Thesis for Master of Research (MRes) Degree

Life cycle economic and environmental impact assessment of alternative transport fuels and power-train technologies

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April, 2016

Declaration

I certify that work in this thesis entitled "Life cycle sustainability assessment of alternative transport fuels and power-train technologies" has not previously been submitted for a degree nor it has been submitted as part of requirements for a degree to any other university or institution other than Macquarie University.

I also certify that the thesis is an original piece of research and it has been completely written by me. Any assistance and insights received for my research have bene properly acknowledged.

Finally, I certify that all the information sources and the literature used are properly cited in this thesis.

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Abstract

In this study, we assessed the economic and environmental life cycle impacts of alternative transport fuels via a life cycle approach. The selected fuels include diesel, petrol, LPG, biodiesel, ethanol, hydrogen and electricity. The life cycle analysis is confined to the fuel cycle analysis and it has been divided into 2 major components – (1) Well-to-Tank (WTT) and Tank-to-Wheel (TTW). The system boundary consists of the following three phases: (i) material extraction, (ii) processing and production phase, and (iii) the use phase. The functional unit is defined as "One MJ of fuel input" and "One kilometre distance driven". The modelling is performed using SimaPro 8.05 life cycle assessment software using Recipe mid-point hierarchist methodology for calculating characterisation results and Recipe end-point hierarchist methodology for calculating single score results. The fuel life cycle emissions reported in this study are: air emissions (including greenhouse gas emissions and criteria air contaminants); emissions to water and emissions to soil in µg/MJ. The techno-economic analysis include capital and operating costs. Finally, we combined the environmental life cycle assessment results with economic impact assessment results after normalizing the results with respect to diesel as a reference fuel. Overall, the combined results of environmental and economic impact assessment suggest that the impacts are the highest for CNG followed by LPG, biodiesel and minimum for hydrogen fuel cell vehicles.

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Abbreviations and acronyms

ADP	Abiotic depletion potential
AP	Acidification potential
BEV	Battery electric vehicle
CAC	Criteria air contaminants
CV	Commercial vehicle
CNG	Compressed natural gas
EP	Eutrophication potential
ET	Eco-toxicity
FFV	Flexi fuel vehicle
g CO2-eq.	Grams CO_2 equivalents
GHG	Greenhouse gas
GREET	The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GWP	Global warming potential
HEV	Hybrid electric vehicle
ICEV	Internal combustion engine vehicle
LCI	Life Cycle Inventory
LDCV	Light duty commercial vehicle
LPG	Liquefied petroleum gas
NO_x	Nitrogen oxide
$PM_{2.5}$	Particulate less than 2.5 micron
TTW	Tank to wheel
WTT	Well to tank
US EPA	United States Environmental Protection Agency

1. Introduction

1.1. Life cycle assessment (LCA) framework

Life cycle assessment (LCA) is described as a science-based technique to systematically assess resource consumption and potential environmental impacts associated with a product or service throughout its whole life cycle, from extraction via manufacturing and use to end-of-life by compiling an inventory of relevant energy, material, water and land inputs, and releases to the environment (Wolf et al., 2012).

LCA is known as a 'cradle-to-grave' assessment of systems, ranging from extraction of raw materials from the earth to manufacturing, product use, and recycling/disposal at the end. All life cycle stages are addressed from the perspective that each stage depends on the one before it. Thereby, all environmental aspects are considered in order to provide the most reliable estimations of the trade-offs in technology selection. Figure 1 shows the basic framework for conducting a life cycle assessment. The first step is to define the goals and scope of the study. The second step is to compile an inventory of material, energy, and environmental data required for the analysis. The third stage, in accordance to ISO 14040 standard, is known as life cycle impact assessment. Finally, the results are interpreted to aid the decision-making process. A comprehensive LCA helps to avoid shifting environmental problems from one place to another, as the entire system that brings about a technology or fuel is considered (Shahraeeni et al., 2015).

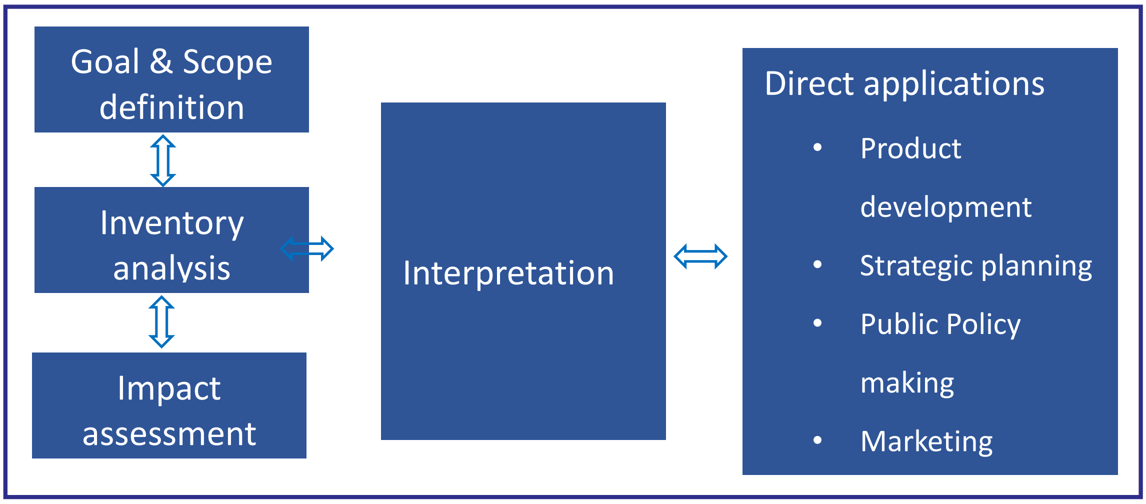

Figure 1. Framework for Life cycle assessment based on ISO 14040:2006.

Incorporating LCA into process design can help identify hotspots early and avoid risks associated with environmental certifications, and thus, ultimately improving the environmental aspects of products at several points of their lifecycles (Silva et al., 2014, Daystar et al., 2015). These environmental improvements promote cost savings, by reducing the generation of waste and rationalizing the use of resources, as well as brand and reputation benefits (Silva et al., 2014).

1.2. Aims of the study

The aim of this study is to conduct a holistic sustainability assessment of the alternative fuels and powertrains in the transport sector (with a special focus on road transport). The selected fuels include diesel, petrol, LPG, biodiesel, ethanol, hydrogen fuel cell and electricity. To summarize, this study has following key objectives:

1. Identify the gaps and variability in the existing literature about Life Cycle Assessment (LCA) of alternative transport fuels (such as biofuels, hydrogen fuel cell and electricity) and advance vehicle powertrains and thus, highlight the most important sustainability indicators used in the previous studies.
2. Compare the environmental impacts of different fuel cycle stages including – (1) raw material acquisition, (2) processing, (3) production and (4) operation phases of the selected alternative transport fuels and vehicle powertrains to identify which alternative fuel and vehicle powertrain combinations are – (1) economically efficient; and (2) best suited for mitigating environmental life cycle impacts (GHG emissions and criteria air contaminants) of the transport sector.
3. Conduct a techno-economic analysis for evaluating the economic impacts of selected fuel technology and vehicle powertrains.

1.3. Thesis outline

This thesis consists of 5 chapters. Chapter 1 relates to the introduction with the concept of life cycle assessment including the aims and objectives of this study. Chapter 2 is the literature review of the existing studies in this area of research. Here, we have critically assessed and surveyed the literature to identify the gaps in the existing studies, required to define the research objectives of our study. Chapter 3 discusses the methods used in our study. In this chapter we discussed (i) how we obtained the relevant data for our analysis via selected methodological approaches, such as accessing databases, literature survey and models; (ii) how we conducted the life cycle assessment using the Simapro model in our study; (iii) how we conducted the techno-economic assessment; and (iv) how we combined the two analysis (ii) and (iii) together to obtain combined results of environmental and economic assessment for selected fuel technology and vehicle powertrain combinations. In Chapter 4, we discuss the results of our analysis. Finally, in Chapter 5, we include summary and conclusions based on the findings of our study. This section also includes recommendations for future research.

2. Literature Review

2.1 Existing LCA studies of alternative transport fuels

Greenhouse gas (GHG) emissions from vehicles are commonly evaluated using traditional methods, such as vehicle simulation and vehicle tests, to estimate tail pipe emissions during the use phase of the vehicles. However, these tests are inadequate since such tests conventionally do not include the emission results from sources other than vehicle tailpipe. Therefore, the life cycle assessment (LCA) studies are preferred to counteract such limitations by incorporating different phases of the vehicle life cycle while considering the data from vehicle simulations to reflect vehicle emission tests and drive cycles (Tong et al., 2015). In the context of transportation systems, it is recommended that the LCA of a vehicle technology should include both the vehicle cycle impacts (such as vehicle production, manufacturing, and recycling) and the complete fuel cycle impacts (including fuel production, transport and the driving phase where the fuel is consumed) (Shahraeeni et al., 2015).

The unavailability of appropriate methods, tools and data poses challenges in precisely evaluating the broader social and economic impacts of road sector transport. A number of transport sector LCA studies (Arpornpong et al., 2015, Brondani et al., 2015, Ning et al., 2013, Petersen et al., 2015) conducted in the past are primarily focussed on the confined environmental impact categories, such as greenhouse gas emissions, energy consumption and some mid-point indicators. In contrast, it is imperative to consider the socio-economic effects of transportation representing the general well-being of individuals and societies, for example, accessibility, affordability, equity, travel time, congestion and noise (Onat et al., 2014b). Furthermore, Onat et al. (2014b) discussed the relatively new concept called Life Cycle Sustainability Assessment (LCSA) as an effective tool for conducting sustainability assessment research to cover triple bottom line (TBL) impacts, such as social, economic and environmental impacts. Similarly, in an another study by Luthra et al. (2015), they emphasized that sustainability assessment is particularly relevant in the context of developing countries since sustainability essentially accounts for common societal issues, such as unemployment, impoverishment and equity, which are more prevalent in the developing countries as opposed to the developed countries (Luthra et al., 2015). Furthermore, in order to better understand the sustainability approach, Santoyo-Castelazo and Azapagic (2014) proposed a simplified framework for conducting a combined sustainability assessment of energy systems, as shown in Figure 2.

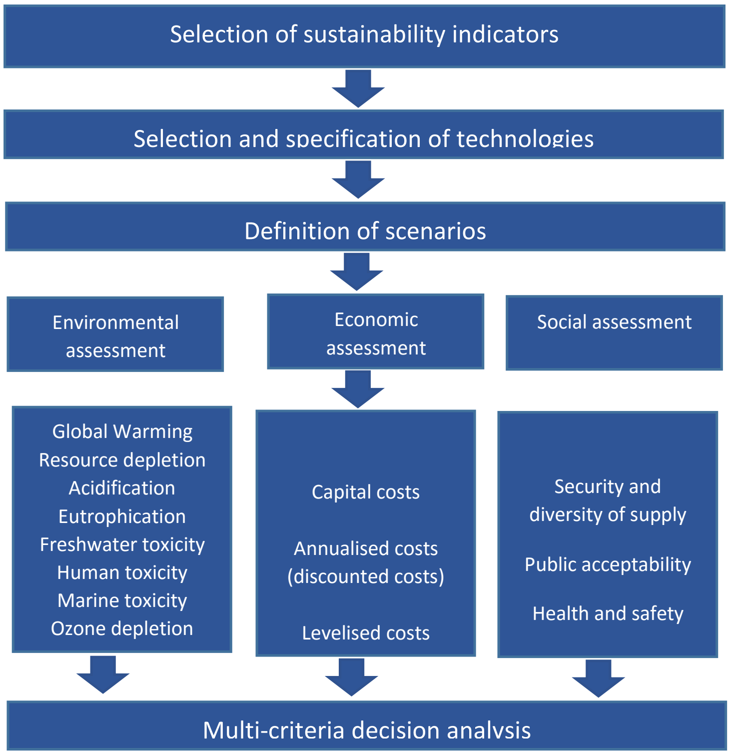

Figure 2. Framework of decision-support for combined sustainability assessment of energy systems (Santoyo-Castelazo and Azapagic, 2014).

In Table 1 below, we summarize some of the key studies on the basis of inclusion of the considered environmental or sustainability indicators.

Table 1. Summary of the selected studies differentiated based on the methodological approach, data sources used and type of indicators considered.

Study (year)	LCA included	Methodology used	Software's / Instruments used	Database used	Environmental indicators	Economic indicators	Sustainability indicators
Petersen et al. (2015)	√	Pinch point methodology; Process modelling (Thermochemical and biological) and Process Environmental Assessments.	SimaPro and GREET 2.7	NA	√	X	X
Brondani et al. (2015)	√	Energy efficiency analysis	SimaPro	Eco-Indicator 99 assessment method.	√	X	X
Arpornpong et al. (2015)	√	Sensitivity analysis; The product carbon footprint (CFP) methodology; Combination of CML 2000, IPCC 2007, Eco indicator 99, and Recipe methods.	SimaPro 7.1; GREET Model; ReCiPe model; Carnegie Mellon's EIO-LCA software	Ecoinvent (version 2.1); The Thai and international LCI database (USLCI 2013); IPCCC 2006	√	X	X
Onat et al. (2014a)	√	SWOT (Strengths , weaknesses, opportunities, threats) analysis; SMARt-CHP (small mobile agricultural residue gasification unit for decentralized; The emissions were monitored by a Horiba analyzer (NDIR – Nondispersive Infrared Analyzer).	NA	The Bureau of Labor Statistics The Global Footprint Network; Bureau of Economic Analysis,	√	√	√
Manara and Zabaniotou (2014)	X	SWOT (Strengths , weaknesses, opportunities, threats) analysis.	SMARt-CHP; NDIR (Nondispersive Infrared Analyzer)	NA	√	√	√
Santoyo-Castelazo and Azapagic (2014)	√	Life cycle costing; Social sustainability assessment; Multi-criteria decision analysis; Scenario analysis	NA	Eco invent; GEMIS	√	√	√
Ning et al. (2013)	√	Cost-benefit evaluation	GaBi & Chemical process simulator Aspen Plus.	Eco-indicator 95 system	√	√	X

2.2. Comparative assessment of different generation of biofuels.

The commonly available alternative fuels are bio-diesel, compressed natural gas, liquefied propane, ethanol, hydrogen, fuel cell and hybrid-electric, among others. Biofuels are commonly defined as solid, gaseous or liquid fuel produced from biomass (Demirbas, 2009, Clark et al., 2012) They can be classified into four different generations, such as 1st, 2nd, 3rd and 4th generation of biofuels on the basis of biomass feedstock (e.g., sugar cane or oils, lignocellulosic biomass, such as wood or algae). Biofuels obtained from different generations of feedstock offer unique advantages and challenges (summarized in Table 2). Biofuels can be produced in diverse forms (e.g., gaseous or liquid) and can be used in combination with diverse vehicle powertrains, for instance internal combustion engine vehicles or fuel cells (Demirbas, 2009, Holden and Gilpin, 2013, Dutta et al., 2014).

The penetration of biofuels in road transport sector as an alternative fuel for internal combustion engine vehicles (ICEV) could help reduce the environmental and health impacts of fossil fuels (Liaquat et al., 2010). In contrast to the petroleum based fuels, biofuels are associated with lower CO_2 emissions since they fix CO_2 from the atmosphere during photosynthesis and release the same amount when combusted (Clark et al., 2012). Moreover many biofuels are oxygenated (e.g., bio-alcohols) and help mitigate particulate and NO_x emissions from combustion. Nevertheless, the first generation biofuels is often disapproved due to the controversy of food-fuel competition impacting the food prices, since the first generation biofuels are often made from feedstock crops that also serve as food. Furthermore, the first-generation biofuels negatively impacts GHG emissions, biodiversity, land use, water usage and water fouling (Clark et al., 2012, Dutta et al., 2014, Holden and Gilpin, 2013). In this perspective, the second to fourth generation of biofuels are promoted as they do not create the food versus fuel competition. This has shifted the focus towards algae as an alternative biofuel feedstock (Dutta et al., 2014).

