Environmental life cycle feasibility assessment of hydrogen as an automotive fuel in Western Australia

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ABSTRACT

A life cycle assessment has been undertaken in order to determine the environmental feasibility of hydrogen as an automotive fuel in Western Australia. The criterion for environmental feasibility has been defined as having life cycle impacts equal to or lower than those of petrol. Two hydrogen production methods have been analyzed. The first is steam methane reforming (SMR), which uses natural gas (methane) as a feedstock. The second method analysed is alkaline electrolysis (AE), a mature technology that uses water as a feedstock. The life cycle emissions and impacts were assessed per kilometer of vehicle travel.

Initial results found that hydrogen production under the SMR scenario produced less greenhouse gas, photochemical oxidation and eutrophication emissions per kilometer than petrol. Petrol produced less greenhouse gas and eutrophication emissions than hydrogen produced under the AE scenario, but the only improvement was in the terms of photochemical oxidation emissions. "Hotspot" analysis showed that while the usage life cycle phase of hydrogen produced very few emissions, the reliance on electricity and fossil fuels

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during production was responsible for emission levels higher than those from petrol. After wind-generated electricity was incorporated, the emissions were significantly reduced below the levels of those from petrol under both SMR and AE scenarios. However, with the incorporation of wind-generated electricity, the production of hydrogen, particularly from electrolysis, is more environmentally friendly than the SMR process.

Keywords:
Hydrogen fuel
Life cycle assessment
Environmental feasibility

1. Introduction

There is a growing necessity for an alternate energy carrier to replace the ever decreasing, and high emissions generating, supplies of fossil fuels. This is particularly notable in the transport sector, where the overwhelming majority of vehicles operate on petroleum products [1]. Considering the enormous environmental, and economic impact of the transport industry, the introduction of alternative fuels will be key to a sustainable transport sector [2].

With petrol as the most common vehicle fuel, the Western Australian transport sector generates approximately 14% of the state's total greenhouse gas (GHG) emissions. This is attributable to the heavy reliance on passenger vehicles for most West Australians, coupled with the sparsely populated landscape and large distances between population centers [3]. In 2007, approximately 78.9% of the total vehicle fleet was registered as using unleaded petrol and 85.9% of these vehicles were classed as passenger vehicles [4]. With ownership of private vehicles in Australia on the increase (up 13.1% from 2004 to 2009) [4], transportation is a major factor in the ever increasing demand for fossil fuels [5], in turn having a significant effect on the Western Australian environment [6].

With the overwhelming majority of Western Australia's vehicles operating on petrol, environmentally damaging emissions are constantly being introduced into the atmosphere, resulting in the per capita GHG emissions for Western Australia being significantly higher than for other Australia states [3]. These passenger vehicles are also the primary emitters of nitrogen oxides (NO_x) and volatile organic compounds (VOCs) causing photochemical smog and negative health impacts [7].

Considering the growing atmospheric pollution and the current energy crisis, studies have been conducted in Australia that assess the environmental feasibility of alternative transport fuels such as liquefied petroleum gas (LPG), liquefied natural gas (LNG), bio-diesel and ethanol. While the use of these fuels reduces GHG emissions, they can have other environmental impacts during the combustion stage. For example, ethanol was a potentially renewable fuel with reduced carbon monoxide (CO) emissions compared to petrol, but the NO_x emissions resulting from combustion were significantly higher than those from petroleum products [8].

Alternative fuels may produce relatively less GHGs than conventional fuel during combustion, but more emissions are produced during the production process. For example, a study in 2011 by Biswas *et al.* [9] found that biodiesel production and combustion from canola is not "carbon neutral", as GHGs are emitted from production of farm inputs and during crop growth. Similarly, LNG has been considered one of the safest and cleanest fossil fuels [10, 11, 12, 13, 14, 15] in comparison with other fossil fuels such as coal and oil in terms of NO_x, sulphur dioxide (SO_2) and carbon dioxide (CO_2) emissions, but the production and liquefaction of LNG is energy intensive and not free of environmental impacts. Therefore, a life cycle assessment (LCA) that takes into account emissions from all stages needs to be conducted to assess the environmental impacts of alternative fuels and to identify the most polluting processes for applying mitigation strategies.

Many alternative fuels have been studied over the years; however, the fuel which appears to be a more promising alternative is hydrogen due to its clean burning characteristics and limitless supply. Although research into hydrogen fuel is limited in Australia, a 2003 Australian study identified a number of hydrogen feed stocks suitable for mass production in Australia. These feed stocks included coal, fuel oils, industrial chemical by-products, coal, coal seam methane and natural gas [16].

