Life Cycle Assessment (LCA) of the
Hydrogen Fuel Cell, Natural Gas, and Diesel Bus Transportation
Systems in Western Australia

Prepared for the Government of Western Australia
Department for Planning and Infrastructure

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Abstract

As part of Western Australia’s Sustainable Transport Energy Programme (STEP), three hydrogen fuel cell buses were on trial in Perth for three years. The buses were manufactured by DaimlerChrysler, with fuel cells supplied by Ballard Power Systems, and a hydrogen supply provided by BP.

The Life Cycle Assessment (LCA) of the Perth fuel cell bus trial determines the overall environmental footprint and energy demand by studying all phases of the complete transportation system, including the hydrogen infrastructure, bus manufacturing, operation, and end-of-life disposal. LCA’s of the existing diesel and natural gas transportation systems are developed in parallel.

The methodology follows the international standards for Life Cycle Assessment ISO 14040-14043, as closely as possible. The findings clearly show the relative environmental and energetic magnitude of each life cycle phase, providing the feedback required to focus future efforts on critical processes.

The life cycle models are designed to be flexible, allowing for future scenario analysis examining different primary energy sources, fuel production processes, and expected improvements in technology. Concepts for sustainable bus transportation can be incorporated using the methodologies and boundary conditions defined during this project. Continued efforts to develop and refine these models can lead to industry opportunities as the entire product life cycle moves towards optimisation, and important problems are resolved in the early stages of the emerging hydrogen economy.

Overall lifecycle impacts are assessed in terms of primary energy demand, global warming potential, eutrophication potential, acidification potential, and photochemical ozone creation potential. Interestingly, the global warming potential of the Perth fuel cell buses is slightly worse than Perth’s diesel bus fleet, and slightly better than Perth’s natural gas bus fleet. Sensitivity analyses were conducted to examine the effects of expected hydrogen and fuel cell innovations and found that a reduction of greater than 50% is achievable in all impact categories. Scenario analyses were conducted exploring different methods of hydrogen production from electrolysis powered by wind, natural gas reformation, and electrolysis powered by conventional electricity available on the South West Interconnected System.
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<th>Full Form</th>
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<tbody>
<tr>
<td>ABARE</td>
<td>Australian Bureau of Agricultural and Resource Economics</td>
</tr>
<tr>
<td>AGO</td>
<td>Australian Greenhouse Office</td>
</tr>
<tr>
<td>AP</td>
<td>Acidification Potential</td>
</tr>
<tr>
<td>BP</td>
<td>British Petroleum</td>
</tr>
<tr>
<td>CML</td>
<td>Centre of Environmental Science (The Netherlands)</td>
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<tr>
<td>CNG</td>
<td>Compressed Natural Gas</td>
</tr>
<tr>
<td>CUTE</td>
<td>Clean Urban Transport for Europe</td>
</tr>
<tr>
<td>DBNGP</td>
<td>Dampier to Bunbury Natural Gas Pipeline</td>
</tr>
<tr>
<td>DEC</td>
<td>Department of Environment and Conservation</td>
</tr>
<tr>
<td>DOE</td>
<td>Department of Energy (US)</td>
</tr>
<tr>
<td>DPI</td>
<td>Department for Planning and Infrastructure</td>
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<tr>
<td>ECTOS</td>
<td>Ecological City Transport System (Iceland)</td>
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<tr>
<td>EEV</td>
<td>Environmentally Enhanced Vehicle</td>
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<tr>
<td>EP</td>
<td>Eutrophication Potential</td>
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<tr>
<td>EU</td>
<td>European Union</td>
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<tr>
<td>FC</td>
<td>Fuel Cell</td>
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<tr>
<td>FCV</td>
<td>Fuel Cell Vehicle</td>
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<tr>
<td>GCV</td>
<td>Gross Calorific Value</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse Gas</td>
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<tr>
<td>GM</td>
<td>General Motors</td>
</tr>
<tr>
<td>GPM</td>
<td>Gallons per Minute</td>
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<tr>
<td>GWP</td>
<td>Global Warming Potential</td>
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<tr>
<td>HP</td>
<td>Horsepower</td>
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<tr>
<td>ICE</td>
<td>Internal Combustion Engine</td>
</tr>
<tr>
<td>IKP</td>
<td>Institute for Polymer Testing and Polymer Science (Germany)</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization of Standardization</td>
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<tr>
<td>LCA</td>
<td>Life Cycle Assessment</td>
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<tr>
<td>LCI</td>
<td>Life Cycle Inventory</td>
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<tr>
<td>LCIA</td>
<td>Life Cycle Impact Assessment</td>
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<tr>
<td>LHV</td>
<td>Lower Heating Value</td>
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<tr>
<td>Acronym</td>
<td>Description</td>
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<td>---------</td>
<td>--------------------------------------------------</td>
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<tr>
<td>LNG</td>
<td>Liquefied Natural Gas</td>
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<tr>
<td>NEMP</td>
<td>National Eutrophication Management Program</td>
</tr>
<tr>
<td>NEPC</td>
<td>National Environment Protection Council</td>
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<tr>
<td>NEPM</td>
<td>National Environment Protection Measure</td>
</tr>
<tr>
<td>NMVOC</td>
<td>Non-methane Volatile Organic Compounds</td>
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<td>NPI</td>
<td>National Pollutant Inventory</td>
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<tr>
<td>P5</td>
<td>Ballard Phase 5 Fuel Cell Engine</td>
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<tr>
<td>PGM</td>
<td>Platinum Group Metals</td>
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<tr>
<td>PM</td>
<td>Particulate Matter</td>
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<tr>
<td>POCP</td>
<td>Photochemical Ozone Creation Potential</td>
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<tr>
<td>PSA</td>
<td>Pressure Swing Adsorption</td>
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<tr>
<td>PTA</td>
<td>Public Transport Authority</td>
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<tr>
<td>RISE</td>
<td>Research Institute for Sustainable Energy</td>
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<tr>
<td>STEP</td>
<td>Sustainable Transport Energy Programme</td>
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<td>SWIS</td>
<td>SouthWest Interconnected System</td>
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<tr>
<td>TTW</td>
<td>Tank-to-Wheels</td>
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<tr>
<td>WA</td>
<td>Western Australia</td>
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<tr>
<td>WTT</td>
<td>Well-to-Tank</td>
</tr>
<tr>
<td>WTW</td>
<td>Well-to-Wheels</td>
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Chapter 1

Introduction

Western Australia’s greenhouse gas emissions per capita are higher than any other Australian State, and higher than other developed countries including the US and the UK [1]. Strong economic and population growth in Western Australia (WA) have driven an increase in energy consumption of about 4% per year over the last 15 years. National electricity production has risen by 8.5% between 2001 and 2005, but production of renewable hydroelectricity has fallen by 6% as water flow decreased due to extended dry conditions. Australia is a net exporter of energy (coal, liquid natural gas, and uranium), and a net importer of liquid hydrocarbons (crude oil, propane, and other petroleum products). Domestic oil production is decreasing, and oil imports are rising. In 2005 the transport sector accounted for 24% of total energy consumption [2]. This situation is clearly not sustainable; drastic changes in transport energy and fuel supply are imminent.

The Sustainable Transport Energy Programme (STEP) is an initiative to trial alternative transport fuels for Western Australia. The project includes three buses manufactured by DaimlerChrysler, operating with fuel cell engines from Ballard Power Systems, and a hydrogen supply provided by BP. The STEP trial is in partnership with the Clean Urban Transport for Europe (CUTE) trial, the Ecological City Transport System (ECTOS) trial in Iceland, and the HyFLEET:CUTE program. This is the largest and most public demonstration of hydrogen fuel cell vehicle technology in the world.

Recent reports have evaluated the potential for a hydrogen economy in the Australian context [3], and current activities in the field [4]. These studies have presented a qualitative overview but have not been effective in setting up a policy framework for hydrogen. There is a recognised need for detailed quantitative analysis and testing [5].

1.1 Hydrogen and Fuel Cells

Two major forces are pushing the development of alternative fuel technologies: the imminent peak in oil production and the increasing severity of irreversible harmful environmental effects
resulting from our fossil-fuel combustion based economy.

A wide range of alternative fuels are under development, but hydrogen is steadily emerging as a favoured solution among scientists and policy-makers. Unlike oil or natural gas, hydrogen is not an energy source but rather an energy carrier that can be used to fuel vehicular or stationary power generators. Because hydrogen readily forms chemical bonds, it is most abundantly found in molecules such as water \((H_2O)\) or the hydrocarbons \((CH_4, C_2H_6, C_3H_8, \text{ etc})\). The hydrogen atoms must be separated from these compounds prior to use in a zero-emission fuel cell, and this separation process consumes energy. Therefore, hydrogen is similar to electricity in that it must be produced from another primary energy source, such as fossil fuel combustion or renewable energy sources. The main advantage that hydrogen holds over electricity is the ease with which hydrogen energy can be stored and transferred between storage vessels. For example, a battery-powered electric vehicle may take 8 hours to recharge, whereas a hydrogen storage cylinder can be refilled in a less than 4 minutes.

1.2 Research Objectives

Several research projects have been commissioned to develop a better understanding of the fuel cell buses, the hydrogen supply, the public perception, and the industry opportunities in Western Australia. One of these projects is the Life Cycle Assessment (LCA) of the Perth fuel cell bus trial; a study to evaluate the manufacture and operation of the entire fuel cell bus project. The scope includes hydrogen production, hydrogen transport and dispensing, bus manufacture, bus operation, emissions, waste, and disposal of all materials at the end of their useful life. LCA’s of the existing diesel and CNG transportation systems are developed in parallel, using the same principles and boundary conditions, to provide an accurate basis for comparison.

The Government of Western Australia, through the Department for Planning and Infrastructure, has commissioned the research projects to develop academic knowledge and expertise from this initial investment in hydrogen fuel cell technology. The knowledge gained from this research may be used to define the direction of future programs and policies. The results of the Life Cycle Assessment will provide the Government of Western Australia with the answer to a critical question: When evaluated within the scope of energy, materials, emissions and waste, is the life cycle of hydrogen fuel cell technology an improvement over the existing diesel and CNG technologies?

Once an accurate LCA model has been established, a series of scenario and sensitivity analyses are undertaken to examine the life cycle consequences of a different hydrogen infrastructure and expected technology developments. Scenario analysis can provide insight on the possibilities and impacts of changes over a broad spectrum of variables: Which parameters are most significant to the Life Cycle balance? What are the consequences of alternative hydrogen production technologies? How would possible improvements in fuel cell bus technology affect the
life cycle balance? The specific scenarios to be studied have been developed in conjunction with the Department for Planning and Infrastructure (DPI) and the Public Transport Authority (PTA).

1.3 Partnership with the CUTE Evaluation Studies

The Life Cycle Assessment has been identified by the European Union as a significant work package in the evaluation of the European fuel cell bus trials. The Institute for Polymer Testing and Polymer Science (IKP) at the University of Stuttgart is leading this effort. The results of the European LCA provide an unprecedented comprehensive report on the full Life Cycle Assessment of the largest fuel cell bus trial in the world [6]. Each of the cities participating in the trial has developed a unique hydrogen infrastructure to fuel the buses, and this broad scope of hydrogen supply pathways provides a diverse data set.