In an another study by Holden and Gilpin (2013), a framework was proposed for comparing biofuels against other competing strategies as an effort for promoting sustainable development with the basis of the effectiveness of these strategies to promote sustainable development. These competing strategies include alteration (e.g., promoting mode shifts), reduction (e.g., avoiding trips) and other development of advance fuels and technologies (such as hydrogen and electricity). They also analysed different biofuel pathways, as shown in Figure 3.

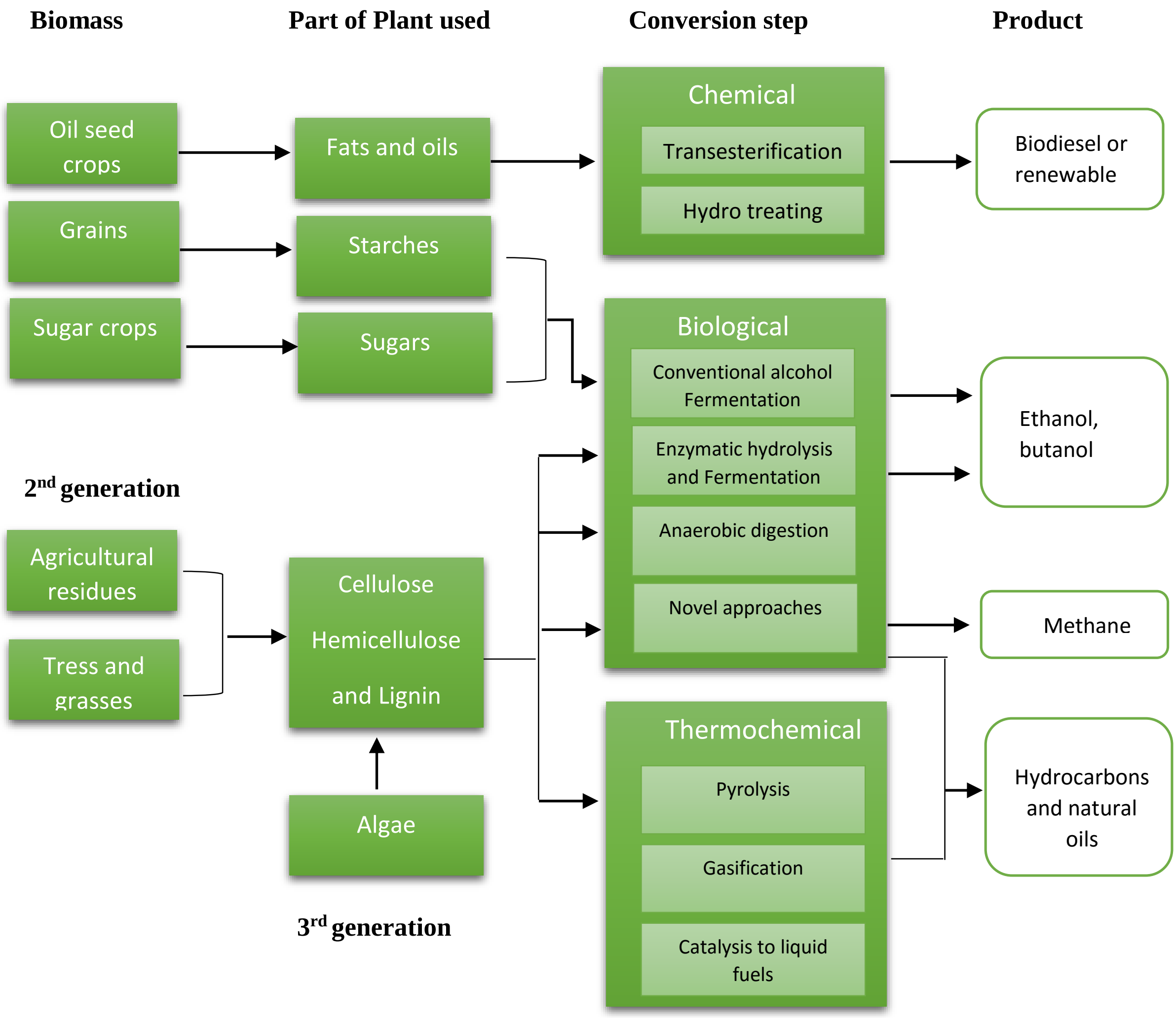

Figure 3. Flowchart of current and emerging biofuel pathways, adopted from Holden and Gilpin (2013).

Furthermore, Clark et al. (2012), Holden and Gilpin (2013) and Dutta et al. (2014) assessed the merits and demerits of biofuels while addressing the sustainability aspect of the fuels (summarized in Table 2).

Table 2. Advantages and disadvantages of biofuel options, adapted from Dutta et al. (2014).

Generation	Advantages	Disadvantages
First	GHG savings; Simple and low cost conversion technology	Low yield Cause food crisis as a large portion arable land required for growing crops
Second	GHG savings; utilize food wastes as feed-stock; no food crop competition; use of non-arable land for growing energy crops	Costly pre-treatment of lignocellulosic feedstock; Highly advanced technology need to be developed for cost effective conversion of biomass to fuel
Third	Easy to cultivate algae; higher growth rate; No food crop competition versatility; can use wastewater, seawater	More energy consumption for cultivation of algae (for mixing, filtration, centrifugation etc.); Low lipid content or biomass contamination problem in open pond system
Fourth	High yield with high lipid containing algae; More CO_2 capture ability High production rate	High cost of photo-bioreactor; initial investment is high; research is at its primary stage

2.3. Environmental impacts of biofuels

Biofuels, such as ethanol and biodiesel, are two alternative fuels with potential to reduce dependence on fossil fuel imports while reducing GHG emissions into the atmosphere (Demirbas, 2009). Demirbas (2009) discussed the air quality benefits of using biodiesel in conventional diesel engine and found that:

(1) Replacement of conventional diesel fuel by biodiesel fuel considerably reduces emissions of particulate matter, carbon monoxide (CO), unburned hydrocarbons, sulphates, polycyclic aromatic hydrocarbons and nitrated polycyclic aromatic hydrocarbons emissions.

(2) Emission reductions are increased with the increase of the percentage of biodiesel blended into diesel fuel. Conversely, the use of biodiesel in conventional diesel engine vehicle increases NO_x emissions. The increase of NO_x emissions with increase in biodiesel concentration could pose a significant challenge in areas out of attainment for ozone. It is found that when the biodiesel blends (B20 and B100) are used in the same model compression-ignition (diesel) vehicles then NO_x emissions increased from 1.86 to 2.23, respectively.

(3) Diesel fuel blend, which is oxygenated, is potentially beneficial for reducing the emission of particulate matter (PM) and such fuels have the potential to be an alternative to diesel fuel. Furthermore, the use of ethanol blends led to reduction in CO and HC emissions from the vehicle tail pipe (Demirbas, 2009). This was likely due to the presence of higher oxygen content in the ethanol fuel.

(4) Using statistical analysis it was found that the use of ethanol fuel blend E10 caused significant reduction in CO emissions (-16%) without any significant changes in NO_x, CO_2, CH_4, N_2O or formaldehyde emissions. Similarly, the use of ethanol blended fuel E85 resulted in significant decreases in NO_x emissions (-45%), without any significant changes in CO and CO_2 emissions.

Table 3. Comparison of percentage emissions from biodiesel vs. conventional diesel [adapted from Demirbas (2009)].

Emission type	Pure biodiesel	20% Biodiesel + 80% petro diesel
	B100	B20
Total unburned hydrocarbons (HC)	−67	−20
Carbon monoxide	−48	−12
Particulate matter	−47	−12
NO_x	+10	+2
Sulfates	−100	−20
Polycyclic aromatic hydrocarbons	−80	−13
Ozone potential of speciated HC	−50	−10

Solomon (2010) found that the use of low sulphur biofuel blends is beneficial for the air quality and such biofuel blends do not cause significant damage to the air quality, e.g., carbon monoxide emissions are reduced by 25 - 50% in case of ethanol and biodiesel blends. Bio-diesel blends also offer the benefits of reducing particulate emissions to as much as 50% and hydrocarbons by about two-thirds. However, the study also reports that production and use of the biofuels (ethanol and biodiesel) leads to increase in nitrogen oxide emissions, largely due to the on-farm emissions from fertilizer use.

MacLean and Lave (2003) conducted a sustainability assessment of various fuel/vehicle options for classifying the best combination of vehicle powertrain and fuel types with fewer life cycle emissions. Their findings revealed the sustainability challenges of using existing ethanol blended fuels (such as E10 for ICEV vehicles and E85 for flexible-fuelled vehicles). Their findings reveal the following key results:

1. The well-to-tank emissions dominate the life cycle emissions of ethanol blended fuels;
2. The greater efficiency (80-95%) of cellulosic (such as grasses and trees) based ethanol depends on the considered fossil fuel inputs i.e. the efficiency of such fuels is dependent on the fuel production pathway and, most importantly, the amount of fossil fuel inputs into the ethanol production.
3. GHG emissions of a maximum of only 15 g of CO_2 equiv/MJ of ethanol according to the studies evaluated) in spite of having higher cost.
4. Ethanol from corn or fossil fuels would be cheaper but far from sustainable and would have high GHG emissions if produced using current methods. For instance, the well-to-wheel GHG emissions (CO_2 equiv/km) vary from 0 g of CO_2 equiv/km (cellulose based E85 fuel) to 160 g of CO_2 equiv/km (corn based E85 fuel).

Similarly, Williams et al. (2009) discussed the potential of GHG emissions savings by switching to the next-generation feedstocks (as shown in Table 4). The study recommends the production of next generation feedstocks over the conventional corn-grain or soybean production in the U.S for reducing the overall GHG emissions. The evaluation of the life-cycle GHG emissions from ethanol derived from municipal solid waste (MSW) established that MSW based ethanol results in fewer (approximately 60−80%) GHG emissions as opposed to the conventional corn-grain ethanol, and further, they also suggested that pre-sorting of marketable aluminium, glass, steel and plastic materials can reduce GHG emissions by approximately 50% in comparison to unsorted MSW-based ethanol.

Table 4. Projected emissions to air, water use and waste streams from ethanol conversion for the next-generation feedstocks and cellulosic conversion [adapted from Williams et al. (2009)]

Model estimates (kg per L of ethanol)							
		Forest residues		Switch grass		Corn stover	
		Biochemical	Thermochemical	Biochemical	Thermochemical	Biochemical	Thermochemical
GHG	CO_2 (vent)	0.75	0.85	0.75	0.85	0.75	0.82
	CO_2 (flue gas)	2.74		2.89		2.11	
	CH_4	0.00003	0	0.0001	0	0.0001	0
Air Pollutant emissions	CO	0.002	0.00	0.003	0	0.002	0
	NO_x	0.002	0.005	0.003	0.027	0.002	0.033
	SO_2	0.003	0.0003	0.004	0.003	0.003	0.002
Water use	Fresh	7.20	2.56	8.61	2.17	6.16	2.67
Waste water	Treated (offsite)	0.00	0.03	0.00	0.03	0.00	0.03
Solid waste	ash/sand	0.03	0.03	0.16	0.37	0.14	0.05
Solid waste	gypsum waste	0.23	0.00	0.28	0.00	0.24	0.00
	sulphur	0.00	0.0002	0.00	0.002	0.00	0.001

a - Emissions from scrubbed CO_2 vent; b - Emissions from flue gas; c - kg per ton (dry) assuming 2000 dry metric tonnes per day and 15% moisture content of feedstock.

2.4. Vehicle life cycle emissions with reference to GREET Model

The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) is designed and maintained by Argonne National Laboratory and it gives relevant information and data of life cycle GHG emissions, energy consumptions and criteria air pollutants emissions for a diverse range of light-duty vehicles on the basis of numerous fuel conversion pathways. It inspects the relative burdens associated with the well to wheel process, the vehicle cycle and the vehicle operation phase. Further, it also offers meaningful insights into the environmental friendliness of natural gas-based personal mobility alternatives. The GREET model covers life cycle analysis in two cycles – the fuel-cycle (or WTW) and the vehicle-cycle (Figure 4). GREET 1 series is utilized for fuel cycle analysis and includes the following fuel cycle stages - energy feedstock recovery (e.g. crude oil recovery), energy feedstock transportation (e.g. crude transportation), and fuel production (e.g. petroleum refining to gasoline and diesel), fuel transportation, and fuel use in vehicles. The GREET 2 series is used for the vehicle-cycle analysis which includes the following key stages - raw material retrieval (e.g. iron ore mining), material manufacturing (e.g. steel manufacturing), vehicle part fabrication (e.g. engine manufacturing), vehicle assembly, and vehicle disposal and material recycling. However, the GREET model has its own limitations. Firstly, the GREET model only contains energy consumptions and criteria air pollutant emissions in its inventory for all of the processes it modelled. This is sufficient for the calculation of life cycle global warming potential and cumulative energy demand, but is inadequate for calculation of impact categories related to human health and ecosystem quality, where water emissions and other air pollutant emissions, especially those of copper, lead and arsenic, can significantly affect the results. Secondly, the GREET model does not consider water flows in the life cycle of the vehicles. This makes it quite challenging to evaluate water footprint, which is presently one of the important topics in life cycle modelling (Wang et al., 2007, Hawkins et al., 2012, Dai, 2014, Wang et al., 2015).

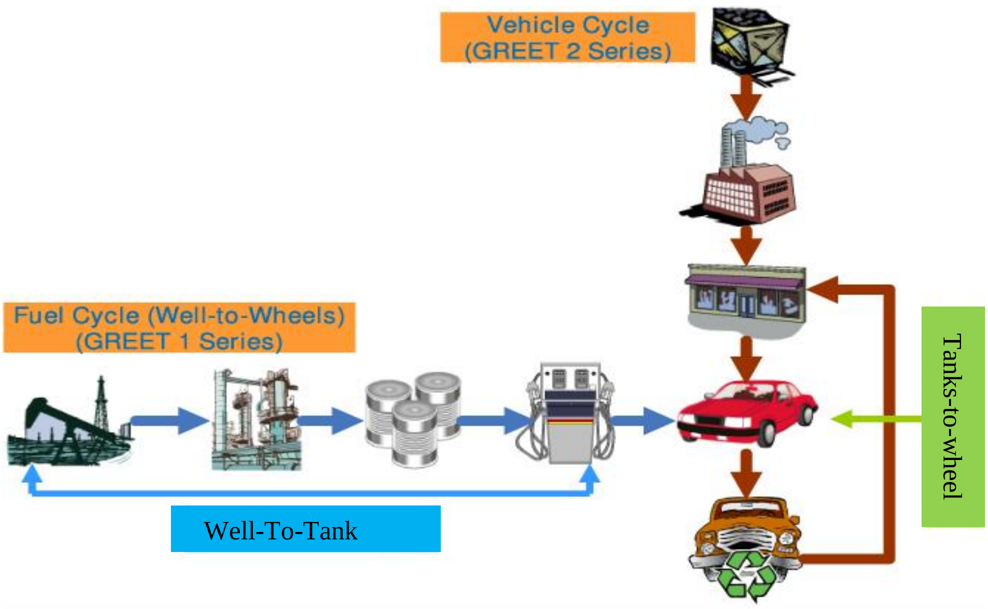

Figure 4. Life-cycle analysis of vehicle/fuel systems with the GREET model
Adopted from Wang et al. (2007)

2.5. Modelling life cycle impacts using Simapro

According to ISO 14040 standard, there are three phases of LCA. The first stage is goal and scope definition followed by life cycle inventory analysis and the third stage is Life cycle impact assessment (LCIA). The final stage of the LCA is the interpretation phase. In LCIA stage, the primary flows from the life cycle inventory are translated into their prospective contributions to the environmental impacts that are considered in the LCA and thus it is helpful for the interpretation phase to answer the questions raised in the goal definition (Hauschild and Huijbregts, 2015).

