GV to HFCV. Among the vehicle components, the fuel cell (19% of HFCV impact) and the hydrogen tank (15% of HFCV impact) were found to be the two most GWP contributing components. The reason for higher impact for the hydrogen tank was the use of carbon fibre accounting for 84% of the impact. In comparison, the use of the platinum catalyst was responsible for 55% of the fuel cell impact, which was the main reason for the higher impact for the fuel cell.

Table 1 Breakdown of GWP emission.

Process	GWP (kgCO_2/VKT)
Electricity required for hydrogen production	4.74E-01
Water desalination	2.10E-05
Compression of hydrogen for distribution	5.84E-03
Hydrogen distribution to refuelling station by diesel tanker	1.31E-02
Compression of hydrogen for storage at refuelling station	1.95E-03
Compression of hydrogen for storage in vehicle	4.72E-04
Vehicle materials equivalent to 113 kW HFCV	
Hydrogen tank (87.5 kg, 5 kg hydrogen capacity)	9.36E-03
Fuel cell 114 kW	
Catalyst	1.13E-02
Membrane	3.26E-03
Gas diffusion layer	2.61E-03
Membrane electrode assembly	2.48E-04
Bipolar plate	2.64E-03
Fuel cell assembly	5.14E-04
Other components	
Cooler	1.32E-03
Transmission differential	4.09E-03
Battery	4.30E-03
Motor	2.90E-03
Electronics: inverter, converter and control unit	1.83E-02
Total	5.57E-01

Water consumption and land use requirements of hydrogen production and storage were also found to be 2.41 and 14.91 times, respectively, higher than gasoline. Sixty percent of the water requirement was associated with the production of hydrogen and the remaining 40 percent was from vehicle materials. Electricity requirement for hydrogen production alone contributes to 48% of the life cycle water consumption. Besides, the fuel cell catalyst (23% of HFCV water consumption) and battery (20% of HFCV water consumption) production were the key water consuming components among the vehicle materials. Similar to the GWP emission, electricity consumption during the hydrogen production stage was responsible for about 87% of the total life cycle land use impact.

3.2 Social Sustainability

Social sustainability was evaluated based on the four social indicators of local job creation, occupational health and safety, fossil fuel depletion and human health. The hydrogen fuel has the potential to create 2.44E-04 man-hours job per VKT (vehicle kilometre travel) locally in WA compared to 1.54E-05 man-hours per VKT by gasoline (Table 2). It has been found that the electricity consumption during the hydrogen production (54.97%), hydrogen distribution (25.62%), and the staff requirement in the hydrogen production plant (18.36%) were the three key stages of job creation during the hydrogen production. This local job creation could further be increased to 1.29E-03 man-hours/VKT if the vehicle assembly were carried out locally in WA. The job creation at the refuelling station for both the fuels was assumed to be the same, and hence was excluded from the analysis. The job creation due to electricity supply for the various activities was based on the methodology of Rutovitz et al. [26]. The plant construction phase for the inputs required for hydrogen production (such as chemicals, electricity etc.) did not consider local job creation as these plants were not solely utilised for the alternative fuels. The detail considerations regarding local job creations and other socio-economic indicators were based on Hoque et al. [20].

Table 2 Local job creation potential of hydrogen as an automotive fuel in WA.

Local job creation through different activity	Job creation, man-hours/VKT
Electricity required for hydrogen production	1.34E-04
Water desalination	2.26E-07
Job creation through hydrogen production plant	4.48E-05
Compression of hydrogen for distribution	1.26E-06
Hydrogen distribution to refuelling station by diesel tanker	6.25E-05
Compression of hydrogen for storage at refuelling station	5.53E-07
Compression of hydrogen for storage in vehicle	1.34E-07
Total from fuel	2.44E-04
Vehicle assembly	1.04E-03
Total	1.29E-03