There are a number of reasons to justify a separate Life Cycle Assessment of the Perth trial, the most significant being the hydrogen infrastructure in Western Australia. Perth is the only city that procures hydrogen as a byproduct of the crude oil refining process; the other cities use a combination of electrolysis, natural gas steam reforming, or dedicated hydrogen production at an oil refinery or chemical plant. The nature of the hydrogen supply in Western Australia implies unique constraints on the quantity, the processing, and the transport of hydrogen from the refinery to the bus depot. The Perth trial is further distinguished by the Fueling Station design which incorporates a hydrogen cooling technology not used in any other city, and which reduces the time required to fill a bus.

Additional differences between the STEP trial and the European trials stem from the Perth city geographical layout and population density. The European trials are conducted in large city-centers with high population density, congested traffic conditions, and a colder climate. The Perth city layout allows for a higher average speed, reduced passenger loading, and higher average temperatures. These and other parameters all have an impact on fuel economy and utilisation rates.

1.4 Modeling

The modeling software to be used is GaBi 4, developed by PE Europe GmbH, a company associated with the University of Stuttgart and partner organisation of IKP. A license for GaBi 4 has been purchased by Murdoch University, and the GaBi database that will be compiled during this project will provide a basis for future LCA work at Murdoch.

The end result of the LCA will be a database and a set of models describing the inputs and outputs of the entire product life cycle. The calculations are based on a functional unit, such as 1 passenger-kilometer. The inputs to the model are materials and energies, and the outputs from the model are the products, emissions and wastes. Different processes or flows can be
placed in the models to allow experimentation with different technologies and functional units, for example the piston hydrogen compressor could be removed from the model and replaced with a diaphragm hydrogen compressor, or the composition of the natural gas supply could be modified to reflect a different heating value. One of the challenges in constructing an LCA model is to ensure flexibility and proper parameterisation. These important aspects have been kept in mind from the early stages, resulting in a structure that can be applied to a wide variety of future technologies and scenarios.

The LCA modelling of the Perth diesel, natural gas and hydrogen fuel bus systems commenced in 2004. Preliminary results were published in 2006 [7] and 2007 [8]. This report is the final deliverable for the LCA work commissioned by the DPI.
Chapter 2

Literature Review

Global interest in alternative fuels has gained great momentum over recent years, with many viable options and no clear solution. LCA is an ideal tool to evaluate these competing technologies, and the field of LCA has advanced to better meet this demand. Many researchers and journalists have attempted to provide a comparison of the competing transport technologies, but difficult assumptions are often required due to the many unknown parameters involved. This characteristic inevitably leads to a wide range of results, with no shortage of arguable conclusions.

2.1 Objectives and Scope

The literature review aims to fulfill the following objectives:

• Review of the top-level literature discussing the energy future and the hydrogen economy;
• Evaluate previous Life Cycle Assessments and similar analyses;
• Determine the technological state of the art;
• Define key areas of interest that will be addressed in this study; and
• Compile a set of references that can be used for comparison and verification of results.

Several of the cited literature include financial or economical analyses. The STEP LCA is limited to the scope of energy and material flows exclusive of financial interest, and thus financial discussion is excluded from the literature review. Also excluded is discussion on the validity of environmental indicators. The indicators used in this study are based on internationally accepted indicators, and have already been established in Australia by organisations such as the Australian Greenhouse Office (AGO) [9], the Department of Environment and Conservation (DEC) [10], and the National Environment Protection Council (NEPC). Descriptions of environmental impact indicator calculations for Life Cycle Assessment (LCA) are provided by the Leiden University Centre of Environmental Science (CML) [11], and the selected impact categories are explained in Section 3.3.3.
2.2 The Hydrogen Economy

Top-level studies of the hydrogen economy are important in setting up the framework that helps to guide the LCA. In the Australian context, the National Hydrogen Study [3] discussed exploratory scenarios for different levels of future hydrogen integration, with largely speculative discussion of the issues and economies regarding potential hydrogen supply and end-use. An article written by Dicks et al. [5] provided an overview of the Australian energy industry and the potential roles for hydrogen, and noted that the qualitative approach of the National Hydrogen Study is unlikely to help define transitional pathways for the introduction of hydrogen, rather “detailed models for energy pathways specifically for the Australian context need to be developed and tested.” The LCA of the STEP project explicitly addresses this demand. In the same article, it was noted that proven Australian petroleum reserves will only last 10 years at current consumption rates.

In January, 2006, McDowall and Eames published a paper that reviews the “forecasts, scenarios, visions, backcasts and roadmaps to the hydrogen economy” [12]. The main drivers for hydrogen typically include climate change, energy security, local air quality, and international competitiveness. The common barriers discussed are the absence of a hydrogen refueling infrastructure, high costs, and technological immaturity. The study concludes that a significant weakness in the existing hydrogen-futures literature is a lack of real-world detail, as well as a common ‘glossing over’ of important issues. The key deficiencies they identified are categorically addressed by the STEP LCA, as explained in Table 2.1.

<table>
<thead>
<tr>
<th>Deficiency raised in [12]</th>
<th>Addressed by the STEP LCA</th>
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<tbody>
<tr>
<td>Many studies lack participation from stakeholders</td>
<td>Key LCA data provided by the participating organisations</td>
</tr>
<tr>
<td>Usually a top-down global and theoretical perspective, lacking analysis of local issues and actual test data</td>
<td>The STEP LCA uses a bottom-up approach with data generated from field testing</td>
</tr>
<tr>
<td>Insufficient discussion of broader environmental issues, such as end-of-life waste and recycling</td>
<td>The STEP LCA examines the complete life cycle</td>
</tr>
<tr>
<td>Tendency to examine hydrogen in isolation</td>
<td>The STEP LCA includes parallel examination of the established diesel and CNG transportation systems</td>
</tr>
<tr>
<td>Most studies appear pro-hydrogen, and pre-occupied with ‘exotic’ technologies</td>
<td>The LCA is numerical with transparent discussion of assumptions</td>
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Table 2.1: Common deficiencies in the hydrogen-futures literature

The case for the hydrogen economy has been challenged, and will likely remain a matter of debate until a hydrogen economy clearly emerges or drops from the list of popular alternative energy solutions.
“Until there is a surplus of renewable electricity it is not beneficial in terms of carbon reduction to use renewable electricity to produce hydrogen for use in vehicles or elsewhere, [...] higher carbon savings will be achieved through displacing electricity from fossil fuel power stations.” [13]

This fact is well known and has been stated in a number of recent journal articles, such as Joffe [14], Ramesohl [15], and Hennicke [16]. Some researchers have concluded that hydrogen based transportation should not be a focus of science and engineering efforts because they claim there are other more competitive technologies. The work of Mazza and Hammerschlag [17] looks at different scenarios for the use of renewable energy in the United States, with a cursory examination of the fuel production pathways. They contrast the efficiency of using electricity to produce hydrogen with a number of other potential uses for that electricity. The study concludes that it would be more efficient to run purely electric vehicles with lithium-ion batteries than to use the electricity in an electrolyser to run fuel cell vehicles. This is not a new idea, as electric vehicles with battery storage have been in production for decades, but they have never gained a strong foothold in the automotive market. The reason could arguably be attributed to the long refueling time (recharge time) and the limited performance of the vehicles. An electric drivetrain can easily be designed to outperform a conventional internal combustion vehicle, but electric vehicle control systems typically dampen the high-power transient demands of acceleration to conserve battery power and extend battery life. With a properly sized motor and power control system an electric vehicle can achieve very high torque at very low speed, thus acceleration is more limited by the capabilities of the tires to maintain sufficient friction with the road. Fuel cells are similar in response - when the reactants are supplied to the stack in sufficient stoichiometry, electricity can be drawn nearly instantaneously. A 700 bar hydrogen storage system on the current fuel cell bus would provide a range roughly equivalent to a diesel bus. Hydrogen vehicles can be refueled in about 12 minutes, and a robust fuel cell design can withstand high-power transients without any damage that might reduce the lifetime. Hydrogen vehicles meet the customer criteria of range, refueling time, and vehicle performance, and therefore have the potential to capture market share where battery-electric vehicles have previously failed.

A study was conducted by researchers at Stanford University which investigated the change in energy and emissions that could be expected if the entire transportation fleet of the United States were instantaneously converted from conventional Internal Combustion Engine (ICE)s to hydrogen Fuel Cell Vehicle (FCV)s [18]. The study looks at four possible scenarios which contrast different methods of hydrogen production:

- Hybrid vehicles with fossil fuel ICE (as the base case for comparison);
- Hydrogen FCV fueled by hydrogen from decentralised steam reforming;
- Hydrogen FCV fueled by hydrogen from electrolysis powered by wind turbines; and
• Hydrogen FCV fueled by hydrogen from centralised coal gasification.

The scenarios show that the focus is on different methods of hydrogen production. Comparing the scenarios in terms of readiness to market, the first scenario of hybrid ICE vehicles are available to consumers, the second scenario of natural gas steam reforming is the most common method of hydrogen production in use today, and the last scenario of a large-scale coal gasification plant is something that has never been built. The study assumed an instantaneous shift to each scenario, thus establishing a snapshot of the energy emissions. They draw some important conclusions which help provide a basis for the LCA of the STEP trial:

1. For a range of reasonable FCV efficiencies, replacing the fleet with hydrogen fuel cell vehicles would result in a significant reduction in air pollutant emissions;
2. Replacing the current fleet with hydrogen fuel cell vehicles with fuel derived from natural gas, wind or coal would reduce greenhouse gas emissions by 14, 23 and 1%, respectively; and
3. If hydrogen is produced from natural gas with no carbon sequestration and 1% leak rate of methane in the feedstock gas pipeline (greater than expected), the scenario still achieves a 14% reduction in greenhouse gas emissions.

Colella et al. also noted that hydrogen economies can be designed to be inefficient and polluting, or they can be designed to increase efficiency and reduce emissions; the key finding is that the design must encompass the entire transportation system lifecycle.

From the above literature, one can conclude that there is an abundance of forecasts and scenario analyses examining the hydrogen economy, but a lack of data derived from test programs. There is also significant variation in the contribution hydrogen will make in the future transport energy mix, largely depending on the degree to which the actual technology matches the assumptions that were made at this stage.

2.3 The CUTE Trial Evaluation

The CUTE project includes nine cities in Europe operating a total of 27 fuel cell buses. Each city operates three buses, and has had to establish the fuel supply pathway and other infrastructure required to support this new technology. The CUTE project is in association with ECTOS and STEP, which also operate three buses each [19].

As part of the CUTE trial, an official work package (Work Package 9) has been defined to evaluate the environmental, technical and economical impacts of fuel cell bus technology, including hydrogen production methods, bus operation, and comparison to conventional bus systems (diesel and CNG). The methodology for this analysis is discussed in the technical report Deliverable 36 [20], and is in accordance with the international standards ISO 14040ff.
The same methodological framework will be applied to this thesis, but in the Australian context and with Australian data and boundary conditions. When comparing Australian to European data, the hydrogen production, bus operation, and conventional bus technologies are all unique. In addition, the data inventory that the environmental analysis is based on will be different because Australian environmental data sources, such as the National Pollutant Inventory (NPI) or the AGO, have their own reporting policies and emissions factors that are not always common to those used in the European Union (EU). Methodology is further discussed in Section 2.4 below, and the application of these standards in the STEP LCA is the subject of Chapter 3.

The technical report Deliverable 37 gives a detailed account of the Life Cycle Assessment applied to the fuel cell, CNG and diesel versions of the Citaro bus that are evaluated in the CUTE trial [21]. This document describes the objectives of the LCA and details the modeling of the different bus systems and fuel infrastructures, as well as a general overview of Life Cycle Inventory (LCI) methodology. Much of the data published can be employed for validation purposes in the STEP LCA, including descriptions of the diesel and natural gas Citaro construction, the emissions from the Mannheim bus manufacturing plant, bus utilisation data, and fuel consumption statistics for the European fleet.