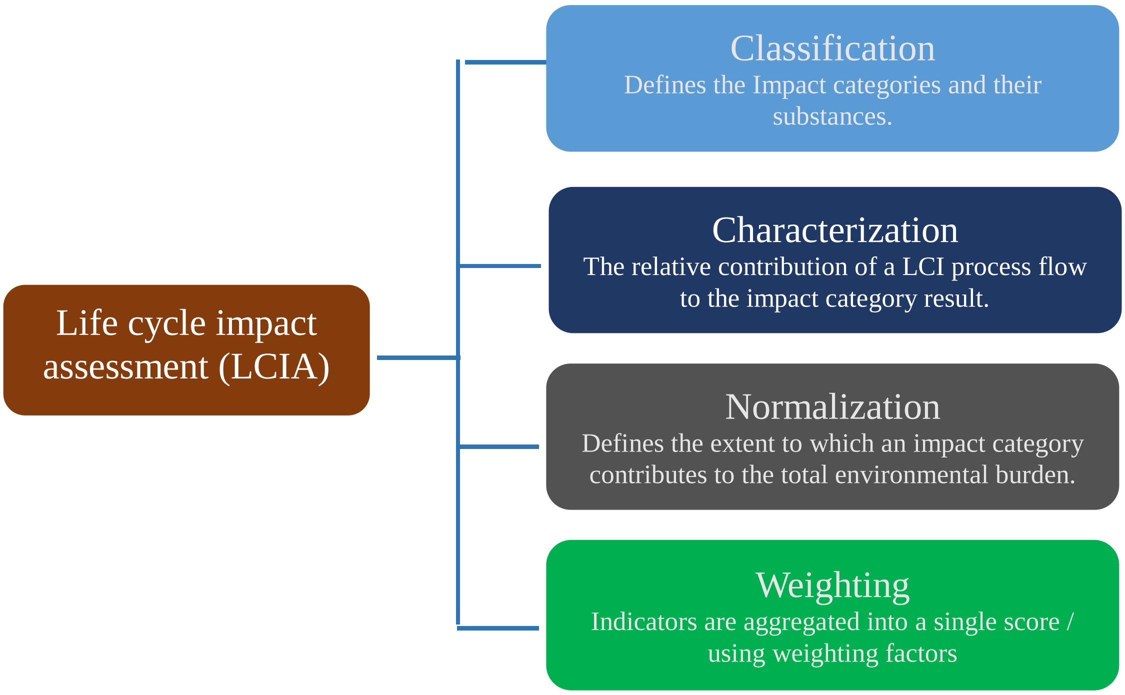

Figure 5. Modelling life cycle Impact assessment (LCIA) using SimaPro

Characterization is used to indicate the comparative severity of a substance with respect to a similar substance. This is done for a selected pollutant category, for example, greenhouse gases (GHG's), energy consumption or radioactive substances. The characterization factors are used to illustrate the conditions derived from the existing scientific literature. One similar example from this category could be the radiative forcing for methane, for instance, as per the data from the Intergovernmental panel on climate change (IPCC), the radiative forcing of methane is 25 times higher than that of carbon dioxide (CO_2). Conventionally, the quantities to be characterized are stated in terms of a reference substance. For GHGs, this reference is CO_2 eq. For methane, this value is 25 which means that one kilogram of methane has the same radiative forcing as 25 kilograms of CO_2 (Frischknecht and Büsser Knöpfel, 2013). In order to obtain characterization factors, the LCI results are compared against each impact category and then substances contribution to an impact category are listed and then multiplied by a characterization factor specific to that impact category to reveal the relative contribution of the substance (Goedkoop et al., 2008). The essential condition for the application of these characterisation factors is that such factors should incorporate the recommendations of the legislation (Frischknecht and Büsser Knöpfel, 2013).

Generally, different impact assessment methods offer the possibility for comparing impact category indicators against reference value for that category. In technical terms, the impact category results are divided by a reference value, for example, one of the examples of normalization is a commonly used reference where the average yearly environmental load in a country is divided by the number of inhabitants living in that country. This is explained with the equation proposed by Sleeswijk et al. (2008) as shown below :

$$\mathbf{A_{e,s} = \sum_{i} \sum_{x} Q_{e,x,i} \ x \ M_{x,i,,s}} \qquad \textbf{Eq. 1}$$

Where,

$A_{e,s}$ (e.g. in kg-eq./year) is the normalization factor for impact category e in refernce system s,

$Q_{e,x,i}$ (e.g. in kg-eq//kg) is the normalization factor related to impact cetgory e for substance x released to or extracted from enviornmental compartment I, and

$M_{x,i,s}$ (e.g. in kg/year) is th release or extraction of subtance x to or from compartment i in reference system s.

2.6. Strategies for mitigating transport sector emissions.

The transport sector emissions, mainly the emissions from on-road vehicle fleet, pose serious threat to a sustainable lifestyle in the modern day cities overburdened by rampant growth of long-lived greenhouse gases and short lived on-road vehicle fleet due to high rate of urbanisation and industrialization (Uherek et al., 2010). However, the technologies exist for the reduction of such particulate matter (PM) emissions from the transport sector. For instance, a commonly used technology for mitigation of diesel particulate emissions is particulate traps as discussed in a study by Shahraeeni et al. (2015). It has been found that the diesel-powered engines equipped with the particulate traps emitted considerably higher PM in contrast with CNG-powered engine for all fuel life cycle stages, excluding the fuel dispensing stage (Shahraeeni et al., 2015).

In a similar study for comparative life cycle analysis of diesel and CNG powered vehicles, Rose et al. (2013) concluded that in comparison to diesel vehicles, CNG vehicles have comparatively lower GHG and criteria air emissions (CAC’s) over the entire lifetime in addition to the substantial cost savings which are possible in case of CNG powered vehicles in contrast with conventional diesel powered vehicles. Demirbas (2009) suggested biodiesel as a feasible alternative to conventional diesel based vehicles owing to the similarities between diesel and biodiesel fuels. One of the practical strategies to reduce NO_x emissions in a biodiesel engine is to run the engine very lean while lowering the temperature since NO_x emissions increase with the increase in combustion temperature, the span of high temperature combustion period, and the availability of biodiesel, up to a combustion point (Demirbas, 2009). Additionally, Demirbas (2009) also indicated that when gasoline is blended with ethanol it leads to increase in the fuel consumption, engine torque and also reduces carbon monoxide (CO) and hydrocarbon (HC) emissions. In a similar study, Beer et al. (2002) stressed the use of three-way catalyst is an effective emission reduction technology which can reduce several air pollutants simultaneously including CAC's (e.g., CO, HC & NO_x emissions) in contrast to a two-way catalyst which has limited capacity to reduce NO_x emissions. Further, it is revealed that the stoichiometric process is more effective in reducing the PM emissions considerably as opposed to the lean burn conditions. In fact, it is reported that stoichiometric conditions reduce the PM emissions up to one-tenth of lean burn conditions. However, the stoichiometric process has a demerit that it is not as effective as lean-burn process for reduction of CO_2 emissions (Beer et al., 2002).

In a more recent study, Connolly et al. (2014) analysed several energy systems including a hundred percent renewable system with diverse energy pathways for transport fuels, such as electricity, hydrogen and synthetic fuel. In their study, hydrogen has been proposed as an energy compact fuel for applications, including long-distance driving (heavy duty transport vehicles such as trucks). Nevertheless, considering the high production costs of hydrogen fuel, liquid fuels, such as methanol/DME, are strongly recommended as sustainable transport fuels.

Apart from the above mentioned strategies, Haller et al. (2007) suggested other measures for realizing significant reduction in transport sector emissions, for instance, vehicle age, tyre characteristics, weight and driving patterns. Hence, substantial emission reductions can be achieved with a combination of the following measures: (1) selecting high efficient vehicles; (2) proper vehicle maintenance; (3) improving driving habits. Furthermore, in order to achieve considerable costs and emission savings, it is crucial for businesses to carefully assess the incremental costs and benefits of selected alternative fuel technologies and vehicle powertrains while contemplating the recent trends of existing carbon based markets. The businesses should consider the prospects of improving the fuel consumption behaviour. Considering the present state of alternative fuel markets, it appears quite challenging to implement and promote the penetration of alternative fuels on a massive scale (Haller et al., 2007).

Overall, from literature survey, we conclude that –

1) The LCA of a vehicle technology should include both the vehicle cycle impacts (such as vehicle production, manufacturing, and recycling) and the complete fuel cycle impacts (including fuel production, transport and the driving phase where the fuel is consumed).
2) It is imperative to precisely evaluate the socio-economic effects of transportation, for example, accessibility, affordability, equity, travel time, congestion and noise.
3) There are very few studies which have included social and economic indicators apart from environmental indicators.
4) Biofuels obtained from different generations of feedstock offer unique advantages and challenges. The second to fourth generation of biofuels are promoted as they do not create the food versus fuel competition.
5) The efficiency of biofuels is dependent on the fuel production pathway and the amount of fossil fuel inputs into the ethanol production.
6) The biofuels derived from next-generation feedstocks can result in significant GHG emissions savings.
7) Technologies exist for the reduction of air pollutants including GHG emissions and CAC's, such as particulate traps, two way catalyst, three way catalyst etc.
8) Significant emission reduction can be achieved by adopting a diverse combination of following measures: (1) selecting high efficient vehicles; (2) proper vehicle maintenance; (3) improving driving habits.

3. Methodology

3.1. Goal and scope definition.

In this study, we performed Well-to-Wheel (WTW) life cycle analysis and techno-economic analysis for selected alternative transport fuels. The life cycle analysis is performed following the ISO 14040 standardized LCA procedure with the Simapro software developed by PRe Consulting Group. The data collection relies on GREET model, life cycle inventory database Eco-Invent, produced by the Swiss centre for life cycle inventories and the secondary data obtained from various technical reports, government reports, websites, sugar industry and literature survey. Environmental life cycle impacts are assessed with Recipe endpoint (H) life cycle impact assessment (LCIA) methodology. The studied impacts are: climate change, freshwater eutrophication, marine eutrophication, human health, photochemical oxidant formation, particulate matter formation, freshwater eco-toxicity, marine eco-toxicity, agricultural land occupation, urban land occupation, water depletion, metal depletion, and fossil depletion.

3.2. Functional unit.

Generally, for LCA studies it is critical to report all relevant inputs and outputs in the Life Cycle Inventory (LCI) phase and the final impact scores in Life Cycle Impact Assessment (LCIA) phase in relation to a reference flow known as the functional unit (FU). The FU has a substantial influence on the selected environmental impact results since these are essential for effective decision making, designing policies and the industries (Daylan and Ciliz, 2016). For our study, we define the functional unit as “1 MJ of fuel input”. The single score environmental impact assessment results calculated on the basis of the functional unit “1 MJ of fuel input” are also expressed in the functional unit “1 km of distance driven”. Further, the techno-economic impact assessment is based on the functional unit “1 km distance driven”.

3.3. Defining life cycle boundaries of the present study.

In this study, we analysed the emissions during the fuel cycle for selected fuel types (diesel, petrol, LPG, CNG, biodiesel, ethanol, hydrogen (fuel cell) and electricity (Australian mix)). The system boundary (Figure 6) has been divided to include the following stages: material extraction, processing, and fuel production phase and vehicle operation phase. The life cycle analysis is confined to the fuel cycle analysis and it has been divided into two major components: (1) Well-to-Tank (WTT): including upstream impacts, such as raw material extraction, treatment, manufacturing and delivery and (2) Tank-to-Wheel (TTW): refers to the use phase of the vehicles including direct impacts, such as tail pipe emissions and direct energy utilization during the operation of vehicles. The emissions are estimated for the following three compartments: (1) atmospheric emissions or airborne emissions (including greenhouse gas emissions and criteria air contaminants) in units of g/MJ; (2) emissions to water (or, water borne emissions) in in g/kJ; and (3) emissions to soil in units of µg/MJ.

The atmospheric emissions are presented in terms of six emission types: greenhouse gases (GHG) expressed as $CO_{2\text{-}e}$, and criteria pollutants such as: nitrogen oxides (NO_x), particular matter ($PM_{2.5}$), carbon monoxide (CO), non-methane volatile organic compounds (NMVOC's) and sulphur dioxide (SO_2). We consider four different vehicle powertrain technologies for eight different fuel types (as shown in Table 5). The life cycle emissions of the alternative transport fuels (such as, gasoline, biodiesel, ethanol, LPG, CNG, electricity and hydrogen fuels) are compared against conventional diesel transport fuel. Furthermore, we performed contribution analysis to understand the environmental impact of selected fuel types for different impact categories.

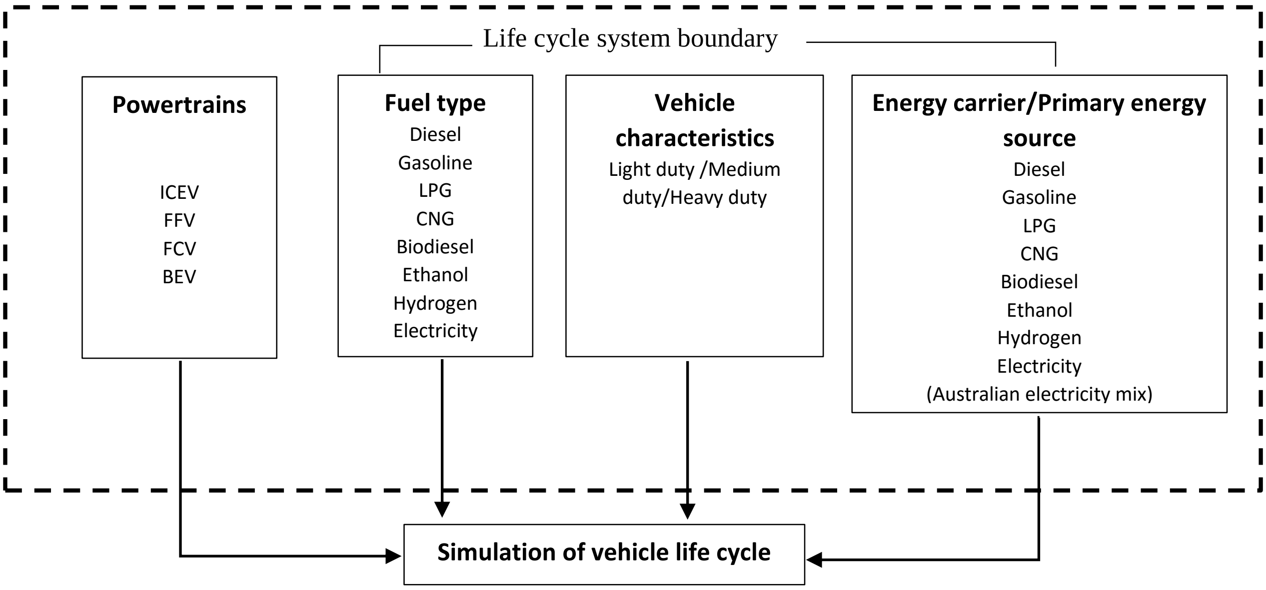

Figure 6. Life cycle system boundaries of the present study. Adapted from Bauer et al. (2015).

Table 5. Investigated alternative transport fuels and vehicle powertrain combinations.

Vehicle powertrain	Fuel type
Internal combustion engine vehicle (ICEV)	Diesel, gasoline, biodiesel, LPG, and CNG
Flexi Fuel vehicle (FFV)	Ethanol
Fuel Cell vehicle (FCV)	Hydrogen fuel
Battery electric vehicle (BEV)	Electricity (Australian electricity mix)

3.4. Life cycle inventory assessment (LCIA)

We obtained life cycle inventory data using a combination of data sources such as – (1) eco-invent 3.2 database published by the eco-invent centre (Eco-inventCentre, 2015); (2) the GREET Model (TheArgonneNationalLab, 2015); (3) literature survey of existing peer-reviewed articles and government reports and (4) online sources. Furthermore, the fuel economy data is obtained following the criteria of most fuel efficient vehicles in the selected vehicle category. This data is obtained from the green vehicle guide for Australia (Greenvehicleguide.gov.au., 2016) as shown in Table 6.

Table 6. Fuel economy data for specific car models by fuel types.

Model	Fuel Type	Energy consumption (kwh/km)	Fuel consumption (L/km)
Mini F56 Cooper D Hardtop (2014) 1.5 L, 3 cyl	ICEV (Diesel)	NA	0.037 l/km
Audi A1 Sportback 1.0 TFSI 1 L, 3 cyl	ICEV (Petrol)	NA	0.042 l/km
Ford FG X Falcon XT (2014) 4 L; 6 cyl	ICEV (LPG)	NA	0.117 l/km
Honda Civic Natural Gas (2015) 1.8 L, 4 cyl	ICEV (CNG)	NA	0.076 l/km
Ford Focus FWD FFV 2 L, 4 cyl	ICEV/FFV (Ethanol/E85, Petrol)	NA	0.1023 l/km
BMW IO1 i3	BEV	0.129	NA
The Hyundai ix35 FCEV	FCEV (Hydrogen)	NA	0.0095 kg/km

Data Source: Greenvehicleguide.gov.au. (2016).