For the occupational health and safety indicator, 32 responses from the supply chain of the hydrogen fuel were collected based on 5-point Likert scale, where 5 was the level of complete satisfaction [14, 27]. All the respondents scored the required level of safety score of 5, provided that the safety protocols of hydrogen production and use were implemented. The respondents had also suggested the requirement of necessary trainings and promotional campaigns regarding the safe use of hydrogen. Also, it is worth mentioning that WA is already in a very suitable position in terms of hydrogen production and use due to having trained LNG industry personnel with skills that follow the safety protocols for the use of pressurised gas. Besides, three hydrogen buses were operated in WA by the public transport authority in Perth as a trial during the period of 2004 - 2007 [28]. The trial of the hydrogen bus was safely performed, and also the passengers were satisfied with the service. The safety score of hydrogen as a transport fuel was also found to be similar to that of gasoline in a European study [29].

The human health indicator was evaluated based on the comparison of exhaust gas emissions from the GV and HFCV. The CO, PM and NO_x emissions from the combustion of these fuels were compared as direct exposures to these pollutants as they are detrimental to human health according to the suggestions by local experts. Gasoline vehicles produce around 2.75E-01 gm/VKT, 2.00E-03 gm/VKT and 1.80E-03 gm/VKT CO, NO_x and PM, respectively [30]. Since the hydrogen vehicle does not produce any exhaust emission from HFCV except for the non-toxic water vapour, it met the sustainability criteria for human health. Nevertheless, the HFCV and gasoline vehicles produce almost the same amount of water vapour during their combustion. The calculated amounts of water vapour were 8.70E-02 and 9.32E-02 kg/km from GV and HFCV, respectively [31]. Whereas, the conservation of fossil fuel associated with the hydrogen production in the base case scenario was found to be negative (-2.43E+00 MJ/VKT) due to the higher fossil fuel use compared to gasoline. Electricity that was mainly produced from the fossil fuel (92.5%) in WA [1], was responsible for 80% of the total life cycle fossil fuel used. Therefore, inter-generational social equity was not achieved due to the hydrogen fuel's inability to conserve non-renewable fossil fuel resources for the future generations.

3.3 Economic Sustainability

Three economic indicators, life cycle cost, carbon reduction credit and net benefit, were calculated. A summary of the data for economic assessment is in Table 3. The life cycle cost of the base case hydrogen vehicle was found to be 79 cents/VKT, with a contribution of 31 cents from hydrogen fuel and the remaining 48 cents as an additional cost for the HFCV. This additional cost for HFCV with respect to gasoline was considered to be paid upfront by the user during the purchase of the vehicle. The estimated hydrogen fuel cost per km was 22.6 cents higher than that of gasoline (8.13 cents/VKT). The electricity required for the hydrogen production (82%), hydrogen distribution (12.5%) and initial plant capital (4%) were the main contributors to this increased cost. If hydrogen vehicles were assembled locally, the cost could have been reduced from AUD 80752 to AUD 70,649 based on the cost of the components as published by Miottti et al [15]. The fuel cell (46%) and hydrogen tank (19%) were the two main costly items or economic hotspots for the hydrogen vehicle. Among others, the battery, electric motor, controller, inverter and converter were responsible for 2%, 3%, 1%, 4% and 1% of the total cost, respectively. The gasoline vehicle cost was estimated based on the local market price that was AUD 26,709.

Table 3 Summary of assumptions for the estimation of hydrogen fuel cost*.

Activity/input	Estimations	Reference
Electricity+	0.39 AUD/kWh	[32]
Desalinated water	1.17 AUD/KL	[33]
Plant cost	144 M AUD	[18]
Plant capacity	50,000 kg/day	[18]
Replacement cost	15% replacement cost in every 7 years	[34]
Plant life	35 years	[18]
Discount rate	7%	[18]
Source of plant cost	100% debt on a 7% interest rate over the project life	[18]
Inflation rate	3%	[19]

Maintenance cost	5% of the yearly capital cost	[21]
Labour requirement for the plant	12 staff	[34, 35]
Producer margin	10% of the production cost	[36]
Distribution of hydrogen to retailer	2.30 AUD/kg	[37]
Average distance of hydrogen distribution in WA	138.39 km	[1]
Retailer margin	5.70%, based on local retailer margin for gasoline	[38]
Goods and Service Tax	10% of selling cost, based on the profit margin of locally produced alternative fuel	[39]
Carbon reduction credit	40 AUD/tonnes CO_2	[40]
The estimated cost to manufacture HFCV	70649 AUD, based on the cost published by Miotti et al	[15]
Cost of gasoline vehicle	26709 AUD, Based on current gasoline vehicle price in WA	[41]

*AUD refers to Australian Dollar +Plant is considered to be operated 24 hours and electricity cost is based on peak and off-peak tariff.