A number of other publications have emerged from research in partnership with the CUTE project, such as the modeling of a hydrogen refueling structure for London by Joffe et al. [14], and a study in Stockholm examining the climatic effects on fuel cell bus operation by Haraldsson et al. [22]. An overview of the fuel cell bus and hydrogen production technologies used through the CUTE trial can be found in the CUTE Technology Brochure [19], and a final summary of achievements including the final LCA findings was published at the conclusion on the trial [6].

### 2.4 LCA Methodology

A number of methodologies are in use today, some according to international standards while others are original to the application. Another approach which has emerged in parallel with LCA is the Well-to-Wheels (WTW) study. They are similar with the exception that WTW studies are specific to transport applications whereas LCA studies can be applied to any product system. WTW studies are often subdivided into Well-to-Tank (WTT) and Tank-to-Wheels (TTW), with a final aggregation to arrive at the WTW data. LCA studies tend to examine a wider range of impact categories, while WTW studies tend to have better access to primary data (they are usually sponsored by the automotive industry). There are no standards for WTW studies, while LCA studies sometimes conform to the ISO 14040 series of standards, although many LCA studies do not make this claim.
2.4.1 The ISO 14040ff Standards

The ISO 14040 series of standards have gained international acceptance, and their popularity has increased through the publication of independent guides that help LCA practitioners to apply them, such as those published by Guinée et al. at Leiden University [11].

Life Cycle Assessment aims to provide a comprehensive evaluation of complex issues, and adherence to internationally accepted standards helps to improve the reliability of the LCA and increase confidence in the results.

The LCA studies that were conducted as part of the CUTE project follow the ISO 14040 series of standards, as described in Deliverable 36 [20], and as such this study will adhere to the ISO standards and the CUTE methodology as closely as possible to ensure the resulting data sets are comparable.

The ISO 14040 standard defines LCA as follows:

“LCA studies the environmental aspects and potential environmental impacts throughout a product’s life (i.e. cradle-to-grave) from raw material acquisition through production, use and disposal.” [23]

<table>
<thead>
<tr>
<th>Standard</th>
<th>Subject</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO 14040 [23]</td>
<td>LCA Principles and Framework</td>
</tr>
<tr>
<td>ISO 14041 [24]</td>
<td>Goal and Scope Definition and Inventory Analysis</td>
</tr>
<tr>
<td>ISO 14043 [26]</td>
<td>Life Cycle Interpretation</td>
</tr>
</tbody>
</table>

Table 2.2: ISO Standards for LCA

The ISO 14040 - 14043 series of standards provide a framework and guidance on all aspects of the LCA process, from conception to critical review. Table 2.2 provides the titles of the standards that are referenced throughout this study.

2.4.2 Other methodologies

Many LCA studies do not adhere to any set of international standards, but rather formulate their own methodology for the purpose of their analysis. A common approach is to calculate the energy equivalence of all steps of the lifecycle, and compare the summation for each system of interest. Studies that use this approach, such as work of Schäfer et al. [27], typically calculate equivalent carbon dioxide emissions as well to include the total greenhouse impact in their comparison. Very little information exists on the exact energy required to manufacture automotive components and assemblies, and thus these studies are inherently based on rough estimates. Other LCA methodologies recently applied to energy and material flows for hydrogen and fuel cells can be found in Colella et al. [18], Granovskii et al. [28], Spath and Mann [29], and Zamel
and Li [30]. Another interesting methodology is the application of exergy LCA analysis to hydrogen systems, reported by Neelis et al. [31] in an article assessing hydrogen production and storage systems. Exergetic analysis is based on both the first and second laws of thermodynamics, and thus incorporates a quantification of the quality of energy. This can be an important consideration when comparing gaseous and liquid hydrogen systems, as well as component recycling limitations. The collection of exergetic data is beyond the scope of the STEP LCA but the literature can be useful for comparison purposes.

A modeling system which is referenced in a number of prominent WTW studies, including the Australian Comparison of Transport Fuels by Beer et al. [32] and the GM Well-to-Wheels Analyses ([33], [34]), is the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model developed in the United States by Argonne National Laboratories [35]. A history of fuel-cycle research in the United States dating from 1991 to 1999 was included in Wang’s GREET methodology report [36]. The GREET model is a spreadsheet based calculator that provides the user with energy and emissions data for a wide range of fuel supply paths and vehicle technologies. As with any software package, studies using the GREET model may not necessarily conform to the ISO methodology.

2.5 Recent Life Cycle Literature

LCA work requires large amounts of data, and hydrogen technology is developing at a rapid pace. These characteristics sometimes require LCA researchers to make daring assumptions in order to fill gaps in the data. In addition, many LCA studies attempt to project future scenarios, forcing speculative assumptions on the performance of technology which has not yet been invented. Such studies must inherently contain large uncertainty factors, with results and conclusions that cannot be verified by any practical means.

The literature is almost entirely focused on light-duty vehicles, or the total vehicle fleet. The constraints on lifetime, material composition, energy efficiency, and utilisation rates for buses are very different. These and other parameters are key factors in the formulation of the LCA. The only literature identified that relates to the specific case of buses are those associated with the CUTE project ([6],[37],[20],[21]), as well as an LCA comparison of Fuel Cell (FC) and diesel powered buses completed by Faltenbacher et al. in 2000, which was based on an analysis of the Mercedes NeBus concept vehicle [38].

Wang compared seven WTW studies in 2002 [39] and found very wide variation in the results of the studies. The range of results are illustrated in Figure 2.1 for diesel hybrid, CNG hybrid, and FC vehicles. This comparison clearly shows the magnitude of variance in the field of alternative fuel WTW studies, including relatively well-known technologies such as diesel and CNG hybrid engines. This variation can partially be attributed to the lack of standardisation with many studies formulating their own methods to reach a final conclusion, as well as the significant uncertainty in the performance of future automotive drivetrains. The graphs of Figure
2.1 highlight the need for LCA results based on actual testing with clear adherence to a common set of standards.

(a) Reduction in Energy Consumption

(b) Reduction in GHG Emissions

Figure 2.1: Range of results from seven WTW studies

The final LCA report from the CUTE project [37] is an important reference document, as the STEP LCA project uses the same software, methods, and guidelines. There are significant differences between the STEP and CUTE projects, including different energy infrastructures, bus utilisation characteristics, climatic effects, and bus manufacturing. The results from the CUTE LCA serve as the primary reference in validating the initial STEP life cycle models.

There is a great need for LCA studies that examine the current state of technology and the actual performance of state of the art hydrogen fuel cell technology as it stands today. The LCA model can be verified against actual operational data, and can then form a foundation for realistic scenario analysis. Many recent LCA studies cite the work done by Weiss et al. [40] at the Massachusetts Institute of Technology, which assessed the alternative technologies for
passenger cars that could be commercialised by 2020. This study was published in 2000, and reports many uncertainties due to the forward projections that had to be made regarding the performance of future technology.

### 2.5.1 Alternative Fuel Transportation Systems

One of the most well-known and comprehensive alternative fuel reports in Australia is the *CSIRO Comparison of Transport Fuels* conducted by Beer et al. [32]. The great benefit of this study is that the same method is used to examine the life cycle of a very broad range of transport fuel alternatives that are currently available to Australia. The results from each individual LCA can thus be easily compared, and are presented relative to the reference fuel - low sulfur diesel. The only hydrogen pathway examined in this study is $H_2$ production from natural gas, which is the predominant and most economical method of hydrogen production worldwide. The study finds that a hydrogen economy based on natural gas would improve emissions of nitrogen oxides, particulate matter, and air toxics, but would be roughly equivalent in emissions of greenhouse gases. The study also concludes that a natural gas based hydrogen economy would be an improvement in health and ecologically sustainable development. The LCA data for hydrogen production from natural gas steam reforming references the publications by Spath and Mann [29], and the fuel cell performance data is based on fuel cell vehicle efficiency and emissions from a study in 1996. The data for natural gas steam reforming is determined for centralised steam reforming, rather than decentralised steam reforming which was implemented at some bus depots during the CUTE project. There is a clear need for current hydrogen production data, such as hydrogen production from decentralised natural gas steam reformers, and hydrogen production from the BP Refinery, with purification by BOC’s plant in Kwinana. The hydrogen infrastructure technology implemented in the STEP project was not included in the CSIRO report. On the vehicle side, the fuel cell vehicle data referenced by the CSIRO report is outdated, and should be replaced by current data from the EcoBuses.

In 2001-2002 General Motors (GM) published the results from two Well-to-Wheels studies of advanced fuel/vehicle systems; one study based on the North American market [33], and the other based on the European market [34]. The format separates the study into two segments, WTT and TTW, which are aggregated to arrive at the final WTW results. In the European study a total of 88 fuel supply pathways were examined based on oil, natural gas, electricity, or biomass, of which 14 produced liquid or gaseous hydrogen. Although this is a formidable range of technologies, the study did not examine hydrogen production from crude oil (the fuel supply pathway implemented in Perth). While hydrogen production from crude oil is not considered an ideal process due to the associated emissions and dependence on a fossil resource, it is a relatively inexpensive and easily implemented source of raw hydrogen. Hydrogen is a byproduct of the petroleum refining process, and much like natural gas, crude oil based hydrogen will likely be used for many years to bridge the gap until renewable resources are available in sufficient
capacity. Therefore it is important that an assessment of crude oil based hydrogen production be conducted at this time. For the TTW segment of the study, GM has selected the Opel Zafira minivan as the base vehicle. Theoretical alternative propulsion systems were modeled by experts to produce a vehicle with similar performance. The study is focused on light-duty vehicles rather than the very different conditions and design considerations relevant to heavy-duty buses. Thus, the GM studies are a very useful reference for LCA data and conclusions, but do not address comparable aims to this LCA.

A prominent study was published in 2002 by Michael Wang examining Fuel choices for fuel-cell vehicles: well-to-wheels energy and emissions impacts [41]. This article is the result of work on the GREET model since 1995, exploring many fuel pathways and vehicle technologies. A total of 18 fuel pathways are examined in this study, but some can be considered obsolete as they are no longer considered viable options and have largely been abandoned by the industry, such as onboard reforming of methanol, gasoline, ethanol and naphtha. A notable point raised by Wang is the difference in efficiency between European and North American oil refineries; North American refineries are optimised to mainly produce gasoline and thus have a lower overall efficiency than the European refineries which produce a broader range of fuels and a larger fraction of diesel. The study concludes that all hydrogen fuel pathways, except for the paths based on grid-based electrolysis and liquid hydrogen from natural gas, will result in a significant reduction of greenhouse gases.

2.5.2 Hydrogen Transportation Systems

The previously mentioned article by Colella et al. [18] looks at the change in emissions and energy use from an instantaneous change to a hydrogen fuel cell vehicle fleet. They use LCA in combination with data from the US National Emission Inventory, and model a switch to alternative transport fuel technologies. Four scenarios are examined; one hybrid fossil fuel scenario, and three hydrogen fuel cell scenarios with hydrogen produced from natural gas steam reforming, wind electrolysis, and coal gasification. An interesting aspect of their methodology is the spatial analysis, which explores the geographical change in emissions. An efficiency factor for the entire US vehicle fleet is determined for each scenario, and an extensive literature review of fuel cell vehicle efficiencies revealed a broad range of estimates with a factor of 2.9 selected as a reasonable multiplier 2. Various estimation methods are used to generate the energy and emissions data from each of the fuel supply pathways. The LCA portion of the study does not reference ISO 14040 or any other standard, thus it is difficult to use the numerical results for comparison purposes. Still this is an important examination of future scenarios. The key findings were summarised in section 2.2.