Different vehicle powertrains have different conversion efficiencies as the conversion efficiency is influenced by the factors, such as the mass of the vehicle and the vehicle driving mode (Beer and Grant, 2007). Therefore, in order to compare selected fuels on the basis of their functionality, we considered the effect of variations in the calorific values of selected fuel types and the vehicle powertrain efficiencies. Hence, while specifying the input data of the selected fuel types in Simapro, we differentiated fuel types on the basis of their net calorific values or lower heating values (MJ/kg) and tank to wheel (TTW) efficiencies (**η**), which were derived from existing literature. These factors are applied to the fuel input data to obtain unit energy (1 MJ) available to the vehicle drivetrain per unit energy (1 MJ) input to the vehicle (details available in Table 7).

Table 7. Calorific values and TTW efficiencies of vehicle powertrains.

S.No.	Fuel type	Net Calorific Value (MJ/kg)	TTW efficiency (η)	Data source
1	Diesel (CI ICEV)	42	0.295	(Pramanik, 2003, Goswami and Kreith, 2007)
2	Gasoline (SI ICEV)	43	0.22	(Das et al., 2000, Goswami and Kreith, 2007)
3	Biodiesel (ICEV)	36.5	0.295	(Ganapathy et al., 2009, Goswami and Kreith, 2007)
4	Ethanol (FFV)	26.9	0.22	(Bayraktar and Durgun, 2005, Goswami and Kreith, 2007)
5	LPG (ICEV)	46.4	0.15-0.27	(Bayraktar and Durgun, 2005, Gupta et al., 2015)
6	CNG (ICE)	44.24	0.14-0.26	(Das et al., 2000, Curran et al., 2014)
7	Hydrogen (HFCV)	119.93	0.46	(Das et al., 2000, Colella et al., 2005)
8	Electric (BEV)	NA	0.77	(Eaves and Eaves, 2004)

In the equation (2) below, we mention the equation for calculating the Tank-to-Wheel efficiency as reported by Patil et al. (2016). They defined the Tank-to-Wheel (TTW) efficiency as the ratio of amount of fuel energy available at vehicle tank to the energy available at the wheel to drive the vehicle.

$$\boldsymbol{TTW\ efficiency = \frac{Energy\ of\ fuel\ available\ at\ the\ wheel}{Energy\ of\ fuel\ in\ the\ vehicle\ tank}} \qquad \textbf{Eq. (2)}$$

Further, it is important to briefly describe the production technologies of the selected fuel technologies in table 7. Hence, below we discuss the production technologies in Australia for the fuel types selected for analysis in our study.

1) **Diesel (Low sulphur diesel):** Also known as automotive diesel oil, is a product derived from the distillation of crude oil. Diesel is one of the middle distillates, which reflects its weight compared to heavier fuel oil and lighter petrol (AustralianGovernmentDepartmentofIndustryInnovationandScience).

2) **Gasoline** : Gasoline is a product derived from the distillation of crude oil. Its primary use is to power passenger motor vehicles and smaller commercial vehicles. The two most common types of petrol grades in Australia are regular unleaded petrol and premium unleaded petrol (AustralianGovernmentDepartmentofIndustryInnovationandScience).

3) **Biodiesel from Rape Methyl Ester (RME) :** Biodiesel from RME is made from Rape oil and imported from the European Union(ALCAS, 2011). It is produced through a chemical process called transesterification. The process creates two products — methyl esters (the chemical name for biodiesel) and glycerin (a valuable by product usually sold to be used in soaps and other products) (BiofuelsAssociationofAustralia, 2015).

4) **Ethanol from sugarcane molasses:** In Australia, ethanol is produced from sugarcane molasses using fermentation process which uses a sugar mill with a collocated distillery producing fuel ethanol from fermentation of molasses, and dunder (stillage) as a co-product. Such sugar mill is is assumed to be based on conventional technologies, and utilizes steam and electricity provided by the mill. Further, it should be noted that Molasses described here, is a co-product of sugar production which contains the residual sugars that cannot be further recovered. Also, stillage is not treated as an economic by-product has is used back on sugarcane farms (Renouf et al., 2011).

5) LPG : In Australia, LPG is mainly propane. It is known Liquefied Petroleum Gas. Liquefied Petroleum Gas (LPG) is predominantly a mixture of hydrocarbon gases (mainly propane (C_3H_8) and butane (C_4H_{10})). These gases can occur either individually or in combination. Under pressure, these gases liquefy, hence the term liquefied petroleum gas. LPG can occur naturally with other hydrocarbons such as wet natural gas in oil and gasfields, or it can be extracted at oil refineries from heated crude oil during the production of other petroleum products using a distillation tower. Fractions of the flow are extracted from the side of the distillation tower at various heights between the bottom and the top. Each extraction point is temperature controlled to extract a specific fraction including gasoline, naphtha, kerosene, diesel, light gas oil and heavy gas oil. These are then sent to unique streams for storage or possible further processing. This LPG can be used as is or separated into its three primary parts: propane, butane and isobutane. It is stored pressurised as a liquid in cylinders or tanks (Mike Roarty, 2001).

6) **CNG :** Australia is gifted with surplus natural gas resources. The most recent assessments indicate Australia has some 144 trillion cubic feet of natural gas, well over 100 times present annual domestic consumption (Roarty, 2008). The natural gas used in natural gas vehicles is the same natural gas that is used in domestic sector for cooking and heats. Compressed Natural Gas (CNG) is produced by compressing the conventional natural gas (which is mainly composed of methane –CH4) to less than 1% of the volume it occupies at standard atmospheric pressure. It is stored and distributed in a rigid container at a pressure of 200–248 bar (2900–3600 psi), usually in cylindrical shapes metallic cylinder (Khan et al., 2015).

7) **Hydrogen (Liquid hydrogen)** : Hydrogen can be produced from a variety of sources including fossil fuels, biomass, water and some industrial waste chemicals, and can be used in fuel cells or other engines or turbines to provide energy and amongst all the hydrogen production sources in Australia, Coal, Natural gas (NG), biomass and water offers the highest potential (McLellan et al., 2005). For utilizing water resources for hydrogen production, electrolysis technique is used which is based on consumes intermittent renewable energy and off-peak electricity from nuclear, hydro or thermal power plants. Globally, water electrolysis is considered to be one of the key technologies for hydrogen generation as it is compatible with existing and future power generation technologies and a large number of renewable technologies (solar, biomass, hydro, wind, tidal, wave, geothermal, etc.) (Badwal et al., 2006).

8) **Electricity (Low Voltage, NSW) :** More than 90 per cent of Australia's electricity production relies on the burning of fossil fuels - coal, gas andW oil. The chemical energy stored in these fuels is used to heat water and produce steam. The steam is then forced under great pressure through a turbine that drives a generator to produce electricity. The complete process involves the conversion of chemical energy to kinetic energy to electrical energy. In a similar way, the kinetic energy of falling water drives turbine blades to produce electrical energy at a hydro-electricity plant, and the kinetic energy of wind drives the blades of a wind-power turbine to produce electricity (Operator, 2010). A transformer converts the electricity produced at a generation plant from low to high voltage to enable its efficient transport on the transmission system. Included processes in AusLCI database used by Simapro: process begins with the delivery of high voltage power into the distribution network and process ends with the delivery of low voltage <= 415 V (ALCAS, 2011).

3.5. Impact assessment method used

We have used Recipe midpoint hierarchist (H) methodology for reporting characterisation results and Recipe endpoint hierarchist (H) methodology for reporting the single score results (Goedkoop et al., 2009).

The Recipe method is used to transform a relatively detailed list of life cycle inventory results into a limited number of single scores which are easier to interpret. Such single score values represent the relative harmfulness of selected environmental impact category. The modelling of the single score is performed on the basis of environmental mechanism to include multiple effects which combine together and lead to a certain level of damage to human health or eco-systems. In order to comprehend the interpretation of 18 mid-point indicators, we reported 3 end-point indicators, as shown in Figure 7, for comprehending the explanation of a large number of midpoint indicators. The end-point indicators are reported to simplify the meaning of the mid-point indicators since the mid-point indicators are used in a broad sense to present and report impact categories independently. Whereas, in case of end point approach, the impact categories are presented and reported independently to the endpoint or damage level. Endpoints are those physical elements that society determines are worthy of protection, for instance, skin cancers, cataracts, malaria, plants, animals and man-made materials (Lim and Park, 2009).

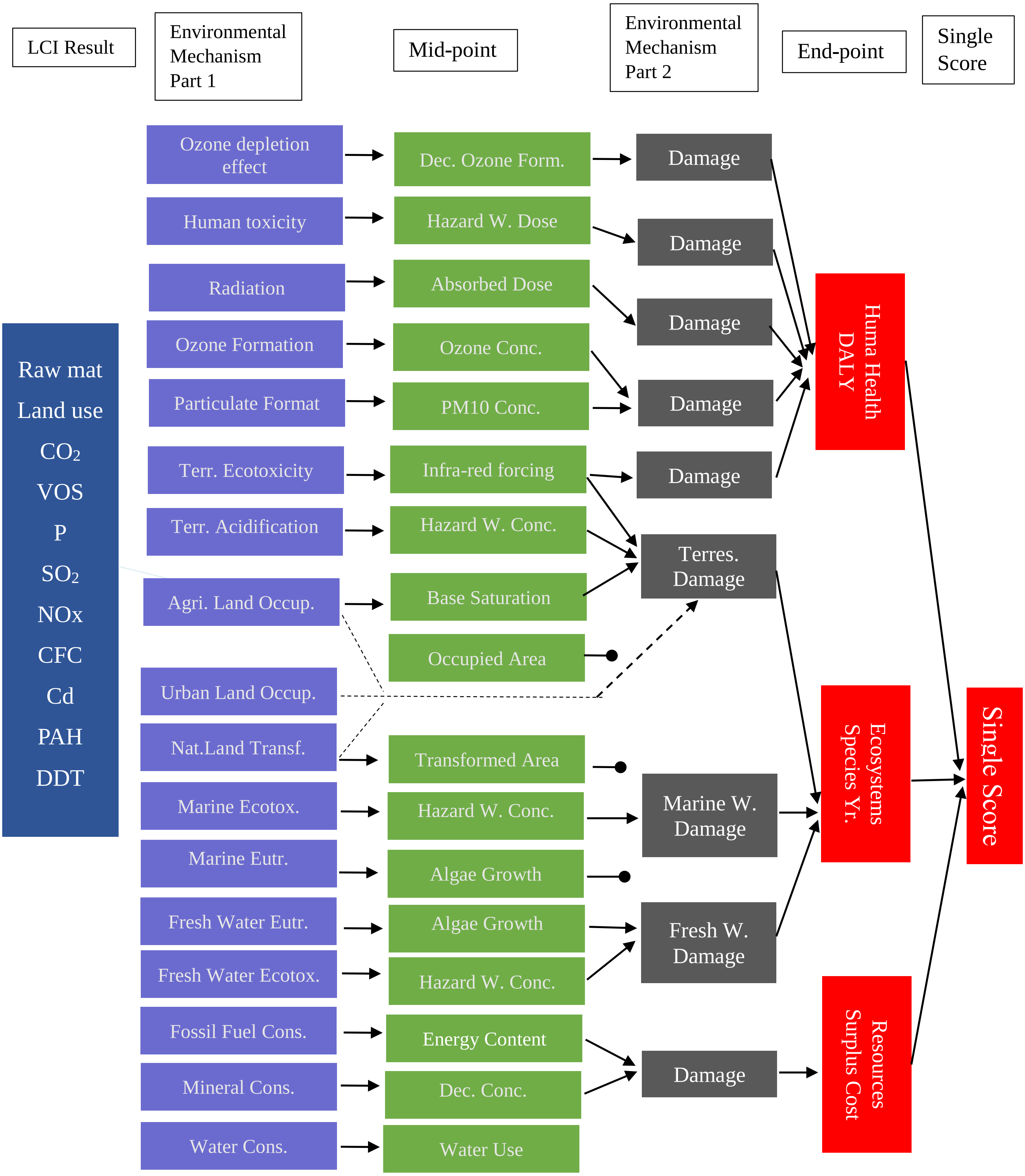

Figure 7. LCI parameters (left), midpoint indicator (middle) and endpoint indicator (right) in ReCiPe 2008.

3.6. Calculating single score in mPt/km for Environmental life cycle analysis.

The fuel cycle impact assessment results calculated in previous steps are converted to a single score using Recipe endpoint hierarchist (H) methodology. The single score is first obtained in the units of mPt/MJ in compliance with the functional unit "Per MJ of fuel input". This is later converted in accordance with the functional unit "Per km of distance travelled". The environmental impact assessment single score results are expressed in mPt/MJ for all selected 8 fuel types. These results are then normalized with respect to diesel fuel for the comparative analysis. The normalized single score results are then combined with the techno-economic analysis results and then the combined environmental and economic impacts are evaluated for selected vehicle powertrain and fuel types (as discussed in sections 3.7 and 3.8).

3.7. Techno-economic analysis

The techno-economic analysis is completed for the selected combination of vehicle powertrains and fuel types to evaluate the technology costs of selected fuel and vehicle powertrain combinations. The economic analysis includes capitals costs and operating costs. The techno-economic assessment can be slitted into 2 components – 1) Economic analysis of the capital costs for selected vehicle powertrain compatible with a specific fuel type; and 2) Economic analysis for the operating costs of the selected vehicle and fuel combination. The data for the costs of the vehicles is obtained from the Australian automobile and transport websites, such as the CarAdvice.com Limited (CarAdvice.com.au, 2016), the NRMA official website (MYNRMA.com.au, 2016), and the Hyundai Motor Company Australia (Hyundai.com.au, 2016). The economic costs are calculated in Australian dollars (A$) on the basis of per kilometre (km) of distance driven. We used NRMA analysis methodology (Carr, 2012) for the assumptions of annual distance covered by the vehicle (15,000 km); vehicle ownership lifetime (5 years) and based on these assumptions, we calculated that the total distance covered by the vehicle over the lifetime of the vehicle is assumed to be 75,000 km. Furthermore, the cost of each vehicle technology is divided by the total distance (i.e. 75,000 km) to obtain the capital costs on per km basis. Similarly, the operating costs of the vehicles are obtained from the costs of the fuel input per km of distance covered in A$/km. Finally, the total costs in A$ is normalized with respect to (w.r.t) diesel to obtain the total costs in A$/km. It should be noted that the techno-economic analysis conducted in this study only accounts for capital and operating costs. We have not estimated annualized costs and levelised costs.

3.8 Combining environmental life cycle analysis with techno-economic analysis

The environmental life cycle assessment results are combined with the economic impact assessment results after normalizing w.r.t diesel fuel types. The two types of analysis (environmental impact analysis and the economic impact analysis) are assigned equal weightage of 50% each and added together to obtain a single value for each vehicle and fuel technology choice. The combined results are then compared with the reference diesel fuel and vehicle technology. It should be noted that in this thesis we have proposed in our developed methodology to assign equal weightage (i.e. 50% each) to both the environmental and economic assessment due to equal importance of both.

4. Results and discussion

4.1. Atmospheric emissions in g/MJ for selected fuel types.

The life cycle inventory (LCI) results are summarized in Tables 8-10. These LCI results are derived mainly from the Australian National Life Cycle Inventory database (AusLCI). The AusLCI is a major initiative delivered by the Australian Life Cycle Assessment Society (ALCAS). The aim is to provide and maintain a national, publicly accessible database with easy access to authoritative, comprehensive and transparent environmental information on a wide range of Australian products and services, covering a range of life cycle stages (Grant, 2015). The detailed information about various data sources utilized for compiling AusLCI database is available at AusLCI website (ALCAS, 2011). Furthermore, other databases are also utilized such as The GREET Model (TheArgonneNationalLab, 2015) for reporting TTW emissions factors and the eco-invent database version 3.2 (Eco-inventCentre, 2015) is also utilized.