Due to the higher GWP emission of hydrogen compared to gasoline, there was a negative carbon reduction credit under the base case scenario. The calculated value was -1.21 cents/VKT. Similarly, the net benefit of the end-user for using hydrogen fuel was also negative due to the higher cost of both the fuel and vehicle compared to its gasoline counterpart. The net benefit of hydrogen fuel with and without the carbon reduction credit was estimated to be -71 and -72 cents, respectively.

4. Scenario Analysis Using Wind-Energy-Based Hydrogen Production

Western Australia is blessed with renewable wind and solar resources. With the small amount of biogas and pumped storage hydro, the wind and solar resources in WA are capable of providing 100% of renewable electricity requirement for the state [20, 42]. These two renewable energy resources along with the skilled workforce of WA could assist in the implementation of the renewable hydrogen projects in the state. Wind electricity is, however, more feasible in WA near the coastline area due to the availability of more wind resources [43, 44]. Hydrogen plant location for the current study was also considered to be near the shoreline of the sea. Besides, most of the renewable energy in WA are currently produced from wind [44]. By considering its potential, a scenario analysis with wind-electricity-based hydrogen production was considered.

4.1 Environmental Sustainability

The revised sustainability results are shown in Table 4. Sample calculations of revised ELCA results related to wind-based scenario has also been provided in Appendix-C for further clarification. A significant environmental benefit was achieved when the hydrogen was produced from wind energy. For example, around 69% and 65% reduction has been achieved compared to gasoline respectively in regard to GWP and FFD impacts. Biswas et al. 2013 [11] found that, wind-generated hydrogen production in WA had the potential of 97% GWP reduction compared to gasoline. The 69% reduction in this study was comparable with the previous study, given the fact that the additional impacts associated with the modification of the hydrogen fuel cell vehicle were considered in the analysis.

Table 4 Improved sustainability scenario with wind power.

Indicators	Revised results	Comparison with base case	Comparison with gasoline
GWP	7.76E-02 kgCO_2/VKT	86% reduction	69.36% lower than gasoline
Land use	4.33E-07 ha.a/VKT	85% reduction	2.28 times higher than gasoline
Water consumption	7.79E-04 m^3/VKT	48% reduction	26% higher than gasoline
FFD	1.01E+00 MJ/VKT	81% reduction	65% lower than gasoline
Local job creation	Without LVAP*: 4.34E-04 man-hours/VKT With LVAP*: 1.48E-03 man-hours/VKT	Without LVAP*: 44% higher With LVAP*: 12% higher	Without LVAP*: 28 times higher than gasoline With LVAP*: 96 times higher than gasoline
OHAS	5	-	-
Human health	Same as base case	-	-
Conservation of fossil fuel	1.90 MJ/VKT	81% reduction	65% lower than gasoline
+Life cycle cost	58 Cents/VKT	27% reduction	7.09 times higher than gasoline
Carbon reduction credit	0.70 cents/km	158% increase	Gasoline carbon emission is considered as reference.
+Net benefit	Without carbon reduction credit: -49.53 cents/km With carbon reduction credit: -48.80 cents/km	Without carbon reduction credit: 30% increase With carbon reduction credit: 32% increase	Gasoline cost is considered as reference (8.13 cents/VKT).

*LVAP: Local vehicle assembly plant; +Electricity for hydrogen plant is considered to source directly from wholesale electricity market through power purchase agreement (PPA).