Granovskii et al. [28] conducted an LCA of hydrogen fuel cell and gasoline vehicles which

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1 Wang created the GREET model at Argonne National Laboratory in the United States
2 Ratio of hydrogen fuel cell vehicle efficiency to conventional fossil fuel combustion vehicle efficiency
2.5. Recent Life Cycle Literature

uses a first-principal methodology based on economic and energy life cycle assessment software. The study tends to use theoretical calculations for all data, even when established data sources are readily available (such as in the case of crude oil pipeline efficiency). The results show that hydrogen produced from natural gas steam reforming or photovoltaic electrolysis is less energy efficient than the current gasoline based transportation system. Hydrogen from wind power results in the greatest reduction in Greenhouse Gas (GHG) emissions and non-renewable energy consumption. The calculation methods are detailed throughout the article, but do not conform to the ISO 14040 standards, and therefore the results may not be directly comparable with the CUTE and STEP models.

Zamel and Li [30] conducted an LCA of the fuel cell and internal combustion engine vehicles in Canada. The study does not conform to ISO 14040, but uses a methodology that separates the life cycle into a fuel cycle and a vehicle cycle, with the fuel cycle calculations carried out using GREET, and the vehicle life cycle derived from published literature. As such, this study does not bring any new information on the state of the technology, rather it applies the available information to construct an LCA specifically for a mid-size passenger vehicle in Canada. An interesting aspect of their study examines hydrogen production using electricity from nuclear energy, where they conclude that such a fuel supply path could achieve a 50% reduction in energy and an 87% reduction in GHG emissions. They also calculate the recycling of materials and find that the use of 100% recycled material translates to a 45% decrease in emissions when compared to 100% virgin material. They calculate the current 30% use of recycled material in vehicle manufacturing translates to a 13% reduction in energy and carbon dioxide emissions. The results from this study can be compared to the results of the STEP LCA on a relative basis and the unique analysis of nuclear energy and recycling effects give some interesting insights on areas for further research.

2.5.3 Specific Components and Subsystems

A frequently cited article on the LCA of hydrogen production processes was published in 2004 by Koroneos et al. [42]. The study examines hydrogen production from a reference fossil source (natural gas steam reforming) and several renewables sources (photovoltaics, solar thermal, wind power, hydro power, and biomass), in accordance with the ISO 14040 standards. Like the CSIRO Comparison of Transport Fuels, the data for steam methane reforming is taken from Spath and Mann [29], which as mentioned before is based on centralised hydrogen production. The study concludes that hydrogen produced from photovoltaic sources results in the worst environmental performance due to the heavy environmental impact of photovoltaic manufacturing, combined with the low overall efficiency photovoltaic systems.

The previously mentioned exergetic LCA of hydrogen production and storage systems [31] examined steam reformation and water electrolysis, with storage in gaseous form, liquid form, or in metal hydrides. The STEP buses store hydrogen in gaseous form; liquid and metal hydride
storage systems are not evaluated in the STEP LCA. Neelis et al. reinforce these exclusions with their conclusion that storage of hydrogen in compressed gaseous form is significantly more exergetically efficient than the liquid or metal hydride alternatives.

Pehnt [43] researched the LCA of fuel cell stacks in 2001, in accordance with the ISO 14040 standards. This study used the same software that is in use for the STEP LCA (GaBi 4), and examines a Ballard Power Systems 75kW fuel cell stack. Pehnt provides several important findings in the LCA of fuel cell technology, including an in-depth discussion of the allocation rules regarding Platinum Group Metals (PGM) extraction, and the life cycle impacts of reduced PGM loading. The most significant contributors to the emissions profile are the sulfur dioxide emissions from extraction and processing of PGM, and the energy consumption to manufacture bipolar plates. Pehnt determines the change in ecological footprint due to recycling, and concludes that there is great promise in recycling the PGM to improve the fuel cell stack life cycle.

In a 2002 article, Handley et al. [44] addressed the question of recycling options for fuel cell stacks. Their research was aimed at the EU vehicle waste directives and the recycling strategies that would best meet those targets. They conclude that there are several external factors which can influence the end-of-life strategy for PEM fuel cells, with a possibility to recycle all components of the fuel cell stack.

Another notable LCA, though not directly applicable to the STEP LCA, is the study of hydrogen production using high temperature electrolysis powered by nuclear energy, published in 2006 by Utgikar and Thiesen [45]. Electrolysis conducted at high temperature (1150 to 1200 °K) achieves higher energy efficiency over conventional low temperature technologies. This study examines a novel approach combining a high temperature electrolyser with primary energy from an advanced nuclear reactor designed to operate at the ideal electrolyser temperature. The study is in accordance with ISO 14040, focusing on global warming potential and acidification potential. Utgikar and Thiesen conclude that this novel hydrogen production technology would reduce global warming potential to one-sixth, and acidification potential to one-third, respectively, of hydrogen production using conventional steam methane reforming. They note that this reduction is roughly equivalent to hydrogen production from wind and hydropower, with the advantage of much greater energy density and consistent production capacity.

### 2.5.4 Fuel Efficiency of Fuel Cell Vehicles

This LCA will use actual fuel efficiency data from the STEP fuel cell bus trial. The HY-205 fuel cell engine installed in the Perth buses are designed to demonstrate high reliability, and

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3The STEP fuel cell buses contain two Ballard Mk902 150kW stacks.

4PGM are mainly extracted in South Africa and Russia as a byproduct of nickel mining. In determining the allocation rules for PGM extraction, Pehnt concludes that the process should be allocated on an economic basis. The allocation rules applied for the STEP LCA are in accordance with ISO 14040, and are explained in section 3.2.3.

5A description of fuel cell stack construction can be found in Section 4.3.1.
design tradeoffs were made to increase reliability at the expense of energy efficiency. The fuel economy of future fuel cell buses will be dramatically higher than the present demonstration vehicles, and scenario analysis based on the current LCA model can determine the effects of this increase in energy efficiency. Several literature sources are referenced to estimate the fuel economy of a future fuel cell bus, although many are based on light-duty vehicles.

Ahluwalia et al. [46] studied the fuel economy of fuel cell light-duty vehicles in comparison to conventional gasoline internal combustion vehicles. The study is based on the modeling of a theoretical fuel cell engine, with energy efficiency estimations taken from the literature of possible component suppliers. An important key finding of the study is the importance of the minimum operating current of the fuel cell engine. The STEP buses have an idle speed and draw a minimum current from the fuel cell stacks at all times. This can have a significant impact on the fuel economy of a vehicle that operates in city traffic conditions. Ahluwalia et al. conclude that a hydrogen fueled fuel cell compact, mid-size, and sport utility vehicle, would achieve 2.7, 2.7, and 2.5 times the fuel economy of conventional gasoline fueled vehicles.

Colella et al. [18] used a similar theoretical technique to estimate a fuel cell vehicle efficiency ratio of 2.9, and validate this estimation with several sources:

- Toyota Prototype Test Data: 3.1 (Ratio of FCV over present-day ICE)
- Toyota Future Vehicle Estimation: 3.8 (Ratio of FCV over present-day ICE)
- National Research Council: 2.4 (Ratio of FCV over advanced hybrid ICE)
- Rocky Mountain Institute: 2.4 (Ratio of FCV over advanced hybrid ICE)

In addition, Colella et al. note that these should be considered low estimates because they do not account for other future vehicle improvements such as weight reduction using advanced materials, and aerodynamic drag reduction.

The GM studies also use a theoretical simulation to estimate the fuel consumption of a wide range of alternative propulsion systems in comparison to the benchmark gasoline ICE. The vehicle platform is kept constant with alternative powertrains modeled to meet the same performance criteria of acceleration, range, top speed, and gradeability. The modeling software is proprietary and uses a database of component performance maps to calculate the power and energy flow through the vehicle, accounting for all inefficiencies and losses. They claim the models have been validated against several conventional and hybrid powertrains, as well as electric vehicle concept cars, with a fuel economy error within 1% of test results. The GM North American study uses a full size pickup truck for the vehicle platform, and the European study uses an Opel Zafira minivan. The results are reproduced in Table 2.3.

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6Based on the Lower Heating Value (LHV)s of gasoline and hydrogen.


<table>
<thead>
<tr>
<th>FC Powertrain</th>
<th>Gasoline ICE Powertrain</th>
<th>Efficiency ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Drive</td>
<td>Direct Drive</td>
<td>2.1 - 2.3</td>
</tr>
<tr>
<td>Hybrid</td>
<td>Direct Drive</td>
<td>2.4</td>
</tr>
<tr>
<td>Direct Drive</td>
<td>2010 Hybrid</td>
<td>2.1</td>
</tr>
<tr>
<td>Hybrid</td>
<td>2010 Hybrid</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Table 2.3: Results from the GM North American and European simulations

Schäfer et al. [27] use a Matlab Simulink program to back-calculate the fuel efficiency for theoretical light-duty vehicles using gasoline, diesel, and hydrogen FC drivetrains using technology representative of the year 2020. Their analysis includes improvements to the overall vehicle as well, including weight reduction through the widespread implementation of advanced materials and increased aluminium content, drag reduction through aerodynamic improvements, and reduction of tyre rolling resistance. For the purposes of this literature review, the results for the technologies relevant to the STEP LCA are converted to a ratio of the advanced vehicle efficiency to the baseline 2001 gasoline ICE vehicle efficiency, as summarised in Table 2.4.

<table>
<thead>
<tr>
<th>Advanced Vehicle and Powertrain</th>
<th>Efficiency ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>1.61</td>
</tr>
<tr>
<td>Gasoline Hybrid</td>
<td>2.31</td>
</tr>
<tr>
<td>Diesel</td>
<td>1.90</td>
</tr>
<tr>
<td>Diesel Hybrid</td>
<td>2.69</td>
</tr>
<tr>
<td>Fuel Cell</td>
<td>3.49</td>
</tr>
<tr>
<td>Fuel Cell Hybrid</td>
<td>4.20</td>
</tr>
</tbody>
</table>

Table 2.4: Simulation results from Schäfer et al. for fuel efficiencies of vehicles in 2020 incorporating overall vehicle improvements, relative to a baseline 2001 production gasoline ICE

The FC Citaro buses delivered to Perth are designed to demonstrate reliability, and design tradeoffs were made to improve the reliability at the expense of energy efficiency. The CUTE, STEP, and ECTOS trials have proven that the FC Citaro bus is sufficiently reliable to be competitive with CNG buses, and there is now a great opportunity to optimise energy efficiency in the next-generation bus design. The efficiency of the 27 buses that made up the CUTE program is reported in the CUTE final report [6]. Fuel efficiency ratios can be drawn from controlled tests that compared the FC Citaro with a standard Diesel Euro 3 Citaro, on the same route with the same load. Stockholm found the ratio of FC Bus efficiency to Diesel bus efficiency to be 0.67 [22], and Porto found a ratio of 0.76 [47]. Controlled tests were also conducted in Stuttgart resulting in a fuel efficiency ratio of 0.69 for the fuel cell bus, and 0.73 for a CNG EEV bus.

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7A driving cycle is input as an array of vehicle velocity versus time, and the calculation determines power required due to drag, tyre resistance and inertial force. Power is converted to torque, which is then converted to an engine output including losses due to auxiliaries and friction. The mass of fuel required to propel the vehicle can then be determined by multiplying the energy required to complete the driving cycle by the LHV of the fuel.