One of numerous foreign studies into hydrogen as an automotive fuel, a life cycle emissions study for hydrogen fuel production found that hydrogen could potentially be produced with comparatively less emissions than petrol [17]. Similarly, a 2005 Canadian study [18] found that the life cycle emissions from hydrogen could also be comparable to those of petrol when producing hydrogen from natural gas feed stocks. Other studies have assessed the viability of hydrogen from alternative production sources and processes [19, 20, 21].

Western Australia possesses abundant fossil fuel resources, particularly coal and natural gas. Black coal accounts for around 49% of total fossil fuel resources within the state, with natural gas accounting for around 40% and growing as more sources are identified [22]. This makes reforming of natural gas, or steam methane reforming (SMR), an attractive option for Western Australia due to its availability in large reserves. While there are available resources to produce environmentally friendly hydrogen fuel in Western Australia, the upstream activities, such as feedstock production, processing and storage stages, can have adverse environmental impacts because of the state's fossil fuel dependent electricity mix and scattered settlements [8, 22].

This study aims to assess the life cycle environmental feasibility of using hydrogen as an automotive fuel in Western Australia through two commonly used hydrogen production process (SMR and electrolysis). This study utilizes the functional unit VKT (vehicle kilometer travelled) in order to assess the well-to-wheel emissions of vehicles per kilometer of travel, so that there is a common unit of measure between the petrol and hydrogen results.

Firstly, the paper discusses the methodology for carrying out the life cycle environmental feasibility study of hydrogen fuel in Western Australia. Secondly, the life cycle environmental impact of hydrogen fuel has been compared with that of petrol and the "hotspot" – the inputs causing the most pollution – is identified. Finally, appropriate mitigation strategies have been considered for reducing the life cycle environmental impacts of hydrogen fuel use in passenger transport.

2. Methodology

LCAs model the complex interactions between a product and the environment throughout all phases of the product's life. The methodology for this LCA of hydrogen as an automotive fuel has followed the guidelines set out by ISO14040–14043 [23]. The LCA methodology consists of four steps

i. goal and scope
ii. life cycle inventory (LCI) analysis, which provides information on the input data (chemicals and energy) used to determine the life cycle emissions during each life cycle phase
iii. impact assessment, which evaluates the environmental impacts of the emissions of each life cycle phase and classifies impacts into environmental impact categories (e.g. global warming)
iv. Interpretation, which evaluates the LCA model by identifying significant issues based on the results of LCI and LCA, considering completeness and consistency and making conclusions and recommendations (as presented in the results and discussions section of this paper).

2.1. Goal and scope definition

The goal of this life cycle study is to evaluate the environmental feasibility of hydrogen as an automotive fuel in Western Australia. The study also provides a reasonable comparison of the life cycle environmental impacts of hydrogen compared to petrol as a vehicle fuel. For the purposes of this comparative study, the functional unit used is VKT. This allows the identification and comparison of life cycle impacts between hydrogen and petrol vehicles.

Road tests using hydrogen fuel in a Volkswagen Polo (1.4 liter engine) in 2011 gave a maximum speed of 125 km/h and an estimated consumption of 1 kg of hydrogen per 100 km at an average speed of 90 km/h [24]. Therefore, the average consumption of hydrogen (0.01 kg hydrogen/VKT) [24] was used as a functional unit. The same model vehicle with the same engine size consumes 0.059 liters of regular unleaded petrol per kilometer [25]. Using the density of BP unleaded petrol (730 kg/m^3 [26]), the fuel consumption by mass was found to be 0.043 kg/VKT, where VKT is the functional unit for petrol. It should be noted that Volkswagen Polo cars are sold in Australia [27], which justifies their use in this case study.

The life cycle environmental impacts of the use of 0.01 kg hydrogen have been compared with 0.043 kg of petrol for driving a passenger car for 1 km.

This LCA study considers the well-to-wheel approach, which means that it takes into account all stages from resource extraction to eventual fuel consumption.

Three system scenarios have been assessed within this LCA. The first is the LCA of hydrogen as an automotive fuel when the hydrogen is produced by SMR. The second scenario will assess the LCA of hydrogen when the hydrogen is sourced from alkaline electrolysis (AE). Finally, the third scenario is the LCA of petrol for comparison.

The determination of impacts associated with the modification of the existing Volkswagen engine into a petrol–H_2 engine was beyond the scope of this research.

2.2. Life cycle inventory analysis

LCI is the collection of data that describes the inputs required for each stage of the well-to-wheel life cycle. The purpose of these inventories is to provide the basis for an assessment of the environmental impacts of running a vehicle on hydrogen compared to running a vehicle on conventional petrol. Figure 1 presents the life cycle pathways for SMR and AE to produce the same amount of hydrogen required to drive a passenger vehicle for 1 km.