The atmospheric emissions in Table 8 are referred to as "Well-to-Wheel emissions (WtW)" and separated into two life cycle stages – Well-to-tank (WTT) and Tank-to-wheel (TTW) stage. In this study, we have not included biogenic CO2 emissions and we have only included fossil CO_2 emissions. Accordingly, CO_2 emissions shown in table 8 are fossil CO_2 emissions only.

Table 8. Well-to-Wheel (WtW) air emissions in grams per MJ of fuel input.

Life cycle stage	**Substance**	**Fuel type**							
		Dsl	**Petrol**	**Biodiesel**	**Ethanol**	**LPG**	**CNG**	**Hydrogen**	**Electric**
Well-To-Tank	$PM_{2.5}$	0.013	0.021	0.027	0.033	0.001	0.002	0.003	0.022
	SO_2	0.333	0.579	0.116	0.450	0.047	0.007	0.008	0.030
	CO	0.059	0.087	0.091	0.134	0.003	0.039	0.010	0.033
	NOx	0.166	0.259	0.269	0.410	0.046	0.022	0.084	0.989
	NMVOC	0.097	0.135	0.046	0.122	0.025	0.007	0.003	0.017
	CO_2	44.4	81.5	87.6	174.0	23.2	17.34	32.4	364.0
	NH_3	0.001	0.001	1.980	0.477	0.001	0.003	0.001	0.002
Tank-to-Wheel	**Substance**	**Dsl**	**Petrol**	**Biodiesel**	**Ethanol**	**LPG**	**CNG**	**Hydrogen**	**Electric**
	$PM_{2.5}$	0.002	0.001	0.001	0.001	0.002	0.001	0.000	0.000
	SO_2	0.001	0.001	0.211	0.307	0.000	0.000	0.000	0.000
	CO	0.013	0.740	0.065	0.065	0.740	0.703	0.000	0.000
	NOx	0.033	0.028	0.017	0.028	0.028	0.026	0.000	0.000
	NMVOC	0.020	0.021	0.010	0.021	0.002	0.000	0.000	0.000

	CO_2	74.6	71.4	38.3	70.1	63.2	55.0	0.000	0.000

For WTT stage, biofuels have significant criteria air emissions. Similarly, WTT GHG emissions are the highest for electric vehicles followed by biofuels, conventional fuels (petroleum and diesel), hyrogen, LPG and minimum for CNG. The higher WTT GHG emissions from electric vehicles could be atributed to the emissions during the production of batteries during the vehicle production phase which represent a significant portion of environmental impacts in electric vehicle manufacturing ranging from 10-75% of total manufacturing energy demand and 10-70% of manufacturing GHG emissions (Nealer and Hendrickson, 2015). Similarly**,** ethanol has the highest criteria air emissions for WTT stage, except for SO_2 and NO_x emissions. Furthermore, electric vehicles have the highest WTT NO_x emissions in comparison with the other fuel types.

However, for TTW stage, the GHG emissions are the highest for diesel followed by petrol. Additionally, hydrogen and electric are the best performing fuels for the TTW stage with almost zero tailpipe emissions during the vehicle operation. Furthermore, for hydrogen fuel cell vehicles, the overall life cycle burdens depend heavily on the hydrogen production pathway (Simons and Bauer, 2015).

Regarding LPG and CNG fuel types, these fuels have significant tailpipe emissions during the vehicle operation phase or TTW stage. The higher emissions from CNG vehicles in our study is in accordance with the findings in a similar study by Shahraeeni et al. (2015). They conducted a comparative life cycle assessment (LCA) of light duty commercial vehicles (LDCVs) and found that the CNG powered LDCVs are slightly more energy demanding than the diesel-powered LDCVs (2%) when considering the overall life cycle. Additionally, they reported that the total SO_x emission of the CNG-powered vehicle is approximately 75% lower than that of the diesel-powered vehicle and for the criteria air contaminants (VOCs, NO_x, and CO), the CNG-powered LDCV produces less emission only at the feedstock production and fuel production stages, but not during the vehicle operation phase since CNG-powered vehicle requires approximately 17% more energy than for diesel during the operation phase because of the lower energy density of the CNG fuel in comparison with the diesel fuel.

Furthermore, there is a susbtantial variation in GHG emissions for selected fuel types. The variations in GHG emissions is in agreement with the findings of Silalertruksa and Gheewala (2011). In their study, they found that differences in GHG emissions result from the differences in the production environment, for example, bioethanol conversion is an energy intensive process; therefore, using fossil fuels such as coal to produce steam and electricity will cause significantly higher GHG emissions than systems which use biomass. Also, the higher atmospheric emisisons from ethanol can also be attributed to the feedstock chosen for the ethanol production. We selected the ethanol obtained from sugarcane mollases and as per the study by Muñoz et al. (2014), it is well established that the relatively higher impact of sugarcane is related to the emissions during the pre-harvest burning.

Overall, biodiesel and ethanol are not the best performing fuels considering WTT and TTW life cycle stages. These findings are similar to the findings of Muñoz et al. (2014). They established that the production phase of bio-ethanol has significant GHG emisisons due to the contribution from anticipated methane emissions during the degradation when part of the ethanol is partitioned to the water compartment. Such contributions due to methane emissions outweighs the fact that carbon produced from bio-based ethanol production phase is biogenic in nature. Similarly, in an another study, Anantharaman et al. (2013) concluded that biodiesel fuels show a slightly inferior performance when compared to diesel and exhibit higher oxides of nitrogen as compared to diesel, whereas the carbon monoxide, hydrocarbon and smoke emissions were comparable to diesel fuel.

4.2. Emissions to water (g/MJ) for selected fuel types.

The emissions to water are summarized in Table 9. These emissions are reported for the fuel production stage. The emission of substances are reported in g/kJ.

Table 9. Emissions to water in g/kJ for the fuel production stages.

Substance	Diesel	Petrol	Biodiesel	Ethanol	LPG	CNG	Hydrogen	Electric
Acidity	0	0	0.01	0	0	0	0	0
BOD_5	1240	1670	462.46	114.44	27.40	5.32	17.50	212.20
Nitrate	1.35	2.13	3.47	865.85	0.12	0.56	6.32	15.30
Phosphate	2.39	4.68	21.50	8.54	0.28	1.89	7.34	34.80
Solids, inorganic	0.78	1.15	1.77	1.85	0.02	0.30	19.40	0.42
Total dissolved solids (TDS)	0	0	0	4220.28	6660.43	0	0	0
Total suspended solids (TSS)	0	0	0	260.96	411.85	0	0	0

As per details of emissions of substances to water, it is clear that ethanol has highest emissions of nitrates to water which is consistent with the characterisation results highlighting ethanol as the highest damaging fuel across the impact categories such as marine eutrophication and water depletion. In comparison with other fuel types, biodiesel production processes leads to higher acidity of water bodies and thus this perturbation in acidity has impact on the survival, metabolism and growth of the living organisms (Mohan et al., 2011).

From the Table 9 above, it is apparent that the biochemical oxygen demand (BOD_5) is the highest for petrol while the nitrate and phosphate concentrations are highest for ethanol and electricity. The increase in the concentration of phosphates and nitrates lead to eutrophication. Similarly, LPG has the highest emissions of total dissolved solids (TDS) and total suspended solids. Moreover, the concentration of inorganic solids released to the water is the highest for hydrogen FCV in comparison with other fuels.

The emissions of toxic substances to water bodies is linked to the growth in the production demand for biofuels leading to increased agricultural activity, for instance, tilling more land, and application of excessive chemicals, such as fertilizers and pesticides which have negative effect on water quality via degradation of local groundwater and eutrophication of distant coastal waters (Dominguez-Faus et al., 2009).

4.3 Emissions to soil in µg/MJ for the selected fuel types.

The emissions to soil from the full life cycle of fuel production and use for the selected fuel types are summarized in Table 10. These emissions are reported for the production phase and based on “1 MJ of energy produced by the fuel input” oriented functional unit perspective.

Table 10. Emissions to soil in µg/MJ for the production phase of the selected fuel types.

Substances	Fuel type							
	Diesel	**Petrol**	**Biodiesel**	**Ethanol**	**LPG**	**CNG**	**Hydrogen**	**Electric**
METALS/METALLOIDS								
Arsenic (total)	1.12	1.52	0.232	0.204	0.026	0.03	0.156	3.43
Barium	1330	1770	119	81.4	0.498	2.87	4.66	15.5
Cadmium	0.042	0.069	1.240	20.9	0.015	0.177	0.109	0.067
Chromium (III)	13.4	17.9	1.62	1.58	0.054	1.5	0.507	1.26
Chromium (VI)	17.3	27.9	34	24.6	2.43	7.24	37.7	431
Cobalt	30.7	45.8	35.6	26.2	2.49	8.73	38.2	432
Copper	0.424	0.694	0.91	0.495	0.077	0.186	1.04	0.164
Lead	11.3	18.2	22.7	17.7	1.69	7.08	25.7	272
Manganese	0.179	0.291	2.540	1.53	0.056	0.868	0.733	1.28
Mercury	110	149	19.2	13.2	1.03	2	11.1	11.6
Nickel	0.001	0.002	0.042	0.051	0.009	0.001	0.009	0.017
Vanadium	1.57	2.57	3.59	2.2	0.286	1.95	3.86	0.711
Zinc	0	0.001	0.002	0.002	0	0	0.001	0.013
ORGANICS								
Aldrin	0.351	0.575	0.813	1.15	0.054	0.182	0.847	47.5

Polycyclic aromatic hydrocarbons (PAHs)	0	0	0	0.114	0.18	0	0	0
OTHER								
Boron	29.6	40.4	8.4	5.98	0.44	1.34	6.75	76.4
Phosphorus	133	177	12.5	8.75	0.055	0.318	0.676	4.8
Sulfur	1600	2140	169	167	1.96	8.31	91.2	212

The presence of heavy metals, such as cadmium (Cd), lead (Pb), chromium (Cr) and copper (Cu) poses challenges and negatively impacts human health and ecosystems when released to the soil via anthropogenic sources, for instance, combustion of fossil fuels, industries and road traffic (Ramamoorthy, 2015).

In this study, according to Table 10, we can see that the toxic substance emissions, such Cd, is dominated by the production phase of ethanol; the emissions of Cu and V are dominated by the production phase of hydrogen; As, Ba, Cr (III) and Hg are dominated by the production processes for petrol; whereas Cr (VI), Co, Pb and Zn are dominated by the production processes of electricity fuel. Hence, petrol and electricity fuel production phases have the highest impacts on soil quality in terms of emission of toxic substances.

Deposition of the above toxic substances to the soil has wide-ranging effects on the complete ecosystems since these toxic substances permeate into the ground water or can bio accumulate in flora and fauna, and are potentially toxic to crop plants, animals, and humans when the contaminated soils are used for crop production (Ramamoorthy, 2015). Some trace metals (for example, Cu and Zn) are harmless in small concentrations while others, for instance Pb, As, Hg and Cd, are toxic and can potentially act as cofactors, initiators or promoters in many diseases, including increased risk of cancer (Zhang et al., 2012).

4.4. Impact assessment results using Simapro model.

The data derived from the inventory phase is summarized and elucidated via two steps, such as classification and characterization using Simapro 8.05 LCA software. In classification step, the impact categories have been defined, and the input/output data obtained from the inventory is allocated to the environmental impact categories according to their capacity for contribution to different problem areas.

4.4.1. Characterisation results

In the characterization step, LCI results are compared with each impact category using Recipe midpoint (H) methodology. The potential contributions from emissions during the life cycles of 8 selected fuel types (including diesel, gasoline, LPG, ethanol, hydrogen, electricity, CNG and biodiesel) have been calculated for all impact categories. The quantified LCA characterization results summarized based on the functional unit of "1 MJ of energy input to the vehicle". In order to compare all fuel types with respect to (w.r.t) diesel fuel, we normalised the impact category results for all fuels w.r.t diesel fuel and below we summarize the characterization results:

1) Petrol has the highest impacts across ozone depletion and natural land transformation. The ozone depletion impacts are the highest for petrol since petrol has the highest life cycle emissions of atmospheric NMVOC's. NMVOC's are the substances that do not have a global warming effect but influence the formation and destruction of tropospheric ozone (Zevenhoven and Kilpinen, 2001).
2) Electricity has the highest impacts across the categories of climate change, photochemical oxidant formation, marine eco-toxicity and urban land occupation. The climate change impacts are higher for electricity fuel types because the WTT GHG emissions are the highest for electricity in comparison with other fuel types. Similarly, electricity fuel type has significant criteria air emissions during the WTT life cycle stage.
3) Biodiesel has the highest impacts across the categories of particular matter formation, terrestrial acidification, freshwater eutrophication, terrestrial eco-toxicity, freshwater eco-toxicity, agricultural land occupation, metal depletion and fossil depletion. Biodiesel is the worst performing fuel against particulate matter formation category since it has the highest emissions of atmospheric $PM_{2.5}$ over the entire life cycle as opposed to the relatively smaller emissions for other fuel types.
4) LPG has the highest impacts for human toxicity, whereas it has the lowest impact across ozone depletion, freshwater eutrophication, terrestrial eco-toxicity, ionizing radiation, agricultural land occupation, urban land occupation, natural land transformation, water depletion and fossil depletion.
5) E85 has the highest impacts across marine eutrophication and water depletion since ethanol has significant atmospheric (GHG and criteria air contaminants) emissions for WTT and TTW life cycle stage. Though WTT atmospheric emissions from ethanol are greater than TTW atmospheric emissions. The highest marine eutrophication impacts for ethanol production phase is likely due to the excessive runoff of nitrates into lakes and streams near the ethanol

production plants. Similarly, the water depletion impacts are the highest for ethanol, possibly due to increased water demand for cultivation of feedstock required for ethanol production.

6) Hydrogen (FCV) has the lowest impacts across the categories for climate change, photochemical oxidant formation and metal depletion. This is because hydrogen is amongst the best performing fuels for the TTW life cycle stage with almost zero tailpipe emissions during the vehicle operation. Furthermore, hydrogen also has fewer GHG emissions during the WTT life cycle stage, thus, making it as the best performing fuel across the climate change impact category.
7) CNG has the lowest impacts across ozone depletion, marine eutrophication, human toxicity, particulate matter formation, terrestrial acidification, freshwater eco-toxicity, marine eco-toxicity and metal depletion. The lowest impacts of CNG across these impact categories can also be attributed to the lowest WTT life cycle stage atmospheric emissions of CNG.

Table 11. Characterisation results for selected fuel types.

Impact category	Unit	Diesel	Petrol	B100	E85	LPG	CNG	Hydrogen (FCV)	Electric
Climate change	g CO_2 eq/MJ	300.5	375.9	121.9	201.8	260.5	232.1	33.7	383.9
Ozone depletion	g CFC-11 eq/MJ	3.70E-05	5.00E-05	4.60E-06	5.00E-06	2.90E-08	2.00E-07	3.50E-07	5.60E-07
Terrestrial acidification	g SO_2 eq/MJ	0.5	0.8	4.2	1.8	0.1	0.1	0.2	2
Freshwater eutrophication	g P eq/MJ	9.20E-04	1.70E-03	4.10E-02	2.40E-02	9.60E-05	6.30E-04	2.40E-03	1.10E-02
Marine eutrophication	g N eq/MJ	0.013	0.015	0.16	0.26	0.0079	0.0053	0.0057	0.046
Human toxicity	g 1,4-DB eq/MJ	5.2	8.6	13.1	61.5	77.2	1.8	12	65.5
Photochemical oxidant formation	g NMVOC/MJ	0.6	0.5	0.5	0.8	0.4	0.3	0.1	1.1
Particulate matter formation	g PM10 eq/MJ	0.2	0.2	0.7	0.4	0.1	0	0.1	0.6
Terrestrial ecotoxicity	g 1,4-DB eq/MJ	0	0	5.6	0.8	0	0	0	0
Freshwater ecotoxicity	g 1,4-DB eq/MJ	0.1	0.2	3.9	1.1	0.6	0	0.1	0.8
Marine ecotoxicity	g 1,4-DB eq	0.1	0.1	0.7	0.6	0.6	0	0.1	0.8
Ionising radiation	g Bq U235 eq/MJ	0	0	0.2	0.2	0	0	0	0.1
Agricultural land occupation	m^2a/MJ	0.0004	0.0008	1.0399	0.5921	0.0000	0.0002	0.0017	0.0109
Urban land occupation	m^2a/MJ	0.0011	0.0017	0.0031	0.0034	0.0001	0.0008	0.0014	0.0153
Natural land transformation	m^2/MJ	0.0001	0.0002	0	0	0	0	0	0
Water depletion	m^3/MJ	0.0007	0.0010	0.0007	0.0099	0	0.0001	0.0015	0.0007

Metal depletion	g Fe eq/MJ	0	0	0	0	0	0	0	0
Fossil depletion	g oil eq/MJ	3.30E-05	6.40E-05	2.40E-04	1.90E-04	7.80E-07	0.00E+00	0.00E+00	9.50E-05

4.4.2 Single score results in mPt/MJ

In order to integrate various impacts together, we utilized the technique of reporting single score results while applying the weighting factors according to the Recipe end-point (H) methodology. The single score method is utilized in order to simplify the comparisons of varying systems or alterations to the compared systems (Jijakli et al., 2012). Hence, we reported the single score results for our analysis in Figure 8 and Figure 9 below.