8The average fuel efficiency of the CUTE fleet was 24.9 kg/100km.
2.5. Recent Life Cycle Literature

relative to the Diesel Euro 3[37]. The NEBUS was an earlier prototype developed by Daimler-Chrysler in the late 1990’s to demonstrate a concept fuel cell vehicle, and achieved an efficiency ratio of 1.16. Data from the Perth trial shows a ratio of 0.79 in comparison to the Diesel Euro 2 buses currently operated by Transperth ⁹. Overall one can conclude that there is great potential for improvements in the energy efficiency of the FC bus engine as it approaches the theoretical estimates. Note that although the fuel efficiency figures discussed in this section are largely theoretical, they are engineering estimates and can thus be considered realistically attainable (as opposed to the unattainable theoretical limits of thermodynamics).

⁹Calculated using actual data from the STEP FC buses; and Diesel bus consumption of 43 L/100km [48].
Chapter 3

Methodology

The formulation of an LCA is an inherently complex task with many possible pathways to reach the desired objectives. The results can be clear and concise, or they can be complex and diverse, depending on the methods used and the overall design of the LCA. Standardisation is imperative if the results are to be compared with other LCA studies. The methodology for this study will be in accordance with the precedent CUTE LCA conducted by IKP, which referenced the international standards ISO 14040 - 14043.

“LCA studies address, systematically and adequately, the environmental aspects and impacts of product systems, from raw material consumption to final disposal, realizing its relative nature due to the functional unit feature of the methodology.”[23]

To draw an example from the current project, a commercial bus can be studied in the LCA context by separating the life cycle into processes of raw extraction, material processing, manufacturing, operation and disposal, as shown in Figure 3.1. In addition, the study must account for the flow of resources and wastes through each life cycle process, resulting in a comprehensive balance of material and energy.

![Figure 3.1: Life cycle of a commercial bus](image)

The ISO 14040 methodology sets out the definition of the LCA framework, and the interaction between the phases. The overall structure of an LCA is separated into four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation, as shown in Figure 3.2. The central theme in this illustration is that LCA is an iterative technique, requiring the practitioner to constantly revisit and refine all phases as the study develops. The direct
applications of the LCA results certainly influence the study, but they remain external to the standardised methodology.

3.1 Goal and Scope Definition

In accordance with ISO 14041 [24] the reasons for performing the LCA of the STEP Fuel Cell Bus Trial are:

- Evaluation of the environmental impacts of the hydrogen fuel cell bus transportation system, including the fuel infrastructure, bus manufacture, operation, and disposal.
- Evaluation and comparison with the established diesel and CNG bus transportation systems.
- Comparison of the primary energy requirements to operate each transportation system.
- Scenario analysis examining possible future fleet scaling and technology developments.

The results are aimed to be applied for:

- Identification of key areas of interest for future technology improvements.
- Comparison of the transportation systems across a wide range of global and local environmental impacts.
- Input to the strategic decision-making process for future transport energy policy.

The target audience for this study are:

- Decision makers in the State Governments, the Commonwealth, and the transport authorities.
- Corporate managers in the energy and infrastructure sectors, the bus industry, and other automotive manufacturers and suppliers.
3.1. Goal and Scope Definition

- LCA practitioners developing related studies, both within Australia and internationally.
- Any other people interested in transport energy.

3.1.1 Functional unit

The performance characteristics of the different processes can be examined by defining a unit that scales the flows to a familiar context. As defined by ISO, “the primary purpose of a functional unit is to provide a reference to which the input and output data are normalized (in a mathematical sense).”[24].

For the fuel production processes, the main function is to output a unit of energy in the form of a liquid or gas. The diesel fuel infrastructure is easily related to the production of Litres Diesel, while the Australian natural gas industry typically relates to normal cubic metres ($Nm^3$) compressed natural gas. The hydrogen industry typically relates to kilograms hydrogen. The different fuels will be compared on an energy basis using a functional unit of equivalent liters-diesel ($L$-diesel eq.).

The next stage of the transportation system relates to the operation of the buses, with the main function being the transportation of people over a certain distance. In comparing the operation of a bus over a defined route profile the functional unit of kilometres traveled can be used. Since each type of bus also has different passenger-carrying capacity, a functional unit of passenger-kilometres will be used to quantify the passenger transport capabilities of the different bus systems.

3.1.2 Product System

In defining the scope of the LCA, ISO requires a clear statement of the product systems that will be examined. The three product systems that will be studied are the diesel bus transportation system, the CNG bus transportation system, and the hydrogen fuel cell transportation system, including their respective fuel infrastructures.

3.1.3 System Boundary

The system boundaries define the external interfaces of the product system, as illustrated in Figure 3.3. In an ideal LCA the system boundaries will be set out such that all inputs and outputs are elementary flows, however the compilation of such a broad data set requires vast resources. Decisions must be made regarding the depth to which each process will be studied. Early recognition of each process’ relative significance will prevent mis-allocation of resources to areas that have a negligible impact on the final results. As stated in [23], “Resources need not be expended on the quantification of such inputs and outputs that will not significantly change the overall conclusions of the study”.
The cut-off criteria to determine which processes fall outside the system boundary must be justified, and can be based on environmental significance, mass, or energy. Considering that a primary goal of this study is the comparison of environmental impacts, as stated in section 3.1, it follows that the cut-off criteria will primarily be based on environmental relevance. In selecting the unit processes studied in this LCA any process with \( \leq 1\% \) contribution to mass, energy or environmental relevance is deemed indifferent and thus excluded from the system boundary.

### 3.1.4 Data Quality

The reliability of the study results are directly related to the quality of the data. The ISO standards require that the following data quality parameters be addressed [24]:

- Desired age: The key operational and technology-related data, such as emissions measurements, will be as recent as possible, and typically \( \leq 5 \) years old. Auxiliary data that does not change significantly over time, such as steel production, is taken from the GaBi database and could be older.

- Geographical relevance: Australian data will be used wherever possible. If Australian data cannot be obtained it will be supplemented with European or international data. This will be noted and explained in each case.

- Technology: The most recent available technological data will be used to determine a state of the art LCA balance. Future technology developments will also be examined in the scenario analysis. This study does not examine worst-case results due to older technologies.
• Precision: The variation of data values must be accounted for. In some cases a sensitivity analysis may be required to determine the effect of highly-variable data.

• Completeness: The data input to the study will be 100% complete (the ISO standards require the completeness parameter for studies that define a minimum percentage of input from a broad base of reporting data sources).

• Representativeness: As previously stated, Australian data will be used where possible. If important data is supplemented from other sources, the impact of this assumption must be discussed qualitatively and may require further examination through a sensitivity analysis.

• Consistency: The same methodology must be applied to all components of data collection and analysis.

• Reproducibility: Publicly available data will be used where possible, thus allowing an independent LCA practitioner to reproduce similar results. However, due to the highly competitive nature of automotive technology and various other business interests, commercial confidentiality requires that some detailed data must remain undisclosed.

3.2 Life Cycle Inventory

The compilation of the Life Cycle Inventory (LCI) is an enormous task, requiring very detailed enumeration of all energy and material flows for each part of the system to be examined, and a thorough understanding of the critical parameters affecting each process. Process flow diagrams are used to outline the relationships between unit processes and flows across the system boundaries. Each unit process must be qualitatively described to ensure a thorough understanding, and to avoid any overlap (double counting).

3.2.1 Data Collection

The main sources of data for this LCA are company publications, annual reports, articles, books, academic publications, and interviews with industry experts. In all cases the sources are referenced, and any data quality issues are noted. To complete the project within the scope of one thesis, one must use existing data sources as much as possible. The partnership between Murdoch University and the University of Stuttgart allows Murdoch limited access to the Master GaBi Database held by IKP.

The current hydrogen infrastructure in Western Australia has been completely modeled in a parallel LCA project which was conducted in close cooperation with this study, and the resulting model has been supplied as input to this LCA [49].

Calculation procedures are used to relate the raw data to functional units within the models, and all such calculations should use the same mathematical method. For example, the conversion of fossil fuel resources to electrical power requires the product of combustion and
processing efficiencies, and the heating value of the fuel. The electrical grid mix is the sum of a set of fuel processing calculations which are all consistent.

### 3.2.2 Data Validation

The results of the Data Inventory compilation and calculations are checked using methods such as mass and energy balances, and comparison with similar studies. Any discrepancies must be addressed, and data gaps must be filled. This process is consistent with the iterative nature of LCA, usually requiring a return to the data collection phase in an attempt to resolve the data gap, or possibly requiring the researcher to revisit and adjust the goal, scope, or system boundaries.

### 3.2.3 Allocation

In an ideal LCA model, the outputs will be mathematically linked to the inputs by a proportional linear relationship. However, such simplicity is rare in the real world as most industrial processes are nonlinear, have multiple inputs and outputs, and a range of intermediate products as well. It would be incorrect to attribute all the environmental impacts of a complex process to the single output of interest for the current LCA. In such cases allocation is necessary to accurately relate the various flows.

An example applicable to this study is the case of an oil refinery, where the crude oil input is processed to output a range of products, each with different mass flows and energy contents. The diesel fuel output may be the only flow recognised in the LCA, but it would be incorrect to assume all emissions from the refinery are due to diesel production. Allocation is necessary to find a more appropriate scaling of the environmental impact for diesel fuel production, but the basis for allocation must also be decided. A mass basis would yield a different allocation than an energy basis, and in some cases an economical basis may be more appropriate.

\[
\text{crude oil}_{\text{Refinery}} \rightarrow \text{petrol} + \text{diesel} + \text{naptha} + \text{fuel oil} + \ldots
\]

\[
\frac{\text{mass}_{\text{Diesel}}}{\sum \text{mass}_{\text{All Products}}} \neq \frac{\text{enthalpy}_{\text{Diesel}}}{\sum \text{enthalpy}_{\text{All Products}}} \neq \frac{\text{총}\text{ 단가}_{\text{Diesel}}}{\sum \text{총}\text{ 단가}_{\text{All Products}}}
\]

The ISO 14041 standard advises that allocation should be avoided wherever possible by dividing the process in question into small sub-processes with elementary flows, or by expanding the system boundary to account for the additional flows [24]. In many cases these approaches are not feasible because they would greatly increase the data collection workload beyond the scope of the project.

Allocation is regularly encountered in LCA, and each case must be individually evaluated to determine the most appropriate approach.
3.3 Life Cycle Impact Assessment

A main objective of LCA is to determine the outputs to the environment by calculation of the material and energy flows. Outputs with similar environmental impacts can be grouped and classified to aggregate their environmental impact. Such classification quantifies the potential environmental impact of the product system and simplifies the result to a single parameter, such as global warming, smog creation, acidification, etc. The group classifications are referred to as Impact Categories, and the standard ISO 14042 [25] sets out the guidelines for Life Cycle Impact Assessment (LCIA).

3.3.1 Classification

The output substances from the LCA are assigned to one or more impact categories. Each impact category is an independent indicator, so an output substance may be accounted for in several different impact categories. A relevant example is nitrogen oxides, which contributes to smog, acidification, eutrophication, and other impact categories.

3.3.2 Characterisation

After determining the substances that contribute to an impact category, the potential impact of each substance must be characterised in relation to the dominant factor in that category. An example is the GWP impact category, which defines factors for each substance in relation to $CO_2$. Substances which contribute to GWP are scaled to $CO_2$-equivalent using the impact factors defined by the IPCC. For example, each mass unit of methane ($CH_4$) is accounted for as 21 mass units of $CO_2$-equivalent. The total GWP impact is the sum of all contributing substances expressed in units of $CO_2$-equivalent.