2.2.1. Steam methane reforming scenario

The SMR scenario includes seven life cycle stages of well-to-wheel (or production to combustion), which are as follows:

1. Natural gas extraction and distribution: this phase takes into account the energy and resources required to extract and distribute the gas.
2. SMR: this phase takes into account the natural gas, steam and electricity required for the process. The SMR process is assumed to occur at 20 bar.
3. Compression of the hydrogen into large transport trailers: SMR produces hydrogen gas at pressures of around 20 bar; however, large-scale CP-12 hydrogen delivery trucks have 12 storage tubes which operate at 165 bar [28]. Therefore a compressor is used to increase the pressure of the hydrogen to 165 bar for travel and delivery.
4. The distribution of hydrogen gas by tanker truck: the CP-12 hydrogen delivery trailers weigh 42.5 tons and are typically pulled by large diesel trucks. The mean delivery distance was also calculated based on Western Australia. BP locations and the average distance were found to be 233 km. This phase takes into account delivery distance and diesel consumption by a tanker truck.
5. The compression of the hydrogen into medium-term storage tanks at the fuelling station: mid-term storage tanks at fuelling stations contain hydrogen at 300 bar to allow for faster refueling of vehicle tanks [29]. This means that the hydrogen must again be compressed from 165 bar in the delivery tanker tubes to 300 bar using an electrical compressor. The energy required to pump petrol into a fuel

tank was not considered as it is negligible when compared with the energy required to compress hydrogen into a vehicle tank.

6 The compression of the hydrogen into smaller vehicle fuel tanks: from the 300 bar storage cylinders at the fuelling station, the hydrogen gas needs to be compressed to 350 bar inside the vehicle fuel tank [30, 31]. Again, this process is performed by an electrical compressor.

7 Hydrogen used by vehicle: the emissions associated with hydrogen combustion have been sourced from Wallnera *et al*. [32].

Table 1 details the inputs and quantities required for production, delivery and combustion of 0.01 kg of hydrogen gas produced through SMR.

2.2.2: Alkaline electrolysis scenario

LCA for the AE scenario includes five life cycle stages of well-to-wheel analysis, which are as follows:

1 Electrolysis process: this phase takes into account the water, electricity and electrolytes used during the electrolytic process (Table 2). The process used as a basis for this research operated at 8.14 bar [31].

2 Compression of the hydrogen into large transport trailers: compression into the transport trailer requires more energy when the hydrogen is produced by AE as the hydrogen gas is produced at a lower pressure than during SMR. This phase takes into account the electricity required to compress the hydrogen from 8.14 bar to 165 bar for transport.

3 The distribution of hydrogen gas by tanker truck: the distribution method is identical to when hydrogen is produced by SMR.

4 The compression of the hydrogen into medium-term storage tanks at the fuelling station: as with the SMR scenario, the electricity required to compress the hydrogen from 300 bar to 350 bar is taken into account in this phase.

5 Hydrogen use by vehicle: this is same as for SMR.

A separate inventory for petrol has not been developed as the software used has the emission values of petrol production and use.

2.3 Life cycle impact assessment

The environmental impacts associated with the production and use (combustion) of hydrogen includes two steps. Firstly, the energy and material flow data provided in the LCI were input to *Simapro* 7.24 software [33] to calculate the environmental impacts of the production and use of hydrogen fuel. Secondly, the program categorized the emissions for all impact categories and then converted them to equivalent environmental impacts, including global warming, photochemical oxidation, eutrophication, carcinogens, land use, water use, solid waste, embodied energy and mineral depletion impacts.

Step 1: The input and output data in the LCI were input to the *Simapro* software to calculate the emissions for different environmental impact categories due to the use of hydrogen and petrol per VKT. The input/output data of the LCI were linked to relevant libraries in *Simapro*. The LCA Library is a database of energy consumption, emissions and materials data for the production of one unit of an input (e.g. electricity, diesel).

This study utilized the Australian LCA libraries [34] developed by RMIT University for Australian conditions to calculate the emissions associated with the production and use of inputs. The library for the Western Australian electricity generation mix was used to calculate the environmental impacts associated with the use of electricity for hydrogen production, storage and compression [34].

Step 2: *Simapro* software calculated the environmental impacts once the inputs and outputs were linked to the relevant libraries. The program sorted the relevant emissions for particular impacts, and then converted them to an equivalent amount of environmental impacts. The Australian Environmental Impact calculation method, developed locally [34], was used to assess the environmental impacts of the use of hydrogen and petrol for VKT.

3. Results and discussions

3.1. Comparison of environmental performance of hydrogen with petrol

The comparative environmental performance of three scenarios has been carried out. The first scenario is the life cycle of hydrogen when the hydrogen is produced by SMR. The second scenario is for hydrogen produced by AE. The last scenario is the life cycle of petrol.