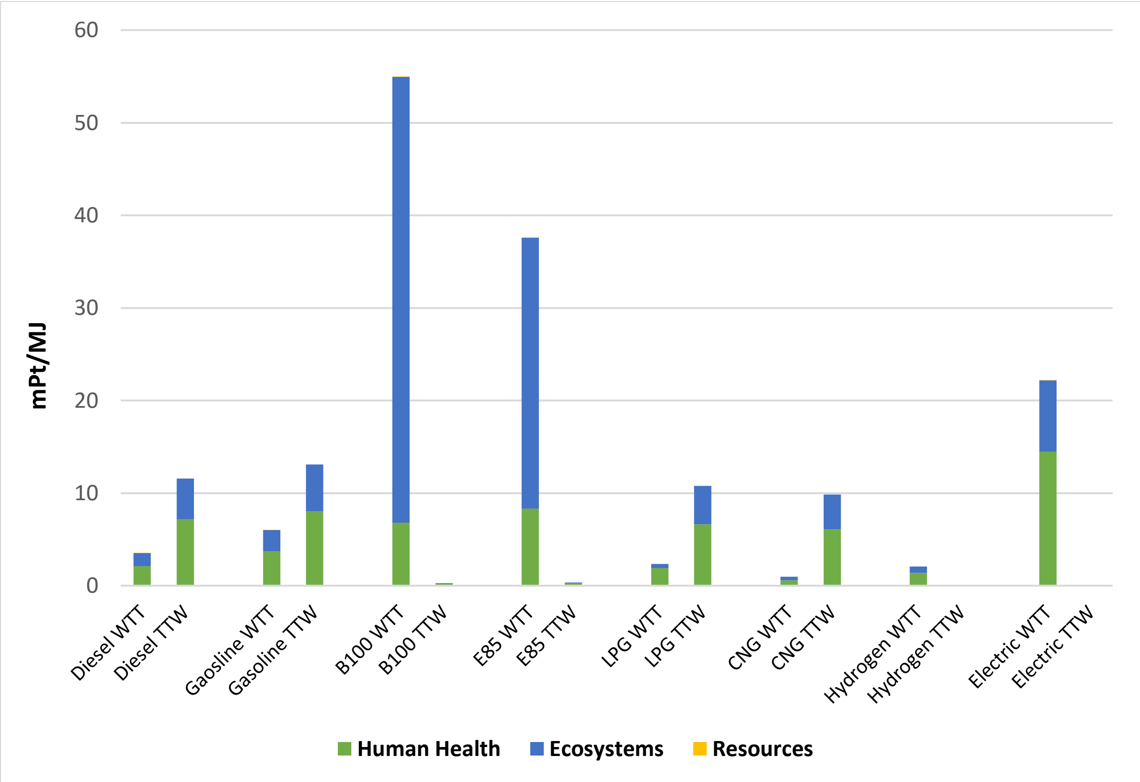

Fig. 8. Single score results (mPt/MJ) for selected fuel types for WTT and TTW life cycle stages.

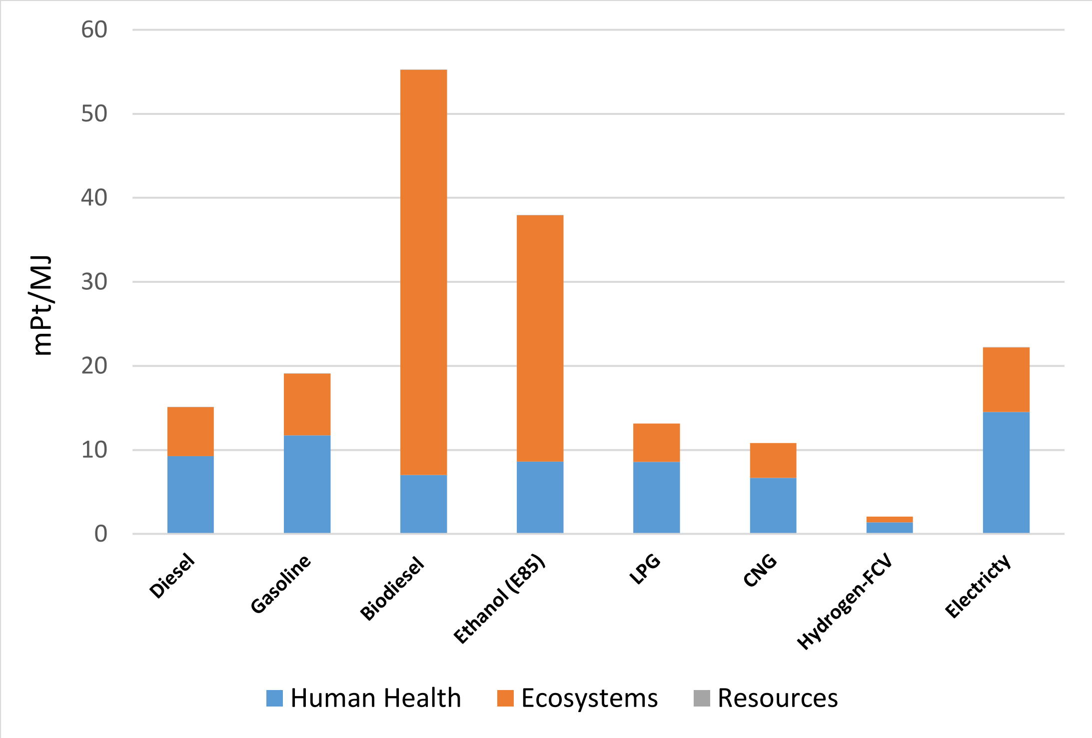

Fig. 9. Single score results (mPt/MJ) for total life cycle of selected fuel types.

Figure 8 and figure 9 illustrate that the overall life cycle single score results (in units of mPt/MJ) are the highest for biodiesel fuel followed by ethanol (E85), electricity, gasoline, diesel, LPG, CNG and the lowest for hydrogen FCV. Furthermore, splitting the single score results into TTW and WTT showst that for the WTT stage the single score impacts are the highest for biodiesel, ethanol (E85), electricity, gasoline, diesel, LPG, hydrogen FCV and minimum for CNG. Considering the TTW life cycle stage, the single score results are the highest across gasoline, diesel, LPG, CNG, ethanol (E85), biodiesel and minimum for hydrogen FCV and electricity. Hence, the conventional fuels (gasoline and diesel) have the highest impacts during the vehicle operation phase (i.e., TTW life cycle stage) in contrast with the alternative fuels which have fewer impacts during the vehicle operation phase or TTW life cycle stage.

4.5. Single Score results in mPt/km.

The single score results obtained in mPt/MJ (based on functional unit “1 MJ of fuel input”) are converted to the units of mPt/km (based on the functional unit “1 km of distance driven”) as shown in Figure 10 and Figure 11. When the single score results are expressed in the units of mPt/km basis, as shown in Figure 10 and Figure 11, then we see that the overall life cycle single score impacts are the highest for ethanol (E85) fuel followed by biodiesel (B100), LPG, gasoline, diesel, electricity, CNG and minimum for hydrogen FCV. Also, when we split the single score results into TTW and

WTT then we can observe that for the WTT stage, the single score impacts are highest for ethanol (E85), biodiesel (B100), electricity, gasoline, LPG, diesel, hydrogen (FCV) and minimum for CNG.

When the TTW life cycle stage is considered, the single score results are the highest across gasoline, diesel, LPG, CNG, ethanol (E85), Biodiesel (B100), and minimum for hydrogen (FCV) and electricity. Thus, the conventional fuels (gasoline and diesel) have the highest impacts during the vehicle operation phase (i.e., TTW life cycle stage) in contrast with the alternative fuels which have fewer impacts during the vehicle operation phase or TTW life cycle stage. When analysing the damage category, then the LPG fuel is the worst performing fuel across the human health category while hydrogen FCV is the best performing fuel across human health impact category. For the damage to ecosystems category, ethanol followed by the biodiesel are the worst performing fuels, whereas hydrogen FCV is the best performing fuel. All selected fuels have found to have negligible impacts across the damage to resources category.

Furthermore, when normalizing, the single score results for environmental life cycle analysis suggest that the environmental impacts are the highest for ethanol flexi fuel technology (FFV) followed by biodiesel, CNG, LPG, gasoline, diesel, electricity (BEV), CNG and minimum for hydrogen (FCV) technology.

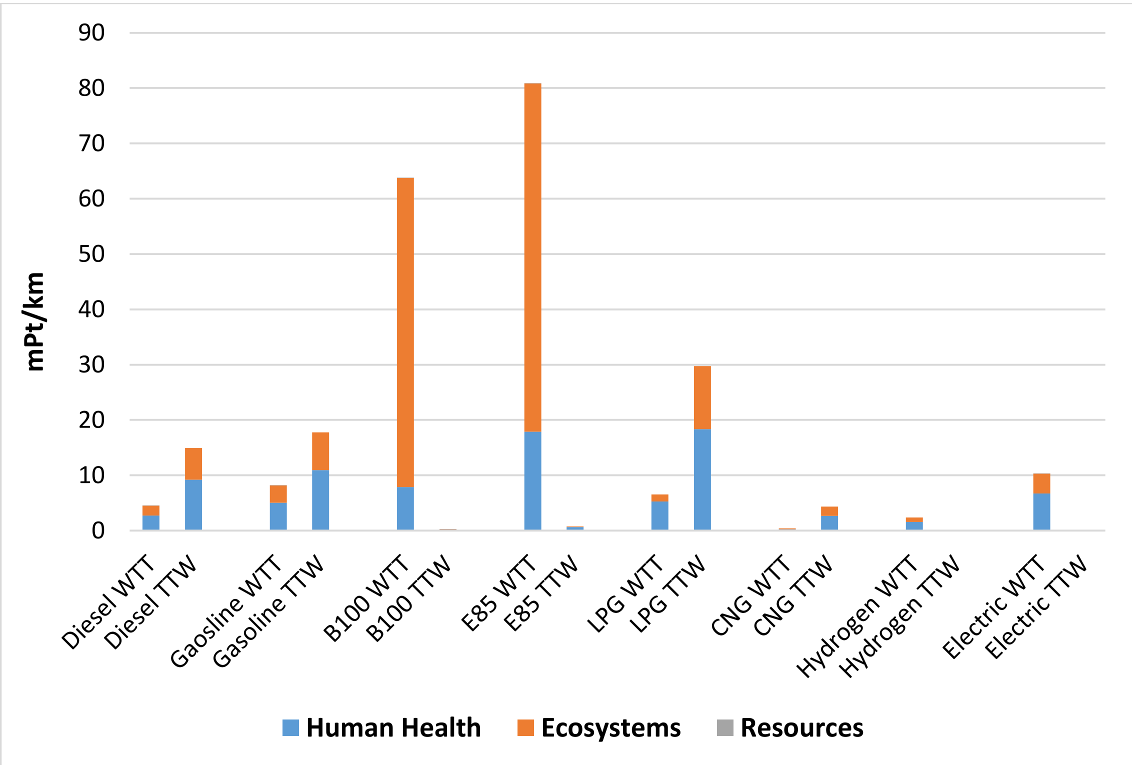

Fig. 10. Single score results (mPt/km) for selected fuel types for WTT and TTW life cycle stages.

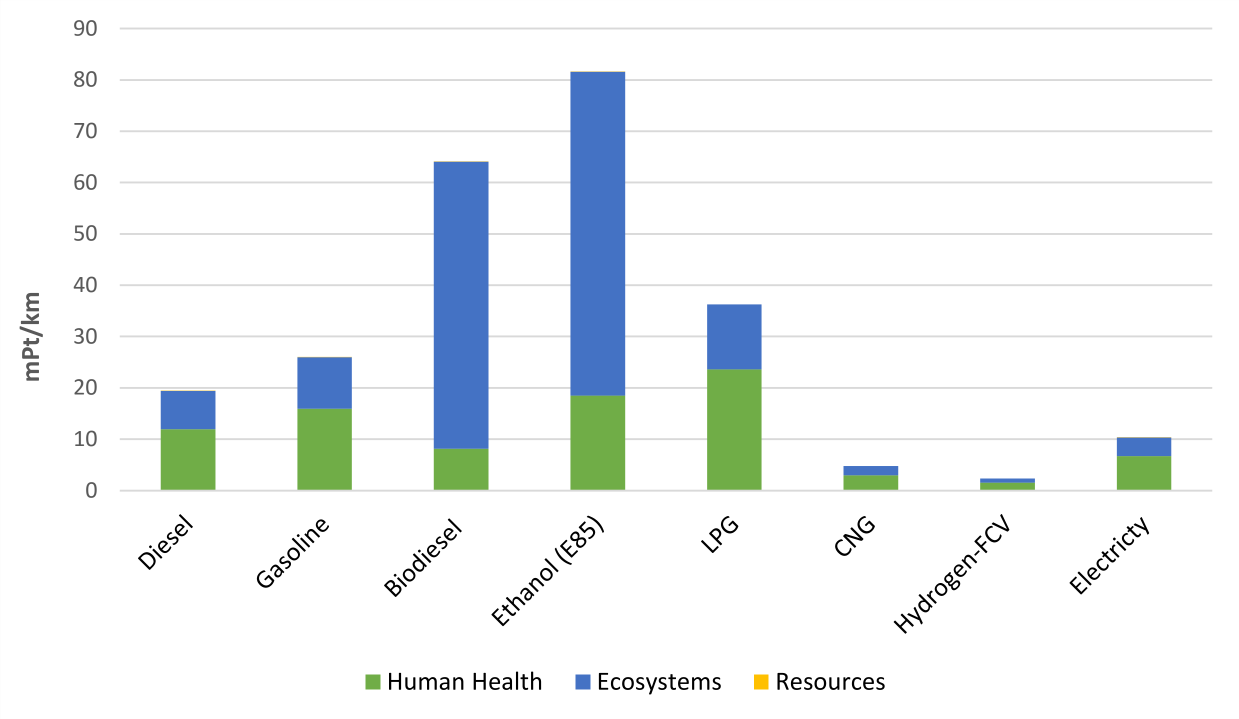

Fig. 11. Single score results (mPt/km) for total life cycle of selected fuel types.

4.6. Techno-economic analysis of selected fuel types.

The costs of selected combinations of fuel technology and vehicle powertrains are evaluated on the basis of functional unit with unit distance driven perspective i.e. "1 kilometre (km) distance driven". The costs are reported in Australian dollars per kilometres (A$/km). This analysis is divided into 2 components – 1) Capitals costs; and 2) Vehicle operating costs. The two costs are then added together with 50% weightage assigned to each type of costs. Furthermore, we also normalized the total costs (A$/km) w.r.t to baseline technology (i.e. diesel vehicles). The details of the analysis are shown in Table 12 below. The total economic costs (including capital and operating costs) on per km basis are the highest for battery electric vehicles (electricity fuel) followed by ethanol based flexi fuel vehicles, biodiesel, diesel, gasoline, CNG, hydrogen (fuel cell) and the lowest for LPG. While the battery electric vehicles (BEV) have lower operating costs but they have the highest capital costs in comparison with other vehicle powertrains. The excessively higher capital costs of BEVs are discussed in previous studies by Wood et al. (2013) and Offer et al. (2010) who stressed on the underlying reasons for the higher economic costs associated with BEVs based on (1) technical reasons, such as low energy density of batteries, i.e. range limitation inhibiting the widespread adoption of BEVs; and inconveniently long recharge times; (2) Economic causes, for instance, high capital costs of batteries linked to the storage of electrical energy; and (3) Infrastructural reasons, such as lack of optimum public refuelling stations.