3.3.3 Selection of Impact Categories

The impact categories must be selected based on the goals and intended use of the results. As stated in [25], if comparative assertions from Life Cycle Impact Assessment (LCIA) are disclosed to the public they should be internationally accepted impact categories, and be environmentally relevant to the spatial and temporal context.

The impact categories selected for this study are listed in Table 3.1 with a short description of their environmental relevance. These are internationally accepted impact categories, and are in accordance with the CUTE LCA methodology [20]. Background information and characterisation factors are published by the Leiden University Centre of Environmental Science CML [11].

In addition to the impact categories, the overall energy demand of each product system will be evaluated as this can be directly related to the consumption of energy resources.
### Table 3.1: Selected Impact Categories

<table>
<thead>
<tr>
<th>Impact Category</th>
<th>Short Description</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global warming Potential (GWP)</td>
<td>Emissions which contribute to global warming</td>
<td>$CO_2$, $CH_4$,...</td>
</tr>
<tr>
<td>Acidification Potential (AP)</td>
<td>Emissions which cause acidification of rain, soil and water</td>
<td>$SO_2$...</td>
</tr>
<tr>
<td>Eutrophication Potential (EP)</td>
<td>Emissions which change nutrient concentration in lakes, rivers and soil</td>
<td>P and N compounds</td>
</tr>
<tr>
<td>Photochemical Ozone Creation Potential (POCP)</td>
<td>Emissions which increase tropospheric ozone production</td>
<td>Hydrocarbons</td>
</tr>
</tbody>
</table>

#### 3.3.4 Impact Categories in relation to Australian Policy

The impact categories selected for this study maintain compatibility with the CUTE LCA, and are directly applicable to Western Australian State and Commonwealth policy.

Many of the key substances and impacts examined in this study are relevant to the National Environment Protection Measures (NEPMs) for Ambient Air Quality [50], National Pollutant Inventory [51], Diesel Vehicle Emissions [52], and Air Toxics [53].

The Western Australian State Sustainability Strategy recognises the need to reduce GHG emissions, and the potential opportunity to use global greenhouse emissions reduction as a driver for innovation and economic development. The Strategy does not specify a target for greenhouse gas emissions, but recognises it as a priority.

“Our sustainability principles could be undermined by climate change unless we take proper account of this issue as a priority.” [54]

The Strategy also discusses Oil Vulnerability and the Hydrogen Economy, and notes that of the many competing technologies in alternative transport “there are no obvious benefits to any one technology”. This statement highlights the necessity for comparative studies such as this, that provide a range of important environmental impacts. The evaluation of the STEP project is specifically mentioned as one of the actions in the Strategy, as well as the State policy to purchase only CNG powered buses for Transperth. This study directly addresses these two actions.

The preservation and improvement of air quality is addressed in the Strategy, through reduction of pollutants from industrial and transport emissions. The Strategy notes that particle pollution causes an estimated 2,400 deaths per year in Australia, with an estimated health cost of $17.2 billion. The impact categories selected for this study do not account for particulates, but they are tracked in the LCA model and will be presented as an individual substance (ie. not as part of an aggregated impact category).

The POCP impact category relates to the Strategy’s objective for smog reduction through transport emissions. Motor vehicles are a primary source of compounds that react to form smog.
3.4 Interpretation

The State Sustainability Strategy discusses the implementation of the Air Quality Improvement Plan which places a priority on vehicle emissions, and references the Air Quality National Environment Protection Measure (NEPM) in setting out the standards and objectives for air pollutant reduction.

While acid rain is not cited as a major threat to Western Australia in the State Sustainability Strategy, acidification of soil is recognised as a threat to agriculture. The primary causes for soil acidity are the removal of agricultural products and the leaching of nitrogenous fertilisers. The AP impact category will be calculated, but is not of particular interest for this study because acidification due to vehicle emissions is not considered a significant problem.

Eutrophication of soil and water is briefly mentioned in the State Sustainability Strategy, with agriculture indicated as the primary source of pollution. Water bodies and water quality are affected by eutrophication due to changes in algae growth and resultant oxygen depletion, which can create toxins lethal to humans and fish habitats. The National Eutrophication Management Program (NEMP) [55] is an initiative to research the reduction of algal blooms, but does not examine the transportation or fuel production industries. The EP impact category accounts for the combined eutrophication of water and soil from the product systems in this study.

The DEC monitors several atmospheric pollutants from motor vehicles such as carbon monoxide, nitrogen dioxide, tropospheric ozone, particles and sulfur dioxide. These substances are all hazardous to human health and have been linked to “increased incidence of cancer, birth defects, genetic damage, central nervous system defects, immunodeficiency, and disorders of the respiratory and nervous systems”[10]. All of these substances are accounted for in the LCIA, the LCI, or both.

3.4 Interpretation

The final phase of an LCA is interpretation, which takes the study through to evaluation of the data collected and calculated, and provides feedback for changes to the other phases of an LCA. The ISO 14043 [26] standard states that three elements must be satisfied in the interpretation phase:

1. Identification of significant issues based on the results of the LCI and LCIA.
2. Evaluation which considers completeness and consistency checks.
3. Conclusions, recommendations and reporting.

The first element requires that findings from the LCA be reported along with statements on data quality and uncertainty. The results should reflect the objectives defined in the goal and scope of the study. Significant issues can be drawn from the LCIA, or the LCI for substances that are not accounted for in the impact categories. Essential contributions such as energy production can also be reported as a significant finding.
The evaluation element is intended to increase confidence in the reliability of the study. The techniques required for evaluation are checks for completeness, sensitivity, and consistency. Checking the completeness requires the LCA practitioner to review the models in a search for data gaps. Sensitivity checks quantify how uncertainty in the data can effect the final results. A consistency checklist reviews the consistent application of the goal and scope, the product systems, data quality requirements, spatial/temporal considerations, allocation rules, and impact assessment methods.

The third element in interpretation is the reporting of conclusions and recommendations for the target audience. If the conclusions are not consistent with the goal and scope of the study, or the data quality requirements, further iteration through the LCA phases will be required until consistency is achieved. Recommendations must be based on the final conclusions of the study, and be relevant to the intended application. The final report should be unbiased with transparent discussion of the assumptions and judgment decisions.
Chapter 4

System Description

As stated in Chapter 3, the ISO 14040 standard requires that the system boundary for each of the three transportation systems be clearly defined. This study consists of three separate systems which are described in the sections below, namely, the diesel, natural gas, and hydrogen fuel cell, bus transportation systems. The functional processes of each system are drawn in a flow diagram and a system boundary defines which processes are excluded from detailed examination, consistent with the cut-off criteria. Detailed discussion of the subsystems and data collection efforts are reserved for Chapter 5.

4.1 Diesel Bus Transportation System

The processes and phases of the diesel bus transportation system life cycle are illustrated in Figure 4.1. The construction and dismantling phases for all equipment is represented on the left side of the diagram with a yellow background, and the operation phase is represented on the right with a light blue background. The black arrows in the center of the diagram represent the flow of new parts and facilities into the operation phase, and the return of waste materials for dismantling, recycling, and disposal. Each phase of the system requires energy and material inputs, represented by the green arrows, and produces emissions and wastes, represented by the orange arrows. The valuable flow that drives the processes of the life cycle is represented by the blue arrows flowing down through the operation phases and ending in the final output of passenger transport, which has been selected as the functional unit for the LCA. The definition of the system boundary is represented by the black dashed line.

The fuel infrastructure for diesel transportation originates with the exploration and extraction of petroleum deposits in the earth. Crude oil is transported to the BP refinery in Kwinana, mainly by sea. The refinery processes the crude oil and provides a number of products, including most of Western Australia’s transport fuel. The source of crude oil for the kwinana refinery varies quite largely, and is described in more detail in Chapter 5.

The system boundary excludes the manufacturing and dismantling of BP’s Kwinana Refi-
The energy and emissions due to construction of a refinery, when allocated to the emissions from the diesel fuel consumed by the buses, is well below the 1% cut-off criteria and can be considered negligible [49]. Similarly, the construction of the diesel fuel distribution, storage and pumping systems fall well below the 1% cut-off criteria and can be excluded from the LCA. Exclusion of these construction and disposal processes is a common assumption in alternative-fuel LCA 1, as these processes are minor in relation to the quantities of the operation phases.

Diesel fuel is exported from the refinery by pipeline and tanker truck to distribution points around the State. The diesel delivered to Path’s Morley bus depot arrives by truck and is transferred to above-ground vessels. Electric pumps are used to transfer the fuel to the diesel buses.

Bus manufacturing is a significant contributor to the overall life cycle and must be accounted

---

1The application of cut-off criteria is rigorously explained in Chapter 5. Other prominent studies which make the same exclusions are Colella et al. [18] and Faltenbacher et al. [37].
for in the LCA. The buses in Australia operated by Transperth are manufactured in two separate phases of construction. First, a *buggy-chassis* is constructed at a Mercedes Benz EvoBus plant in Brazil, Spain, or Germany. The buggy-chassis is a driving chassis with wheels, suspension, steering, and brakes, that has been shortened to reduce the cost of shipping. An Australian bus body manufacturer receives the imported bus, cuts the buggy-chassis and extends it to full bus length, and builds the body upon it.

The operation of the bus over the vehicle’s lifetime is the phase which drives the entire life cycle system, based on the final functional unit of passenger-kilometres. After a bus completes the operation phase it must be decommissioned and the parts must be recycled or otherwise disposed. All processes of the diesel fuel infrastructure and manufacturing processes must also be dismantled and recycled or disposed at the end of their useful life.

## 4.2 CNG Bus Transportation System

Western Australia contains expansive reserves of offshore and onshore natural gas, mainly concentrated in the North West region of the State. Natural gas amounts to 46% of WA’s identified energy resources, with three producing basins (Caranarvon, Perth, and Bonaparte). The State exports considerable natural gas resources in the form of Liquefied Natural Gas (LNG) [56], with a smaller fraction of production used for domestic consumption in the form of CNG.

The CNG fueling station at the bus depot in Malaga is supplied from the offshore Carnarvon basin. CNG fuel for the bus transportation system flows through several processing plants before being transferred to Perth by pipeline. Distribution stations supply the gas to additional processing facilities and end-use customers.

The Morley bus depot is connected to the natural gas distribution system, and a *state of the art* CNG filling station compresses the gas into cylinders on the buses.

CNG buses operate on the same bus routes as the diesel buses, but with less passenger carrying capacity due to the increased weight of the natural gas storage cylinders on the roof. The manufacturing of a CNG bus is similar to the process described for the diesel bus, with the addition of materials and processes for the fuel storage system installation. The lifecycle and system boundary for CNG bus transportation is depicted in Figure 4.2.

## 4.3 Hydrogen Bus Transportation System

The hydrogen fuel cell bus lifecycle and system boundary are illustrated in Figure 4.3. As expected, the system boundary encompasses a much larger fraction of the lifecycle due to the small operating scale of the trial fleet in Perth. Larger production volumes of hydrogen, and mass-produced components, would reduce the scope by shifting the parts of the system boundary closer to the cut-off criteria.
The hydrogen source for the STEP project is unique, originating at the BP Kwinana oil refinery. Naptha is separated during atmospheric distillation and diverted to a catalytic reforming process. The low-octane heavy naptha fractions are converted to high-octane reformate (gasoline blending components), releasing hydrogen as a byproduct. The byproduct hydrogen amounts to some 60 tonnes/day, of which 150 kg is taken for the STEP project. The bulk of the hydrogen is used internally for the production of low-sulfur diesel, and the remainder is sold to customers or combusted for heat.