Contributions to global warming, photochemical smog and eutrophication have been found to be the predominant environmental impacts in these three scenarios (Figure 2). While hydrogen is a cleaner burning fuel than petrol, the AE scenario produces more life cycle global warming and eutrophication impacts than the latter in the petrol scenario. This is mainly due to the emissions of CO_2 (causing global warning) and NO_x (nitrogen oxides causing euthrophication) from electricity and diesel consumption during upstream activities (alkaline electrolysis, compression for distribution and storage, and transportation) being higher than those for petrol.

The life cycle global warming impacts due to the use of hydrogen produced in the AE scenario are 2.3 times greater than those of petrol. Walwijk *et al.* [35] also found that CO_2-e emissions from electrolytic hydrogen production and use would be higher (approximately 1.6 times) than those from petrol. There are similar results in terms of emissions for eutrophication. Figure 2 indicates that PO_4^--e eutrophication emissions from the AE scenario are significantly greater than for petrol. However, in terms of photochemical oxidation emissions, the results are quite different. Both the hydrogen scenarios produce less SO_x and NO_x (C_2H_2-e emissions) throughout the life cycle from a photochemical perspective.

The SMR scenario produces slightly lower environmental impacts than the petrol scenario. About 4%, 91% and 23% of the global warning, photochemical smog and euthrophication impacts, respectively, can be avoided due to the replacement of petrol with hydrogen fuel produced under the SMR scenario. In addition, hydrogen production from the SMR scenario is less harmful to the environment than the from AE scenario in its global warming, photochemical smog and euthrophication impacts, because electricity consumption in the AE scenario is about 6.7 times higher than that in the SMR process (Tables 1 and 2).

The life cycle emissions from the AE scenario were found to be significantly higher than for the SMR scenario across every environmental impact category. This is likely attributable to the large quantities of coal (37%) and natural gas (60%) in the Western Australian energy mix required to produce the electricity for electrolysis; however, this will be examined in more detail in the following section. Further investigation has been carried out to determine the inputs or processes causing the most environmental impacts (hotspots) so that the appropriate mitigation strategies can be considered for making hydrogen fuel environmentally competitive with petrol.

3.2 Breakdown of environmental impacts of the use of hydrogen produced by steam methane reforming

In order to find the hotspots, the percentage distribution of global warming, photochemical, and eutrophication impacts in terms of inputs for the SMR and AE scenarios have been determined (Table 3).

Greenhouse Gas Emissions: The majority (88.64%) of GHGs are generated by SMR, the generation of electricity and the production of steam. The SMR process itself produces the largest amount of CO_2-e (44.9% of the total emissions).

The generation of electricity, in particular from coal and natural gas, produces the second largest amount of CO_2-e. This life cycle phase accounts for 29.6% of the total emissions due to the heavy reliance on fossil fuels as the primary source of fuel for generating electricity. The production of steam is also a carbon intensive process, accounting for 15.5% of the total emissions.

The results of the SMR model in a 2007 Canadian study (0.3602 kg CO_2-e per VKT) are similar to those in the current study (0.252 kg CO_2-e per VKT) [36]. The difference in emission output is likely attributable to the technical efficiency improvement during this period. The average hydrogen fuel consumption during 2006–12 was 0.0227 kg/VKT, while the present study considered the latest consumption figure in 2011 (0.01 kg/VKT). The emissions breakdown clearly indicates that for GHG emissions to be reduced, improvements need to be made to the aforementioned CO_2-e intensive life cycle phases.

Photochemical Smog Emissions: The major life cycle phases contributing to photochemical emissions are also the production of steam, the steam reforming operation and electricity generation. Together, these three life cycle phases represent 63% of the total C_2H_2-e emissions due to significant levels of NO_x and VOCs released into the atmosphere. The second largest contribution is from tailpipe emissions (30%), mainly NO_x.

Eutrophication Emissions: Eutrophication emissions are produced primarily from the production of steam, the production of electricity and from the steam reforming process. In total, these processes account for 86.83% of the total of eutrophication emissions**.** Producing the steam required for reforming emits 0.016 g of PO_4^--e per VKT while the generation of electricity for the steam reforming and compression processes produces 0.0385 g of PO_4^--e per VKT.

3.3 Breakdown of environmental impacts of the use of hydrogen produced by alkaline electrolysis

Table 3 also shows the breakdown of global warming, photochemical, and eutrophication impacts that would result from the production and use of hydrogen fuel generated by AE. Greenhouse Gas Emissions: The overwhelming majority of life cycle GHGs emitted during the alkaline electrolysis scenario are attributable to the generation of electricity. Table 1 shows that 93.1% of the total GHG emissions are generated from the electricity supply, of which 78.3% of the CO_2-e comes from electricity generation from coal and 14.8% comes from electricity generation from natural gas. AE is very energy intensive, requiring 62.7 kWh per kilogram of hydrogen production which equates to 0.63 kWh per VKT. Although AE itself is virtually emission free, generating the required electricity is currently very carbon intensive.