Table 12. Techno-economic analysis of selected fuel types.

Fuel type	Capital costs (A$/km)	Operating Costs (A$/km)	Total Costs (A$/km)
Diesel	0.439	0.033	0.472
Gasoline	0.360	0.046	0.406
Biodiesel	0.439	0.040	0.478
Ethanol	0.473	0.098	0.571
LPG	0.194	0.074	0.267
CNG	0.357	0.011	0.367
Hydrogen	0.300	0.022	0.322
Electricity	0.933	0.019	0.952

4.7. Combined environmental and economic normalized results.

Figure 12 shows the superimposed environmental and economic impacts for selected fuel and vehicle systems normalized with respect to the baseline technology i.e. conventional diesel technology (ICEV). The combined environmental and economic impacts are the highest for ethanol based flexi fuel technology followed by biodiesel, electricity, LPG, gasoline, diesel, CNG and minimum for hydrogen fuel cell technology. The environmental impacts of petrol, biodiesel, ethanol and LPG dominate over the economic impacts, whereas, for CNG, Hydrogen (FCV), and electricity (BEV), the economic impact dominates over the environmental impacts. This is largely due to a lower technology learning curve in the research and development of the advanced vehicle powertrain options combined with other limitations which impede the commercialization of these technologies. More specifically, considering the case of BEV technology, it has the potential for significant reduction in the environmental impacts of road transportation sector provided such vehicle technology is commercialized with the access to easy recharging fuel stations, extending the range of distance travelled by such vehicles, availability of relatively inexpensive BEVs and finally raising the public awareness about the environmental benefits of the BEVs to gain social acceptance of electric vehicle technology. Overall, it is very much anticipated that advanced vehicle powertrains, such as hydrogen fuel cell vehicle (FCV) technology and battery electric vehicles (BEVs) will very soon compete and gain equivalence to the existing conventional vehicle technologies in terms of total life cycle costs and will significantly contribute towards the decarbonisation of the road transport sector (Offer et al., 2010).

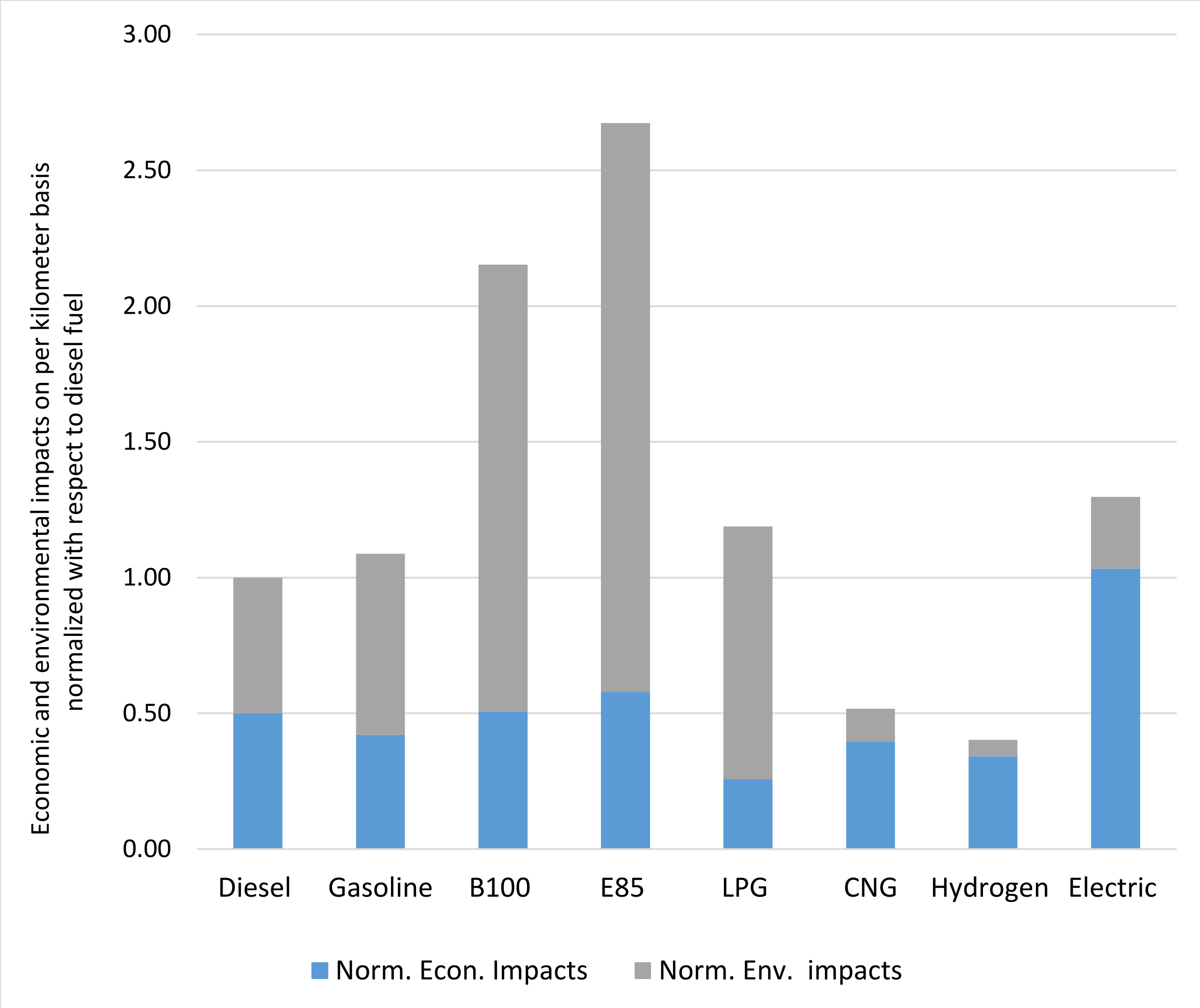

Fig. 12. Environmental and economic impacts superimposed (normalized with respect to diesel fuel).

Finally, it can be drawn from this analysis that alternative fuel technologies including different generations of biofuels have various social, economic, environmental and technical issues associated with them (Dutta et al., 2014). However, inspite of all the challenges, meeting the growing energy demand is of paramount importance via the production and distribution of such alternative fuels. Moreover, it is imperative to ensure the consistent supply of required raw materials (such biofuel feedstocks) to the bio-refineries for the production of the fuels. However, production and supply of raw materials (biofuel feedstocks) as an effort for mitigating energy crisis should not result in possible food crisis in a country (Dutta et al., 2014). Therefore, there is a major uncertainty regarding the performance of biofuels in terms of meeting the expectations of diverse environmental and sustainability criteria when the fuels are produced on a large scale and this uncertainty exists irrespective of the largely positive perception of the next generation biofuels over the conventional fuel technologies (Williams et al., 2009).

In a nutshell, sustainability evaluation of biofuels requires a multi-criteria approach while integrating issues, such as fertilizer volatilization, allocation of co-products and impacts over the land use. There is an urgent need for defining suitable sustainability indicators while considering the energy efficiency through processes, such as co-generation based on co-products and energy savings over different life cycle stages (Lora et al., 2011). Also, it is anticipated that the expansion of biofuel production industries will lead to creation of more jobs and growth in productivity utilizing unfertile marginal lands and wastelands for planation of energy crops (Liaquat et al., 2010).

5. Conclusions and recommendations

5.1. Conclusions

In this study, we completed the life cycle environmental analysis and the techno-economic analysis for the selected fuel and vehicle powertrain systems. This type of analysis is essential to scientifically and precisely determine the sustainability performance of alternative fuels and vehicle powertrain combinations (Simons and Bauer, 2015).

Here, we conclude some of the key findings of our study –

1) The normalized single score results for environmental life cycle analysis suggests that the environmental impacts are the highest for ethanol flexi fuel technology (FFV) followed by biodiesel, LPG, gasoline, diesel, electricity (BEV), CNG, and minimum for hydrogen (FCV) technology. These environmental impact assessment results are combined together with economic impact assessment results for the evaluation of selected fuel and vehicle technology choices while integrating economic and environmental aspects together.

2) The total economic costs (including capital costs and operating costs) on per km basis are the highest for battery electric vehicles (electricity fuel) followed by ethanol based flexi fuel vehicles, biodiesel, diesel, gasoline, CNG, hydrogen (fuel cell) and minimum for LPG.

3) Overall, the combined environmental and economic impacts are the highest for ethanol based flexi fuel technology followed by biodiesel, electricity, LPG, gasoline, diesel, CNG and minimum for hydrogen fuel cell technology.

5.2. Recommendations for future research

It is recommended that existing LCA methodology should be improved and standardized for applying same principles to complex and diverse issues, and thus, to account for the lacking of scientific rationale. Overall, to advance future research on sustainability assessment of alternative transport fuels, we have following recommendations -

1. The future research on sustainability assessment of alternative transport fuels should be precisely focussed on narrowing the uncertainties in the estimations of energy and air emissions including GHG emissions and criteria air contaminates. Thus, repetition of similar life cycle assessments of alternative transport fuels should be avoided wherever possible since

this type of data can be found in the existing scientific articles, reports and databases. Furthermore, the uncertainty of the analysis accounting for the technology and weightages of the economic and environmental impact assessment on the overall sustainability analysis should be included.

2. The life cycle assessment calculations should be repeated for filing the critical gaps in the production phase emissions to water and soil for selected fuel and vehicle technology combinations.
3. The existing life cycle inventories should be updated to include the extensive detailed data of biofuel feedstock production, and processing for the production of biofuels to reflect the local conditions in Australia. Similarly, the life cycle inventories should be updated to include the detailed datasets (capital and operation costs of vehicles, tail pipe emission for hydrogen fuel cell vehicles and electric vehicles, fuel economy data for advance vehicle powertrains) for advance vehicle powertrains (hydrogen fuel cell vehicles and electric vehicles).
4. The life cycle impact assessment should be conducted via more than one methodology in order to validate the impact assessment results obtained by a given method. This will ensure that the impact assessment is objective in approach.
5. The impact assessment of transport fuels should be extended to include the social impacts of alternative transport fuels in terms of social acceptance of alternative transport fuels and advance vehicle powertrains, job creation, impacts on biodiversity and water resources.
6. It is recommended that the future sustainability assessment of transport fuels should include the impacts of alternative fuel production on soil quality.
7. Finally, future research should also focus on the sustainability assessment of efficient pathways for the production and transmission of electricity and hydrogen combined with the inherent efficiency of electric vehicle powertrains to achieve significant improvements in air quality while decarbonising the road transport sector.

References

ALCAS. 2011. *The Australian National Life Cycle Inventory database (AusLCI).* [Online]. Australia: Australian Life Cycle Assessment Society (ALCAS). Available: http://alcas.asn.au/AusLCI/index.php/Contributors [Accessed Decemeber 2015].

ANANTHARAMAN, G., KRISHNAMURTHY, S. & RAMALINGAM, V. 2013. A review on combustion, performance, and emission characteristics of fuels derived from oil seed crops (biodiesels). *Australian Journal of Crop Science,* 7**,** 1350.

ARPORNPONG, N., SABATINI, D. A., KHAODHIAR, S. & CHAROENSAENG, A. 2015. Life cycle assessment of palm oil microemulsion-based biofuel. *The International Journal of Life Cycle Assessment***,** 1-14.

AUSTRALIANGOVERNMENTDEPARTMENTOFINDUSTRYINNOVATIONANDSCIENCE Conventional transport fuels : About conventional transport fuels in Australia. Australia: AustralianGovernment,Department of Industry,Innovation,andScience

BADWAL, S., GIDDEY, S. & CIACCHI, F. 2006. Hydrogen and oxygen generation with polymer electrolyte membrane (PEM)-based electrolytic technology. *Ionics,* 12**,** 7-14.

BAUER, C., HOFER, J., ALTHAUS, H.-J., DEL DUCE, A. & SIMONS, A. 2015. The environmental performance of current and future passenger vehicles: Life Cycle Assessment based on a novel scenario analysis framework. *Applied Energy*.

BAYRAKTAR, H. & DURGUN, O. 2005. Investigating the effects of LPG on spark ignition engine combustion and performance. *Energy conversion and management,* 46**,** 2317-2333.

BEER, T. & GRANT, T. 2007. Life-cycle analysis of emissions from fuel ethanol and blends in Australian heavy and light vehicles. *Journal of Cleaner Production,* 15**,** 833-837.

BEER, T., GRANT, T., WILLIAMS, D. & WATSON, H. 2002. Fuel-cycle greenhouse gas emissions from alternative fuels in Australian heavy vehicles. *Atmospheric Environment,* 36**,** 753-763.

BIOFUELSASSOCIATIONOFAUSTRALIA. 2015. *How is Biodiesel Made ?* [Online]. Sydney, NSW 2000, Australia: Biofuels Association of Australia. Available: http://biofuelsassociation.com.au/biofuels/biodiesel/how-is-biodiesel-made/.

BRONDANI, M., HOFFMANN, R., MAYER, F. D. & KLEINERT, J. S. 2015. Environmental and energy analysis of biodiesel production in Rio Grande do Sul, Brazil. *Clean Technologies and Environmental Policy,* 17**,** 129-143.

CARADVICE.COM.AU. 2016. Australia. Available: http://www.caradvice.com.au/ [Accessed 25 Jan. 2016].

CARR, D. 2012. 2012 Private Whole of Life Fixed Vehicle Operating Costs Available: http://www.mynrma.com.au/images/Motoring-PDF/Car-Operating-Costs-Report-Summary.pdf.

CLARK, J. H., LUQUE, R. & MATHARU, A. S. 2012. Green chemistry, biofuels, and biorefinery. *Annual review of chemical and biomolecular engineering,* 3**,** 183-207.

COLELLA, W., JACOBSON, M. & GOLDEN, D. 2005. Switching to a US hydrogen fuel cell vehicle fleet: The resultant change in emissions, energy use, and greenhouse gases. *Journal of Power Sources,* 150**,** 150-181.

CONNOLLY, D., MATHIESEN, B. V. & RIDJAN, I. 2014. A comparison between renewable transport fuels that can supplement or replace biofuels in a 100% renewable energy system. *Energy,* 73**,** 110-125.

CURRAN, S. J., WAGNER, R. M., GRAVES, R. L., KELLER, M. & GREEN, J. B. 2014. Well-to-wheel analysis of direct and indirect use of natural gas in passenger vehicles. *Energy,* 75**,** 194-203.

DAI, Q. 2014. *Life Cycle Assessment of Natural Gas Utilization in Light-duty Passenger Vehicles.* University of Michigan.

DAS, L., GULATI, R. & GUPTA, P. K. 2000. A comparative evaluation of the performance characteristics of a spark ignition engine using hydrogen and compressed natural gas as alternative fuels. *International Journal of Hydrogen Energy,* 25**,** 783-793.

DAYLAN, B. & CILIZ, N. 2016. Life cycle assessment and environmental life cycle costing analysis of lignocellulosic bioethanol as an alternative transportation fuel. *Renewable Energy,* 89**,** 578-587.

DAYSTAR, J., TREASURE, T., REEB, C., VENDITTI, R., GONZALEZ, R. & KELLEY, S. 2015. Environmental impacts of bioethanol using the NREL biochemical conversion route: multivariate analysis and single score results. *Biofuels, Bioproducts and Biorefining*.

DEMIRBAS, A. 2009. Political, economic and environmental impacts of biofuels: a review. *Applied Energy,* 86**,** S108-S117.

DOMINGUEZ-FAUS, R., POWERS, S. E., BURKEN, J. G. & ALVAREZ, P. J. 2009. The water footprint of biofuels: A drink or drive issue? *Environmental Science & Technology,* 43**,** 3005-3010.

DUTTA, K., DAVEREY, A. & LIN, J.-G. 2014. Evolution retrospective for alternative fuels: First to fourth generation. *Renewable energy,* 69**,** 114-122.

EAVES, S. & EAVES, J. 2004. A cost comparison of fuel-cell and battery electric vehicles. *Journal of Power Sources,* 130**,** 208-212.