Slightly higher amount (26%) of the life cycle water consumption compared to that of gasoline was, however, realized even after considering the wind-generated electricity. This increased use of water may not affect the sustainability of the fuel as seawater is used as feedstock in the hydrogen production plant. Besides, wastewater can also be utilized as hydrogen fuel feedstock. It has been found that around 360 ML wastewater per day is treated by the three large plants in WA [45]. One of these facilities, called the Woodman point Water Treatment Plant (WWTP), is located within 16 km of the Kwinana Industrial Area and has the capacity to treat 140 ML litre of water per day [46]. The use of only 7% water from this plant can fulfil the requirement for all the hydrogen required for the state to replace gasoline, as shown in Table 5.

Table 5 Calculation for the percentage of water requirement for hydrogen production from Woodman point wastewater treatment plant.

Description of calculation	Calculated values
Capacity of Woodman point wastewater plant (A)	140 ML/day [46]
Gasoline requirement for the state (B)	6.20 ML/day [8]
Equivalent hydrogen (C= B÷6) i.e. 1 kg hydrogen is equivalent to 6 L of gasoline according to driving distance per km	1.03 ML/day
Water requirement (D= C×9) i.e. 1 kg hydrogen requires 9 kg of water [47]	9.30 ML/day
Percentage of water requirement from woodman point plant (E=D÷A)	0.066 ≈ 7%

Similarly, higher land use impact for the hydrogen compared to gasoline may not be the issue in the near future as WA has an enormous amount of land to realize its clean energy potential [48]. However, efficiency improvement of these renewable energy technologies is required to produce more power per unit of land, and to address land scarcity and associated deforestation and the loss of biodiversity.

4.2 Social Sustainability Results

Local job creation potential was increased to 1.48E-03 man-hours/VKT with the wind generated hydrogen, which was 12% higher than the grid electricity-based hydrogen model and 96 times higher than the base gasoline. The local job creation potential under renewable energy scenarios was also found to be 28 times higher than gasoline, even without the local assembly plant. The reason for the increase in local job creation with wind electricity was due to the fact that the decentralized electricity generation system involved local staff during the operation and maintenance phase and an increase in jobs in the manufacturing stage as opposed to the centralized electricity grid system [49]. The increase in jobs in the manufacturing phase includes jobs in the local steel industries to supply raw materials for wind turbines [49]. A significant amount of the life cycle fossil fuel conservation (1.90 MJ/VKT) can also be achieved by completely replacing the electricity grid with electricity from wind energy to run the hydrogen plant. The human health indicator remained the same as for the base case scenario as wind energy had nothing to do with the combustion of hydrogen fuels. Similarly, the OHAS score also remained the same as the base case scenario. The respondents expressed that occupational health and safety would further increase with the use of renewable electricity due to the reduction of the hazardous environment compared to fossil fuel-based electricity.

4.3 Economic Sustainability

Renewable electricity for hydrogen production in Australia can be generated at a low price through the long-term power purchase agreement (PPA) with power producing entities [18]. PPA ensures that the electricity is sold at an agreed price for a longer period of time, which is usually subjected to a change up to a certain level based on the wholesale market spot price [50]. This price in Australia could be as low as 6 cents/kWh [18]. An estimated price of 8.3 cents/kWh was considered for this study based on the current wholesale spot price in the Australian national electricity market [51].

Hydrogen fuel cost was found to be 9.6 cents/VKT after considering PPA based wind electricity for hydrogen production plant. The utilisation of the following strategies can make the cost of hydrogen fuel in WA similar to that of gasoline:

- About 5% of cost during production stage can be reduced due to the utilisation of oxygen by-product from the hydrogen production plant [35],
- Soft loans and subsidies can be considered for reducing the capital cost of the hydrogen plant,
- Currently, the goods and service tax (GST) is applied to the end user during the purchase of fuels. Removal of the GST from renewable hydrogen to promote clean burning fuel sale for the public user can reduce the selling cost by 10% [52].