Photochemical Oxidation Emissions**:** Table 3 clearly shows that electricity generation from coal and gas accounts for 73.4% of total C_2H_2-e emissions; however, vehicle tailpipe emissions are also significant. Tailpipe emissions account for 16.5% of the total C_2H_2-e emissions and this is attributable to the combustion of hydrogen within the vehicle engine. NO_x, as well as fugitive hydrocarbon emissions, are also emitted during electricity generation and contribute to the development of photochemical smog.

Eutrophication Emissions: The majority of the emissions (about 93.9%) causing eutrophication are generated during the production of electricity from coal and natural gas, with these processes contributing 84.6% and 9.3% respectively. The first compression stage of hydrogen gas is somewhat significant with a 2.5% contribution. Producing the electricity required for electrolysis emits 0.3 g of PO_4^--e per VKT while the compression processes produces 0.008 g of PO_4^--e per VKT.

3.4 Mitigation and reduction of emissions using wind

The previous sections identified electricity generation as a major source of global warming, photochemical oxidation and eutrophication emissions for both the SMR and AE scenarios. It is clear from the breakdowns of the life cycle emissions that reducing the carbon intensity of electricity production would have the greatest environmental benefit and would significantly reduce total emissions in each impact category.

The implementation of wind-generated electricity for hydrogen production has the potential to substantially reduce the emissions across all impact categories in every life cycle phase, excluding for the vehicle use phase as the only input is hydrogen gas.

Wind power is a promising technology in Australia with a potential to generate renewable and virtually emissions-free electricity. As of 2009, Western Australia’s wind energy capacity was 202.7 MW which represents a significant investment [37] and currently Western Australia has 42 operating wind farms [38,39].

Wind technology is poised to be a potential solution to reducing emissions during hydrogen production by greatly reducing reliance on coal and gas. The potential benefits are greatest for the AE scenario as the only life cycle phase which relies directly on fossil fuels is the transportation of hydrogen by diesel truck.

The emissions from the SMR scenario will also benefit from lower emission levels; however, there is still a reliance on fossil fuels, particularly natural gas, during the extraction and steam reforming processes. This means that although emissions from electricity production will be reduced, there is still potential for significant environmental impacts resulting from the use of fossil fuels.

The efficacy of wind electricity needs to be assessed for both the SMR and AE scenarios before any conclusions can be made regarding the net environmental effects. Figure 3 shows that the environmental impacts can be significantly reduced due to the use of wind energy in the production, delivery and storage of hydrogen fuel. This is because the substitution of coal and natural gas powered electricity with wind generated electricity for production and storage purposes have significantly reduced the emissions of CO_2, NO_x and O_3, which cause global warming, euthrophication and photochemical smog impacts, respectively. About 31%, 19% and 35% of the total global warming, photochemical smog and eutrophication impacts can be reduced by using wind electricity in the SMR scenario. In the AE scenario, global warming and eutrophication impacts have been almost completely eliminated (by 99%) with the use of wind energy in the life cycle of hydrogen fuel.

The replacement of grid electricity with wind electricity could make hydrogen fuel environmentally competitive with petrol from the global warming, photochemical smog and eutrophication impacts perspectives. Although the SMR scenario using grid electricity (coal and natural gas mix) produced less environmental impacts than petrol, a further reduction in environmental impacts is possible when grid electricity is replaced with wind-generated electricity. About 37%, 91% and 64% of the total global warming, photochemical smog and eutrophication impacts can be reduced by replacing petrol with hydrogen fuel under the SMR scenario with wind-generated electricity. The AE scenario has significant potential to reduce global warming (97%), photochemical smog (96%) and eutrophication (98%) impacts due to replacement of petrol with hydrogen fuel.

Therefore, the use of wind-generated electricity in the hydrogen fuel cycle not only reduces overall environmental impacts in hydrogen fuel production but also makes the hydrogen fuel environmentally friendlier than petrol. When grid electricity was used for hydrogen production, the SMR scenario appeared to be more environmentally friendly than the AE scenario. Interestingly, if wind is only source of electricity used in hydrogen production, then the AE scenario becomes much more environmentally friendly than the SMR scenario.

4 Conclusions and recommendations

LCA has been demonstrated as an effective tool for modeling and quantifying the environmental impacts from the use of hydrogen as an automotive fuel. Global warming, photochemical smog and eutrophication have been found to be the predominant environmental impacts associated with the use of hydrogen fuel produced from both SMR and AE. The initial results of the models found that the SMR scenario emitted 0.252 kg of CO_2-e, 0.000079 kg of C_2H_2-e and 0.00012 kg of PO_4^--e per VKT. The AE scenario was found to emit 0.67 kg CO_2-e, 0.000139 kg of C_2H_2-e and 0.000322 kg of PO_4^--e per VKT.