A 2 km pipeline transports the raw hydrogen to a BOC processing plant, where a Pressure Swing Adsorption (PSA) system removes contaminants to produce 99.9999% pure hydrogen. A diaphragm compressor fills a hydrogen trailer to 160 bar for transport to the bus depot. Waste gas from the purification process (also known as tail gas) is returned to BP via a tail gas compressor, as it mainly consists of hydrocarbons with useful calorific value.
The hydrogen trailer travels from the BOC plant in Kwinana to the bus depot in Malaga, a distance of approximately 66 km. The BP refueling station compresses the hydrogen from the trailer into 300 bar buffer cylinders, to reduce bus refueling time. The hydrogen trailer is exchanged when the pressure drops below 50 bar. When a bus is connected to the refueling station the buffers are equalised with the bus cylinders, then the compressor boosts the hydrogen to the final fill pressure. 

Unlike the diesel and CNG buses in Perth, the fuel cell bus is constructed on a steel space-frame, and is completed at an EvoBus manufacturing plant in Mannheim, Germany. The FC buses are heavier than conventional diesel or CNG buses, and therefore have a reduced passenger capacity due to the maximum weight limits of the axles. At the time of this writing no decision had been made on the future of the FC buses after the end of the trial, however the platinum in the fuel cells will likely be recovered and re-used. For the purposes of this LCA the other materials of the FC bus are considered to be scrapped and recycled like any other vehicle.

4.3.1 The Fuel Cell Concept

The attraction between hydrogen and oxygen is the fundamental means of energy conversion in a fuel cell. When hydrogen and oxygen atoms are placed in close proximity they will naturally form a water molecule, releasing energy in the process, because water is a lower energy state. In a fuel cell, approximately half of the energy that is released through the formation of water molecules can be captured as electricity, and the remainder is transferred as heat. The type of fuel cell manufactured by Ballard is called a Proton Exchange Membrane (PEM) fuel cell. The membrane is a solid polymer electrolyte which is unique in that it can conduct hydrogen ions, but not electrons. Thus it can be said that the membrane is an electrical insulator that can conduct positively charged hydrogen ions. When hydrogen and oxygen are separated by such a membrane, and a catalyst such as platinum is present on both sides of the membrane, a natural voltage will develop across the membrane. The voltage can be measured at approximately 0.7V. If an electrical circuit is formed across the membrane, the hydrogen ($H_2$) molecule will split into two positively charged hydrogen ions ($H^+$) and two free electrons. The hydrogen ions move through the membrane towards the cathode, while the electrons travel through the external circuit which contains the load. On the cathode the hydrogen ions combine with oxygen and the free electrons to form two water molecules. This product water is then discharged from the fuel cell.

---

2Settled pressure 350 bar @ 15°C. Maximum pressure during fill is 438 bar.
Anode Reaction:
\[ H_2 \rightarrow 2H^+ + 2e^- \] (4.1)

Cathode Reaction:
\[ 2H^+ + 2e^- + O_2 \rightarrow 2H_2O \] (4.2)

Each fuel cell produces about 0.7v and the cells must be connected in series to develop a useful voltage. The fuel cells are stacked using bipolar plates, resulting in a fuel cell stack.

When a fuel cell is supplied with hydrogen, oxygen, and adequate cooling, it will produce continuous electrical power. The raw electrical power is direct-current, and the fuel cell can be designed to meet whatever voltage and current requirements the application demands by changing a number of parameters, such as the area of each cell and the number of cells in the stack.
Figure 4.3: Hydrogen fuel cell bus system life cycle and system boundary
Chapter 5

Life Cycle Inventory and Modeling in GaBi 4

The Life Cycle Inventory (LCI) is the data collection that describes the processes of the system to be examined. Compilation of the LCI requires the enumeration of all energy and material flows through each process. For complex product systems this can be an enormous task requiring significant time and resources. PE Europe GmbH has provided the GaBi 4 software system and datasets on material and energy flows, eliminating the need for redundant data collection of simple industrial processes.

5.1 The SWIS Electricity Grid

An accurate model of the electricity supply is an important component of the LCA. Hydrogen and CNG compressors are examples of relevant systems that draw significant power from the grid. The BP Kwinana refinery has its own electricity supply operated by the Perth Power Partnership, a natural gas fueled cogeneration plant, which has been included in the refinery model [57]. Establishing an accurate grid mix model is also important for future scenario analyses of alternative fuel production and transportation technologies. The system boundary for the electricity grid model excludes construction and dismantling of the electricity infrastructure.

The electricity supply networks of WA are separated into the South West Interconnected System (SWIS) and the regional power systems. The SWIS is the largest network in WA, and is the grid relevant to this study as it encompasses both Perth and Kwinana. For the 2004/2005 financial year, Western Power had an installed generation capacity of 3.412 GW on the SWIS, and had generated some 13,679.2 GWh [58]. A peak demand of approximately 3,000 MW occurs during the summer months depending on ambient conditions [59]. The fuel supply for the SWIS is primarily coal, but also includes gas, liquids (oil and distillate), and renewable sources.

Western Power is the major supplier of electricity in the state, and the major producer of
electricity on the SWIS. Several private companies operate power generation plants that are connected to the SWIS, but mainly generate power to meet internal company demand. The LCI for the SWIS was compiled using data from the Western Power annual report [60], data from the AGO [9], and data from the NPI [61]. Fuel mass quantities for coal, natural gas, and fuel oil, were converted to units of energy using data from ABARE [62].

Table 5.1 shows some aggregated results from the LCA of the SWIS. These values are calculated by linearly scaling the data input from the LCI to an electrical output of 1 kWh delivered to the customer, followed by aggregation of outputs to calculate the impact categories shown in the table. The model has been validated by comparing the primary energy, overall efficiency, and emissions with published figures in the literature.

<table>
<thead>
<tr>
<th>Flow</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Energy Input</td>
<td>4.52 kWh</td>
</tr>
<tr>
<td>Electrical Power Output</td>
<td>1 kWh</td>
</tr>
<tr>
<td>Global Warming Potential (GWP)</td>
<td>1.02 kg CO₂ equiv.</td>
</tr>
<tr>
<td>Photochemical Ozone Creation Potential (POCP)</td>
<td>3.8 × 10⁻⁴ kg Ethene equiv.</td>
</tr>
<tr>
<td>Acidification Potential (AP)</td>
<td>7.6 × 10⁻⁵ kg SO₂ equiv.</td>
</tr>
<tr>
<td>Eutrophication Potential (EP)</td>
<td>5.5 × 10⁻⁴ Phosphate equiv.</td>
</tr>
</tbody>
</table>

Table 5.1: Results for the SWIS

5.2 The Diesel Fuel Infrastructure

The LCI for the diesel supply includes crude oil exploration, extraction, transport, processing, and delivery to the fueling point at the bus depot in Malaga. The Transperth bus fleet is currently
5.3. The Natural Gas Fuel Infrastructure

Natural gas is similar to diesel, or any other fossil fuel, because the LCI begins with exploration and extraction, mainly concentrated in the North West region of Western Australia. Domestic consumers, such as the CNG bus fueling station at the Path Morley depot, are supplied by pipeline from the North West Shelf. A map of Western Australia’s established drilling wells, transmission pipelines, and gas infrastructure is shown in Figure 5.2 (reproduced from [64]). In Western Australia at the end of the 2004/2005 fiscal year there were 20 onshore wells with a total

using ultra-low-sulfur diesel (≤ 50 ppm).

Most of WA’s fuel is produced at the BP Kwinana refinery, which has a processing capacity of 138,000 barrels of crude oil per day. The BP refinery is versatile in that it can quickly adjust and optimise for different crude oil compositions, allowing the refinery to obtain crude oil from a wide range of geographical sources. The crude oil processed at Kwinana comes from all over the world, with 29% coming from Asia and Africa, 27% from the Middle East, and 44% from domestic Australian fields and the North West Shelf. Approximately 90% of the crude oil is received at the refinery by ship, and the remaining 10% is received by truck.

The refinery has one main input (crude oil) and several product outputs. It would be incorrect to attribute the entire energy and environmental impacts of crude oil extraction to any one refinery product, and thus allocation is necessary. Two allocation rules were applied: The share of crude oil for each refinery product was allocated based on the energy of the product, and the share of energy for each intermediate refinery process was allocated based on the mass throughput. Thus, a product with high calorific value that passes through many refinery processes, such as gasoline, would be allocated a large share of the crude oil input, and the energy required for the intermediate processes [49]. Additional background information on allocation according to ISO 14040 can be found in [23].

The detailed LCI for the BP refinery is credited to Ilg [49], using an existing GaBi refinery template and personal communication with BP experts in Kwinana. Diesel fuel is transported by pipeline to a distribution centre in Kewdale (approximately 50 km), where it is transferred to trucks for transport to the Malaga bus depot (approximately 35 km). Pipeline transport of diesel fuel has been included using generic GaBi models. A typical fuel delivery consists of 35,000 litres, which equates to a mass of 29.6 tonnes [62]. The fuel consumed for transport is calculated at a fuel economy of 30.53 L/100km, derived from data on heavy-duty diesel transport trucks reported in [32].

The diesel pump at Path’s Morley depot is manufactured in the United States, and runs at an output of 18 US Gallons per Minute (GPM), at 1/3 Horsepower (HP) [63]. The bus fueling time measured at the Morley depot was 200 litres, filled in 3 minutes, therefore confirming the flow rate of 66 Litres per minute (17.42 GPM). For the purposes of the LCA model, these figures result in an energy consumption of $6.214 \times 10^{-5} \text{kWh/L}$. 

5.3 The Natural Gas Fuel Infrastructure

Natural gas is similar to diesel, or any other fossil fuel, because the LCI begins with exploration and extraction, mainly concentrated in the North West region of Western Australia. Domestic consumers, such as the CNG bus fueling station at the Path Morley depot, are supplied by pipeline from the North West Shelf. A map of Western Australia’s established drilling wells, transmission pipelines, and gas infrastructure is shown in Figure 5.2 (reproduced from [64]). In Western Australia at the end of the 2004/2005 fiscal year there were 20 onshore wells with a total
of 36,200 meters drilled, and 61 offshore wells with 172,331 meters drilled [65]. The ABARE reports that the national production of natural gas in Australia was 1685 PJ in 2004/2005, with 984 PJ produced from wells in Western Australia [66]. A methodology for calculating the emissions from natural gas production in Australia is provided in the AGO Methodology publication [9].

The LCI for the natural gas infrastructure was modeled using a GaBi standard template. The top-level view of this model is shown in Figure 5.3, with process labels translated from the German database. Much like the Oil Refinery model, this GaBi template was modified to match the natural gas infrastructure in WA by adjusting the parameters that drive the model.

There are eight natural gas processing facilities in WA, and a natural gas storage facility at the depleted gas reservoir in Mondarra. The location and throughput for the processing facilities was taken from [56].

The natural gas transmission infrastructure in WA consists of five onshore pipelines. The CNG fueling station at the Morley depot is supplied by the Dampier to Bunbury Natural Gas Pipeline (DBNGP), consisting of 10 compressor stations, 1788 km of high pressure pipe, and an annual capacity of 595 TJ per day [56].