The life cycle cost of hydrogen was, however, 56 cents/VKT with the additional cost of HFCV (around seven times higher than gasoline) even if the hydrogen fuel cost was similar to gasoline. Similarly, the calculated net benefit (-48.05 cents/VKT) of using hydrogen compared to gasoline was found to be negative. This was due to the fixed additional cost of the hydrogen powered vehicle (i.e. 43,940 AUD) compared to the gasoline powered vehicle. This significant additional vehicle cost cannot just be covered by the subsidy. More research and development and supply chain improvement are required to reduce the cost of the vehicle. To do that, it is essential to expand the use of hydrogen for public transport in WA, like it has been in USA, Japan, and Korea to achieve the economy of scale and reduce the price.

5. Conclusion

The TBL sustainability assessment of hydrogen as an automotive fuel in WA has been conducted using the life cycle approach. Gasoline was found to be environmentally friendlier compared to hydrogen when the hydrogen was produced by using the fossil fuel powered electricity grid. The initial assessment results of the model show that the life cycle impact of GWP, FFD, water consumption and land use were 2.20, 1.83, 2.41 and 14.91 times, respectively, higher than gasoline. The life cycle cost was also found to be 71 cents higher than gasoline. Hydrogen was, however, found to be socially sustainable in regard to local job creation, occupational health and safety and human health indicators. It has the potential to create 1.29E-03 man-hours job/VKT locally in WA, including 2.44E-03 man-hours from fuel production and 1.04E-03 man-hours from vehicle assembly. The occupational health and safety aspects were measured based on the respondents' satisfaction.

All the respondents for this study expressed that hydrogen was a safe fuel for passenger cars with the execution of the relevant safety standard protocols.

The life cycle assessment of hydrogen was further analysed using renewable wind energy generation for the hydrogen production to achieve a better TBL sustainability scenario. The overall reductions in the GWP and FFD indicators in respect to gasoline were 69% and 65%, respectively, due to the shift from coal and gas-based electricity to wind electricity generation. There were also 85% and 48% reduction in the land use and water consumption indicators, respectively, under this improvement scenario, but the values were still higher than that of gasoline. Slightly higher water consumption (26%) for hydrogen may not affect the overall sustainability of the fuel as water for hydrogen feedstock is being sourced from the sea. Alternatively, this water requirement could also be fulfilled by using wastewater in WA. It was calculated that only around 7% water from the WWTP could supply all the water needed to generate hydrogen to replace all the gasoline for WA. Similarly, higher land use impact for hydrogen compared to gasoline may also not be an issue for the state due to the vast amount of unused land available to install large capacity wind generators.

Wind electricity-based hydrogen production also has the potential to improve social and economic sustainability. Around 12% and 81% improvement can be achieved in job creation and conservation of fossil fuel indicators, respectively, for the wind hydrogen model compared to using grid-based hydrogen production. It has been found that hydrogen production plants in WA can purchase low cost wind electricity from the wholesale electricity market through PPA with the power producers. Utilization of by-product oxygen during hydrogen production, low cost electricity through PPA for hydrogen production plant and government's supports, such as subsidies on capital cost, soft loan and removal of GST on fuel for the end user can make the hydrogen fuel cost similar to gasoline. Around AUD 44,000 of cost difference was, however, found between the GV and HFCV. The reduction of the cost of the HFCV through supply chain improvement and research and development are required to attain the economic sustainability of the hydrogen as a fuel for passenger vehicles.

Acknowledgement

The authors also would like to thank the respondents for their participation in the surveys.

Additional Materials

The following additional materials are uploaded at the page of this paper.

1. Acronyms.
2. Appendix-A: The calculation procedures of selected indicators.
3. Appendix-B: Summary of inventory regarding water electrolysis and HFCV. Table A1: Inventory for water electrolysis for 1 m3 of water.
4. Appendix-B: Summary of inventory regarding water electrolysis and HFCV. Table A2: Data summary Inventory for HFCV materials.
5. Appendix-C: Sample calculation for ELCA indicators during wind-based hydrogen production.

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.

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Competing Interest

The authors declare no conflict of interest.

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