In order to determine the feasibility of hydrogen as an automotive fuel, the life cycle impacts were compared to those of petrol. When grid electricity is used in the hydrogen fuel life cycle, the use of hydrogen fuel was found to be environmentally friendlier than petrol from global warming, photochemical oxidation and eutrophication perspectives under the SMR scenario. Except for the photochemical smog impact, the AE scenario produces higher global warming and eutrophication impacts than petrol. The global warming and eutrophication impacts associated with the production and use of petrol have been found to be 2.3 and 1.8 times lower than hydrogen fuel produced from the AE scenario, respectively. For both the SMR and AE scenarios, electricity was a major source of emissions; however, the AE model required nearly seven times the electricity of the SMR model, hence the greater environmental impacts. Natural gas was also a major source of emissions, particularly in the SMR model, as it was required in large quantities during the SMR process.

In order to mitigate the environmental impacts further, the LCAs were reworked so as to incorporate electricity from wind turbines to reduce the reliance on coal and gas. The results from the wind hydrogen models revealed significant improvements in all impact categories and emissions reduction below the levels of petrol.

However, the situation is different when electricity generated by wind is incorporated into the LCA analysis. The incorporation of wind-generated electricity into the SMR model reduced the global warming impact (CO_2-e), photochemical smog (C_2H_2-e) and eutrophication (PO_4-e) emissions by 31%, 19% and 35.0% respectively. More impressively, the CO_2-e, C_2H_2-e and PO_4^--e emissions from the AE model were reduced by 99%, 84% and 99% respectively. Also, hydrogen production can be environmentally feasible compared to petrol under the AE and SMR scenarios when the electricity is generated by wind.

The results of this study could be improved by widening the scope to include consideration of economic factors. The study has indicated that, from an environmental perspective, both hydrogen models can be made feasible by incorporating wind-generated electricity. However, the capital costs of wind-generated electricity have not been considered, nor the prices of grid electricity. For instance, a preliminary review of capital costs found that South West Interconnected System (SWIS) connected wind farms commissioned in Western Australia after 2000 cost, on average, $2.22 million/MW of output [40]. The cost of natural gas and water could also be incorporated into the models to provide an improved environmental-economic analysis, particularly for the SMR model.

This study also assumed that for the wind scenario, the electricity needed for compressing the hydrogen gas was sourced from wind generation. Given that the models employed centralized hydrogen production, where hydrogen gas was transported from a production facility to fuelling stations within the metropolitan area, it is inaccurate to assume that the electricity used at the fuelling station would be sourced from wind turbines. A more accurate emissions model could be developed if the electricity required for compressing the hydrogen was sourced from SWIS.

The study could also include alternative hydrogen storage systems, such as cryogenic liquid hydrogen tanks or hydride systems, as opposed to compressed hydrogen tanks, which may require less energy during refueling.

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Table 1 Life cycle inventory for 0.01 kg of hydrogen required for 1 km of travel using SMR

Inputs	Amount	Unit	Reference
Extraction of natural gas			
Electricity	2.22E-02	kWh	[35]
SMR of natural gas			
Electricity	6.56E-02	kWh	[17]
Natural gas	3.92E-02	kg	
Steam	1.88E-01	kg	
Compression for distribution			
Electricity	2.27E-02	kWh	[39]
Distribution to fuelling station			
Diesel Fuel	0.20	L	[41]
Compression for storage at fuelling station			
Electricity	2.23E-03	kWh	[39]

Compression for storage on board vehicle			
Electricity	5.37E-04	kWh	[39]
Vehicle usage			
NO_x emissions	2.20E-05	kg	[30, 32]
CO_2 emission	8.19E-04	kg	

Table 2 Life cycle inventory for 0.01 kg of hydrogen required for 1 km of travel using AE

Input	Amount	Unit	Reference
AE process			
Electricity	0.63	kWh	[31]
Potassium hydroxide (KOH)	7.05E-05	kg	
Water	0.11	kg	
Compression for distribution			
Electricity	4.00E-02	kWh	[39]
Distribution to fuelling station			
Diesel fuel	0.20	L	[41]
Compression for storage at fuelling station			
Electricity	2.23E-03	kWh	[39]

Compression for storage on board vehicle			
Electricity			
	5.37E-04	kWh	[39]
Vehicle usage			
Hydrogen	1.00E-2	kg	[30, 32]

Table 3 Breakdown of three major impacts in terms of inputs for two hydrogen production processes