ECO-INVENTCENTRE 2015. Eco-invent version 3.2. November 30, 2015 ed.: Eco-invent Centre.

FRISCHKNECHT, R. & BÜSSER KNÖPFEL, S. 2013. Swiss eco-factors 2013 according to the ecological scarcity method. *Methodological fundamentals and their application in Switzerland. Environmental studies*.

GANAPATHY, T., MURUGESAN, K. & GAKKHAR, R. 2009. Performance optimization of Jatropha biodiesel engine model using Taguchi approach. *Applied Energy,* 86**,** 2476-2486.

GOEDKOOP, M., HEIJUNGS, R., HUIJBREGTS, M., DE SCHRYVER, A., STRUIJS, J. & VAN ZELM, R. 2009. ReCiPe 2008. *A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level,* 1.

GOEDKOOP, M., OELE, M., DE SCHRYVER, A. & VIEIRA, M. 2008. SimaPro database manual methods library. *PRé Consultants, The Netherlands*.

GOSWAMI, D. Y. & KREITH, F. 2007. *Handbook of energy efficiency and renewable energy*, Crc Press.

GRAHAM, P., REEDMAN, L. & POLDY, F. 2008. Modelling of the future of transport fuels in Australia: a report to the Future Fuels Forum.

GRANT, T. 2015. AusLCI database manual.

GREENVEHICLEGUIDE.GOV.AU. 2016. *Green Vehicle Guide* [Online]. Available from: https://www.greenvehicleguide.gov.au/Vehicle/ViewMatchingVariants?vehicleDisplayId=25333 [Accessed 15 Mar. 2016].

GUPTA, S., PATIL, V., HIMABINDU, M. & RAVIKRISHNA, R. 2015. Life-cycle analysis of energy and greenhouse gas emissions of automotive fuels in India: Part 1–Tank-to-Wheel analysis. *Energy*.

HALLER, M., WELCH, E., LIN, J. & FULLA, S. 2007. Economic costs and environmental impacts of alternative fuel vehicle fleets in local government: An interim assessment of a voluntary ten-year fleet conversion plan. *Transportation Research Part D: Transport and Environment,* 12**,** 219-230.

HAUSCHILD, M. Z. & HUIJBREGTS, M. A. 2015. *Life Cycle Impact Assessment*, Springer.

HAWKINS, T. R., GAUSEN, O. M. & STRØMMAN, A. H. 2012. Environmental impacts of hybrid and electric vehicles—a review. *The International Journal of Life Cycle Assessment,* 17**,** 997-1014.

HOLDEN, E. & GILPIN, G. 2013. Biofuels and sustainable transport: A conceptual discussion. *Sustainability,* 5**,** 3129-3149.

HYUNDAI.COM.AU. 2016. Australia: Hyundai Motor Company Australia. Available: http://www.hyundai.com.au/cars/suvs/ix35?gclid=Cj0KEQjwwpm3BRDuh5awn4qJpLwBEiQAATTAQSLbKB1fmPyVWmy5LLirl6n9Tg0CO9b_i-jw6t5yNYsaAoL18P8HAQ&gclsrc=aw.ds [Accessed 7 Dec. 2015].

JIJAKLI, K., ARAFAT, H., KENNEDY, S., MANDE, P. & THEEYATTUPARAMPIL, V. V. 2012. How green solar desalination really is? Environmental assessment using life-cycle analysis (LCA) approach. *Desalination,* 287**,** 123-131.

KHAN, M. I., YASMIN, T. & SHAKOOR, A. 2015. Technical overview of compressed natural gas (CNG) as a transportation fuel. *Renewable and Sustainable Energy Reviews,* 51**,** 785-797.

LIAQUAT, A. M., KALAM, M. A., MASJUKI, H. H. & JAYED, M. H. 2010. Potential emissions reduction in road transport sector using biofuel in developing countries. *Atmospheric Environment,* 44**,** 3869-3877.

LIM, S.-R. & PARK, J. M. 2009. Environmental indicators for communication of life cycle impact assessment results and their applications. *Journal of environmental management,* 90**,** 3305-3312.

LORA, E. E. S., PALACIO, J. C. E., ROCHA, M. H., RENO, M. L. G., VENTURINI, O. J. & DEL OLMO, O. A. 2011. Issues to consider, existing tools and constraints in biofuels sustainability assessments. *Energy,* 36**,** 2097-2110.

LUTHRA, S., MANGLA, S. K. & KHARB, R. K. 2015. Sustainable assessment in energy planning and management in Indian perspective. *Renewable & Sustainable Energy Reviews,* 47**,** 58-73.

MANARA, P. & ZABANIOTOU, A. 2014. Indicator-based economic, environmental, and social sustainability assessment of a small gasification bioenergy system fuelled with food processing residues from the Mediterranean agro-industrial sector. *Sustainable Energy Technologies and Assessments,* 8**,** 159-171.

MCLELLAN, B., SHOKO, E., DICKS, A. & DA COSTA, J. D. 2005. Hydrogen production and utilisation opportunities for Australia. *International Journal of Hydrogen Energy,* 30**,** 669-679.

MIKE ROARTY, A. R. 2001. Liquefied Petroleum Gas (LPG). Australia: Parliament of Australia.

MOHAN, S. V., DEVI, M. P., MOHANAKRISHNA, G., AMARNATH, N., BABU, M. L. & SARMA, P. 2011. Potential of mixed microalgae to harness biodiesel from ecological water-bodies with simultaneous treatment. *Bioresource technology,* 102**,** 1109-1117.

MYNRMA.COM.AU. 2016. *Buying a new car* [Online]. Australia. Available: http://www.mynrma.com.au/motoring-services/safety-advice/buying-selling-cars/new-cars.htm [Accessed 1 Feb. 2016].

NEALER, R. & HENDRICKSON, T. 2015. Review of Recent Lifecycle Assessments of Energy and Greenhouse Gas Emissions for Electric Vehicles. *Current Sustainable/Renewable Energy Reports***,** 1-8.

NING, S.-K., HUNG, M.-C., CHANG, Y.-H., WAN, H.-P., LEE, H.-T. & SHIH, R.-F. 2013. Benefit assessment of cost, energy, and environment for biomass pyrolysis oil. *Journal of Cleaner Production,* 59**,** 141-149.

OFFER, G., HOWEY, D., CONTESTABILE, M., CLAGUE, R. & BRANDON, N. 2010. Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system. *Energy policy,* 38**,** 24-29.

ONAT, N. C., KUCUKVAR, M. & TATARI, O. 2014a. Integrating triple bottom line input–output analysis into life cycle sustainability assessment framework: the case for US buildings. *The International Journal of Life Cycle Assessment,* 19**,** 1488-1505.

ONAT, N. C., KUCUKVAR, M. & TATARI, O. 2014b. Towards life cycle sustainability assessment of alternative passenger vehicles. *Sustainability,* 6**,** 9305-9342.

OPERATOR, A. E. M. 2010. An introduction to australia's national electricity market. *Australian Energy Market Operator. http://www. aemo. com. au/About-the-Industry*.

PATIL, V., SHASTRY, V., HIMABINDU, M. & RAVIKRISHNA, R. 2016. Life-cycle analysis of energy and greenhouse gas emissions of automotive fuels in India: Part 2–Well-to-wheels analysis. *Energy*.

PETERSEN, A., MELAMU, R., KNOETZE, J. & GÖRGENS, J. 2015. Comparison of second-generation processes for the conversion of sugarcane bagasse to liquid biofuels in terms of energy efficiency, pinch point analysis and Life Cycle Analysis. *Energy Conversion and Management,* 91**,** 292-301.

PRAMANIK, K. 2003. Properties and use of Jatropha curcas oil and diesel fuel blends in compression ignition engine. *Renewable energy,* 28**,** 239-248.

RAMAMOORTHY, D. 2015. Assessment of heavy metal pollution and its impacts on soil physical, chemical properties and β-glucosidase activities in agricultural lands, Puducherry region.

RENOUF, M. A., PAGAN, R. J. & WEGENER, M. K. 2011. Life cycle assessment of Australian sugarcane products with a focus on cane processing. *The International Journal of Life Cycle Assessment,* 16**,** 125-137.

ROARTY, M. J. 2008. *Australia's natural gas : issues and trends / Mike Roarty,* [Canberra], Dept. of Parliamentary Services, Parliamentary Library.

ROSE, L., HUSSAIN, M., AHMED, S., MALEK, K., COSTANZO, R. & KJEANG, E. 2013. A comparative life cycle assessment of diesel and compressed natural gas powered refuse collection vehicles in a Canadian city. *Energy Policy,* 52**,** 453-461.

SANTOYO-CASTELAZO, E. & AZAPAGIC, A. 2014. Sustainability assessment of energy systems: integrating environmental, economic and social aspects. *Journal of Cleaner Production,* 80**,** 119-138.

SHAHRAEENI, M., AHMED, S., MALEK, K., VAN DRIMMELEN, B. & KJEANG, E. 2015. Life cycle emissions and cost of transportation systems: Case study on diesel and natural gas for light duty trucks in municipal fleet operations. *Journal of Natural Gas Science and Engineering,* 24**,** 26-34.

SILALERTRUKSA, T. & GHEEWALA, S. H. 2011. Long-term bioethanol system and its implications on GHG emissions: a case study of Thailand. *Environmental science & technology,* 45**,** 4920-4928.

SILVA, D. A. L., DELAI, I., MONTES, M. L. D. & OMETTO, A. R. 2014. Life cycle assessment of the sugarcane bagasse electricity generation in Brazil. *Renewable and Sustainable Energy Reviews,* 32**,** 532-547.

SIMONS, A. & BAUER, C. 2015. A life-cycle perspective on automotive fuel cells. *Applied Energy*.

SLEESWIJK, A. W., VAN OERS, L. F., GUINÉE, J. B., STRUIJS, J. & HUIJBREGTS, M. A. 2008. Normalisation in product life cycle assessment: An LCA of the global and European economic systems in the year 2000. *Science of the total environment,* 390**,** 227-240.

THEARGONNENATIONALLAB 2015. The GREET Model. Argonne, Illinois, USA: TheArgonneNationalLab.

TONG, F., JARAMILLO, P. & AZEVEDO, I. M. L. 2015. Comparison of Life Cycle Greenhouse Gases from Natural Gas Pathways for Medium and Heavy-Duty Vehicles. *Environmental Science & Technology,* 49**,** 7123-7133.

UHEREK, E., HALENKA, T., BORKEN-KLEEFELD, J., BALKANSKI, Y., BERNTSEN, T., BORREGO, C., GAUSS, M., HOOR, P., JUDA-REZLER, K. & LELIEVELD, J. 2010. Transport impacts on atmosphere and climate: Land transport. *Atmospheric Environment,* 44**,** 4772-4816.

WANG, H., ZHANG, X. & OUYANG, M. 2015. Energy and environmental life-cycle assessment of passenger car electrification based on Beijing driving patterns. *Science China-Technological Sciences,* 58**,** 659-668.

WANG, M., WU, M. & HUO, H. 2007. Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types. *Environmental Research Letters,* 2**,** 024001.

WILLIAMS, P. R., INMAN, D., ADEN, A. & HEATH, G. A. 2009. Environmental and sustainability factors associated with next-generation biofuels in the US: what do we really know? *Environmental science & technology,* 43**,** 4763-4775.

WOLF, M.-A., PANT, R., CHOMKHAMSRI, K., SALA, S. & PENNINGTON, D. 2012. *The International Reference Life Cycle Data System (ILCD) Handbook: Towards More Sustainable Production and Consumption for a Resource-efficient Europe*, Publications Office.

WOOD, E., WANG, L., GONDER, J. & ULSH, M. 2013. Overcoming the range limitation of medium-duty battery electric vehicles through the use of hydrogen fuel-cells. *SAE Int. J. Commer. Veh,* 6.

ZEVENHOVEN, R. & KILPINEN, P. 2001. *Control of pollutants in flue gases and fuel gases*, Helsinki University of Technology Espoo, Finland.

ZHANG, F., YAN, X., ZENG, C., ZHANG, M., SHRESTHA, S., DEVKOTA, L. P. & YAO, T. 2012. Influence of traffic activity on heavy metal concentrations of roadside farmland soil in mountainous areas. *International journal of environmental research and public health,* 9**,** 1715-1731.

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Appendix

Appendix 1. Amount of fuel consumed per km of distance travelled.

Vehicle powertrain	**Fuel type**	**Amount of fuel consumed (Kg/km; kwh/km)**	**Net calorific value (NCV) (MJ/kg)**	**Amount of fuel consumed (MJ/km) = Fuel (kg/km)* NCV(MJ/kg)**	**Reference**
ICEV	Diesel	0.037 L/km	42	1.29	Pramanik (2003)
	Petrol	0.042 L/km	43	1.36	Das et al. (2000)
	LPG	0.117 L/km	46.4	2.76	Bayraktar and Durgun (2005)
	CNG	0.076 L/km	44.24	0.44	Das et al. (2000)
	Biodiesel	0.037 L/km	36.5	1.16	Ganapathy et al. (2009)
	Ethanol (E85)	0.1023 L/km	26.9	2.15	Bayraktar and Durgun (2005)
Battery electric Vehicle (BEV)	Electricity (Australian mix)	0.4644 KWh/km	NA	0.4644	NA
Fuel cell electric vehicle (FCEV)	Hydrogen	0.0095 kg/km	119.93	1.139	Das et al. (2000)

Appendix 2. Costs of selected fuel types (terminal gate prices) in Australian $/km.

Fuel type	**Amount of fuel consumed (L/km; KWh/km)**	**Costs (AUD per litre)**	**Costs (A$/km)**	**Reference**
Diesel, low sulphur (ICEV)	0.037 L/km	0.90 A$/L	0.0333 A$/km	http://www.pumaenergy.com.au/for-business/terminal-gate-price/
Petrol, PULP (ICEV)	0.042 L/km	1.10 A$/L	0.0462 A$/km	http://www.caltex.com.au/LatestNews/FuelPricing/Pages/TerminalGatePricing.aspx
LPG (ICEV)	0.117 L/km	0.63 A$/L	0.0737 A$/km	http://www.mynrma.com.au/about/news/prices-rising-shop-around.htm
CNG (ICEV)	0.01 kg/km	1.06 A$/kg	0.0106 A$/km	http://www.esaa.com.au/policy/developing_a_market_for_natural_gas_vehicles_in_australia_1_1
Biodiesel (ICEV)	0.037 L/km	1.07 A$/L	0.0395 A$/km	http://www.ecotechbiodiesel.com/terminal-gate-price
Ethanol (E85)	0.1023 L/km	0.96 A$/L	0.098 A$/km	http://www.unitedpetroleum.com.au/wholesale/current-pricing/current-terminal-gate-price
Electricity (Aust mix)	0.4644 KWh/km	0.040 A$/ KWh	0.0185 A$/km	Graham et al. (2008)
Hydrogen (FCEV)	113.9335 KWh/km	0.072 A$/KWh	8.203 A$/km	Graham et al. (2008)

Notes *

1. A$ = Australian Dollar
2. MWh = 3600 MJ
3. Unit conversion calculator @ http://www.convertunits.com/from/MJ/to/MWh
4. Feedstock is the largest component of ethanol production costs.
5. A terminal gate price (TGP) is a wholesale price for bulk supply of petroleum products (as defined in the Oil code) from a fuels terminal that is a shipping facility or a facility connected by product transfer pipeline to a shipping facility, where for spot purchases the transfer of ownership occurs once the petroleum products are loaded into a customer's truck at the terminal loading rack (ie at the "terminal gate").

Appendix 3. Combined environmental and economic analysis normalized w.r.t diesel fuel.

Fuel type	Economic impacts	Env. Impacts	Norm. Econ. Impacts	Norm. Env. impacts	Comb. Env. & economic impacts
Diesel	0.76	19.46	0.50	0.50	1.00
Gasoline	0.64	25.95	0.42	0.67	1.09
B100	0.77	64.09	0.51	1.65	2.15
E85	0.88	81.57	0.58	2.10	2.67
LPG	0.39	36.26	0.26	0.93	1.19
CNG	0.6	4.75	0.39	0.12	0.52
Hydrogen	0.52	2.36	0.34	0.06	0.40
Electric	1.57	10.31	1.03	0.26	1.30