	Global warming impact		Photochemical smog		Eutrophication	
	kg CO_2-e/VKT	%	kg C_2H_2-e/VKT	%	kg PO_4-e/VKT	%
SMR process						
Electricity supply	7.47E-02	29.6%	1.27E-05	17.3%	3.85E-05	32.0%
Steam reforming operation	1.13E-01	44.9%	1.17E-05	16.0%	1.68E-05	14.0%
Steam production from natural gas	3.92E-02	15.5%	2.2E-05	30.1%	4.91E-05	40.8%
Natural gas extraction for steam reforming	1.30E-02	5.2%	2.56E-06	3.5%	5.94E-06	4.9%
Compression of hydrogen for tanker delivery	9.52E-03	3.8%	1.72E-06	2.4%	5.10E-06	4.2%
Compression of hydrogen at the Fuelling station	2.12E-03	0.8%	3.8E-07	0.5%	1.13E-06	0.9%
Hydrogen distribution via tanker truck	2.27E-04	0.1%	6.58E-08	0.1%	1.20E-07	0.1%
Compression of hydrogen for vehicle tank	5.05E-04	0.2%	8.78E-08	0.1%	2.65E-07	0.2%
Vehicular emission	0.00E+00	0.0%	2.2E-05	30.1%	3.28E-06	2.7%

Total	2.52E-01	100.0%	7.31E-05	100.0%	1.20E-04	100.0%
AE process						
Electricity supply	6.23E-01	93.09%	1.02E-04	73.37%	3.03E-04	93.86%
Compression of hydrogen for tanker delivery	3.24E-02	4.84%	8.32E-06	5.98%	7.96E-06	2.47%
Electrolysis of water	8.04E-03	1.20%	4.87E-06	3.50%	6.61E-06	2.05%
Compression of hydrogen for storage	4.35E-03	0.65%	7.52E-07	0.54%	1.74E-06	0.54%
Compression of hydrogen for vehicle tank	1.07E-03	0.16%	1.11E-07	0.08%	2.58E-07	0.08%
Hydrogen distribution via tanker truck	2.68E-04	0.04%	6.96E-08	0.05%	9.67E-08	0.03%
Production of KOH	1.34E-04	0.02%	2.78E-08	0.02%	3.22E-08	0.01%
Vehicular emissions	0.00E+00	0.00%	2.29E-05	16.46%	3.10E-06	0.96%
Total	6.70E-01	100.00%	1.39E-04	100.00%	3.22E-04	100.00%

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Figure 2 Hydrogen models compared to conventional petrol model on an environmental impact basis

Figure 3 Implication of mitigation strategies

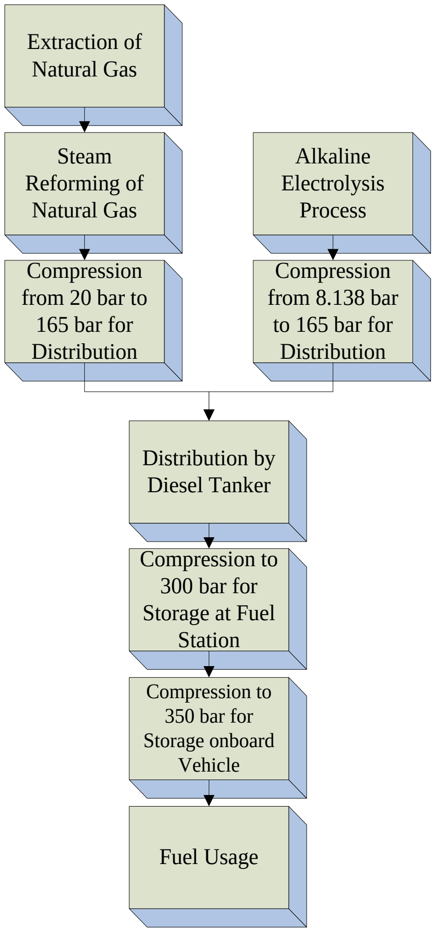

Figure 1 Simplified block diagram for hydrogen fuel life cycle models

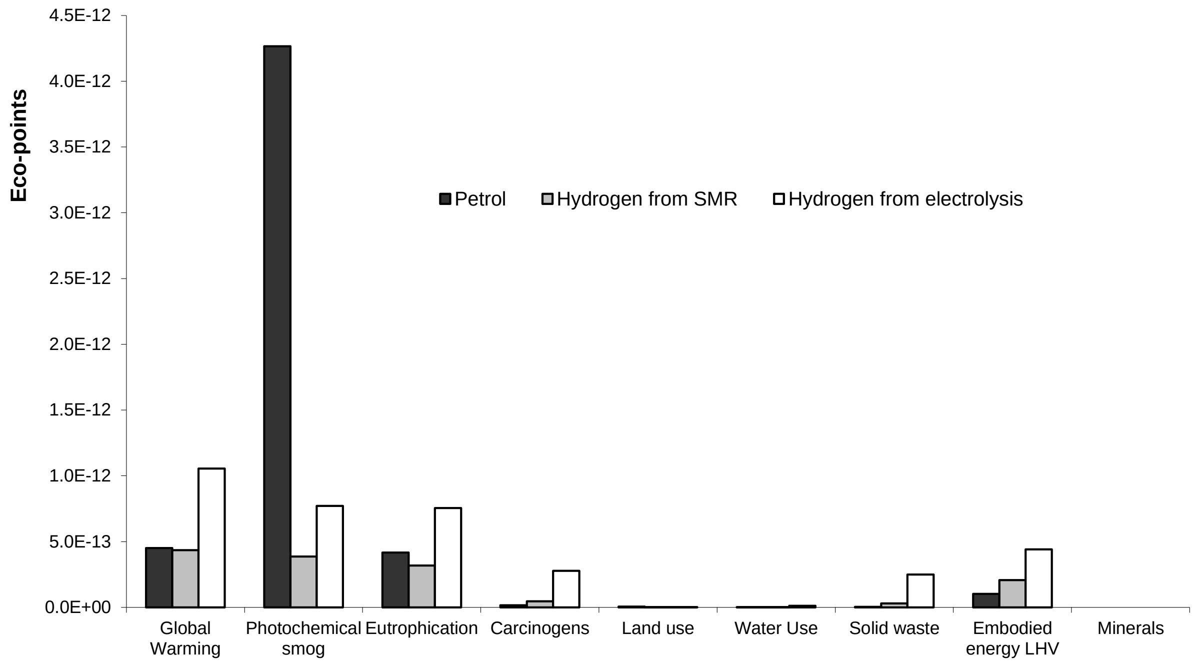

Figure 2 Hydrogen models compared to conventional petrol model on an environmental impact basis

Note: eco-points represent the relative importance of environmental impacts assigned by industry and society.

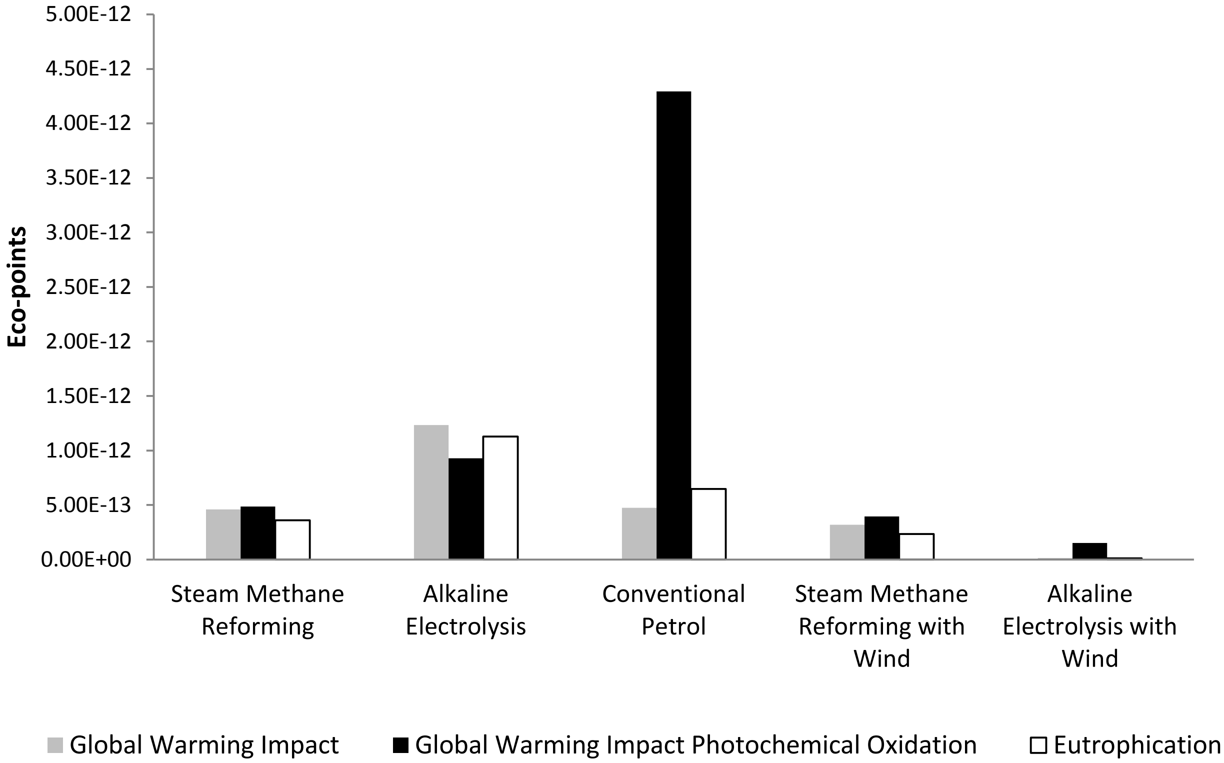

Figure 3 Implication of mitigation strategies