The composition of natural gas entering the pipeline can vary depending on the well, processing facility, and downstream customers. The Dampier natural gas composition for the 1999-2000 reporting year\(^1\) is published in [9], and is reproduced in Table 5.2.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Methane</em></td>
<td>83.9 % vol</td>
</tr>
<tr>
<td><em>Ethane</em></td>
<td>7.2 % vol</td>
</tr>
<tr>
<td><em>Propane</em></td>
<td>3.1 % vol</td>
</tr>
<tr>
<td><em>Butane</em></td>
<td>1.0 % vol</td>
</tr>
<tr>
<td><em>Pentane</em></td>
<td>0.1 % vol</td>
</tr>
<tr>
<td><em>Hexane</em></td>
<td>0.0 % vol</td>
</tr>
<tr>
<td><em>CO(_2)</em></td>
<td>2.3 % vol</td>
</tr>
<tr>
<td><em>Other</em></td>
<td>2.4 % vol</td>
</tr>
<tr>
<td><em>Energy(_{GCV})</em></td>
<td>40.8 MJ/Nm(^3)</td>
</tr>
</tbody>
</table>

Table 5.2: Dampier natural gas composition

The gas inlet pressure to the fueling station is 7 bar, and buses are fueled to a settled pressure of 200 bar\(^2\). The *fast-fill* compressor station at Morley Depot is built by Origin Energy, and includes three electrically operated compressors, a diesel generator for backup power, and a concrete enclosure. The compressors are manufactured by Intermech Corporation in New Zealand, and are capable of filling a natural gas bus in less than 8 minutes. Origin Energy refused to provide operational or construction data for the Morley CNG plant, therefore the LCI

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\(^1\)Previously the AGO calculated natural gas emission factors from the natural gas composition. From 2001 the Australian Gas Association no longer collected composition data from its members. The AGO assumes the emission factors are unchanged [9].

\(^2\)Maximum pressure during filling is 260 bar due to the heat of compression.
Figure 5.2: Map of Western Australia’s Natural Gas Infrastructure
data had to be drawn from literature. The most important parameter, compression efficiency, was assumed to be 96.6% [67].

5.4 The Hydrogen Fuel Infrastructure

A GaBi model for the LCA of the Perth hydrogen infrastructure, including production and delivery of high-pressure gaseous hydrogen, was completed by Ilg [49].

5.5 Bus Manufacture

The diesel and natural gas buses selected for this study are the Volgren/Mercedes-Benz Diesel OC 500LE and CNG OC 500LE. The CNG OC 500 is the latest model delivered to Transperth and is considered representative of current Australian bus design. Transperth is not purchasing diesel buses, but the diesel version of the OC 500 is selected to maintain consistency. The FC Bus is built in Germany, based on a Mercedes-Benz O530 Citaro chassis. General specifications for the three buses are given in Table 5.3.

IKP has conducted very detailed LCA studies on bus manufacturing at the EvoBus plant in Mannheim, Germany, and has also studied the production of fuel cell engines at Ballard Power Systems in Vancouver, Canada. Aggregated models for bus manufacturing of the O530 Citaro have been supplied for the purposes of the present study.

Using the diesel bus model as a basis, the natural gas and hydrogen fuel cell variants are derived by modifying the diesel LCI. For the CNG version of the Citaro, the diesel fuel tank is subtracted and the CNG-specific components are added \(^3\). For the FC Citaro the diesel fuel tank

\(^3\) Additional components for the CNG system include the fuel storage system, fuel piping, and a modified spaceframe to support the roof-mounted components.
### 5.6. Bus Operation

The average bus in Perth travels 55,000 km annually, with a lifetime of 16 years [48]. It is difficult to find suitable emissions data for the vehicles examined in this study due a general lack of publicly available test results. Beer et al. indicated in 2001 that insufficient data exists to accurately assess Australian diesel and CNG buses across the range of important emissions, and unfortunately this situation still exists today [32]. The emissions data used for this study were derived from chassis dynamometer tests on a Euro 3 diesel powered bus, and a CNG EEV powered bus, over a route with average speed 16 km/h (similar to Perth). This test data was provided in confidence.

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Additional components for the FC system include the fuel cells, hydrogen storage system, electric traction motor, power management system, auxiliaries, and a modified spaceframe to support the roof-mounted components.

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>Engine</td>
<td>Mercedes Benz OM 457 hLA</td>
<td>Mercedes Benz M 447 hLAG</td>
<td>Ballard HY-205</td>
</tr>
<tr>
<td>Chassis</td>
<td>Flat-Ladder Steel Frame</td>
<td>Flat-Ladder Steel Frame</td>
<td>Steel Spaceframe</td>
</tr>
<tr>
<td>Body</td>
<td>Extruded Aluminium</td>
<td>Extruded Aluminium</td>
<td></td>
</tr>
<tr>
<td>Empty Vehicle Mass (kg)</td>
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<td>11,950</td>
<td>14,500</td>
</tr>
<tr>
<td>Passenger Capacity [69]</td>
<td>75</td>
<td>59</td>
<td>59</td>
</tr>
<tr>
<td>Engine Power (kW)</td>
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<td>185</td>
<td>205</td>
</tr>
<tr>
<td>Maximum Torque (Nm)</td>
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<td>1050</td>
<td>1050</td>
</tr>
<tr>
<td>Approx. Range (km) [70]</td>
<td>450</td>
<td>350</td>
<td>250</td>
</tr>
</tbody>
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Table 5.3: General bus specifications
5.7 Bus End of Life

Similar to the bus construction section, the data set for the dismantling and disposal of the buses was taken from the IKP detailed LCA studies at the EvoBus plant in Mannheim, Germany, and also from the fuel cell engines dataset derived at Ballard Power Systems in Vancouver, Canada. Aggregated models for recycling and disposal of the materials that were included in bus construction have been included in the LCA models. The models include recycling of the platinum catalyst in the fuel cell.

5.8 Top-level Model and Parameterisation

The previous sections provide some insight into a few of the processes which were modeled in GaBi to arrive at a final aggregation for the entire lifecycle. The final database contains nearly 5,000 processes, some of which are duplicated with variations in the parameters that determine their behaviour. These processes are assembled in GaBi plans, which describe flows
5.8. Top-level Model and Parameterisation

of materials and energy between the constituent processes. The top-level plan for the FC Citaro lifecycle is presented in Figure 5.6. The relative magnitude of energy and materials flows is clearly illustrated, as is the feedback of recycled materials back to the manufacturing processes which offsets the impacts of acquiring virgin materials.

The processes in each model are governed by the parameters which were defined to ensure flexibility for scenario and sensitivity analysis. As an example of the degree of parameterisation which has been built into the database, the parameter list for the CNG Bus Operation process is presented in Figure 5.7. The parameters include user-defined constants (such as the fuel economy) as well as calculated parameters which are defined by equations (such as the emissions of methane).
Figure 5.6: GaBi top-level model of the fuel cell citaro lifecycle with mixed hydrogen sources

Figure 5.7: GaBi parameters for the CNG bus lifecycle
Chapter 6

Life Cycle Impact Assessment

A main objective of LCA is to determine the outputs to the environment by calculation of the material and energy flows. Outputs with similar environmental impacts can be grouped and aggregated to a single parameter, known as an impact category. The impact categories must be selected based on the goals and intended use of the results. As stated in [25], if comparative assertions from Life Cycle Impact Assessment (LCIA) are disclosed to the public they should be internationally accepted impact categories, and be environmentally relevant to the spatial and temporal context.

The impact categories selected for this study are listed in Table 3.1 with a short description of their environmental relevance. Background information and characterisation factors are published by the CML [11]. In addition to the environmental impact categories, the overall energy demand of each transportation system will be evaluated as well.

The life cycle impacts for each of the selected impact categories, as well as overall energy demand, are shown in Figure 6.1. As expected, tailpipe emissions generally dominate the diesel and CNG profiles, while fuel production dominates the hydrogen profile.

6.1 Global Warming Potential (GWP)

The CNG bus produces lower CO$_2$ emissions at the tailpipe than the diesel, but the GWP profile of the CNG system is pulled up by fugitive and tailpipe emissions of methane ($CH_4$). The hydrogen production path in Perth also incurs significant greenhouse emissions, largely due to crude oil extraction and the use of coal-based grid electricity during processing and compression phases. Combined with the increased emissions from bus manufacturing, the FC bus is brought to a total GWP slightly greater than the present diesel system.
Chapter 6. Life Cycle Impact Assessment

(a) Global Warming Potential (GWP)

(b) Photochemical Ozone Creation Potential (POCP)

(c) Acidification Potential (AP)

(d) Eutrophication Potential (EP)

(e) Overall Energy Demand

Figure 6.1: Life Cycle Impact Assessment
6.2  Photochemical Ozone Creation Potential (POCP)

The CNG system achieves the lowest POCP impact, but it should be noted that the fuel production emissions from the FC system are produced at the refinery, effectively displacing these emissions from the city-centres where smog can be a health risk. The diesel emissions at the tailpipe are in the form of $NO_x$ and $CO$, while fuel production emissions are in the form of Non-Methane Volatile Organic Compounds (NMVOC) released during crude oil extraction. The high NMVOCs from crude extraction afflict the hydrogen system as well. The CNG system includes relatively little combustion during the fuel production phase, but significant $CH_4$ emissions.

6.3  Acidification Potential (AP)

Eutrophication and acidification from mobile sources are not primary concerns for Australia, but are worth consideration in evaluating the technologies. The FC system exceeds CNG in the Acidification category due to $NO_x$ and $SO_2$ emissions from fuel production, as well as significant $SO_2$ emissions during platinum extraction.

6.4  Eutrophication Potential (EP)

The eutrophication profile is dominated by the emissions of nitrogen oxides from each transportation system, with the combustion vehicles producing $NO_x$ at the tailpipe and the FC vehicle producing it during fuel production at the refinery.

6.5  Primary Energy Demand

The increased energy demand to operate CNG buses instead of diesel has been well established and is reflected in Figure 6.1(e). The FC system consumes approximately three times the energy of the diesel, but there is significant room for improvement. The current Ballard FC engine was intended to demonstrate a reliable fuel cell vehicle, and design tradeoffs were made to achieve high reliability at the expense of energy efficiency. The high energy demand for hydrogen can also be attributed to the significant construction effort required in Perth to build a hydrogen fueling infrastructure to fuel three buses.
Chapter 7

Interpretation

This project has established a base of LCA research and understanding which can be applied to a wide range of scenario and advanced modeling applications. The assessment clearly shows the relative magnitude each process has on the overall environmental profile, providing the feedback required to focus efforts on the critical processes.

7.1 Bus Manufacturing

The significant increase in energy and emissions to manufacture an FC bus can be attributed to a number of factors, all of which can be mitigated with continued research and engineering efforts. The FC engine includes many new components that have not been optimised for weight or material usage. Future generations will use different design concepts, making many of the components used in this generation obsolete, and dramatically improving energy efficiency. In addition to the overall design concept, there are only 36 of these buses in the world; economies of scale are yet to take effect. Substantial emissions and energy demand can be attributed to fuel cell stack production, partially due to the low volumes and emerging manufacturing technology. Fundamentally, the energy required for fuel stack production is driven up by the use of graphite, while emissions are driven up by the use of PGM as a catalyst. The cost, energy density, and performance of fuel cells are advancing rapidly. Background information and future prospects for fuel cell stack manufacturing and PGM loading are discussed in Pehnt’s LCA of fuel cell stacks [43].

The environmental impact and energy demand to manufacture the Volgren buses are compared to the diesel Citaro in Figure 7.1. The increase in energy and emissions is due to the increased use of aluminium in the Volgren bus body. The aluminium body reduces vehicle weight which translates to an improvement in fuel economy, but has a negative impact on energy expenditure and emissions during the manufacturing phase. Figure 7.2 provides an indication of how a change in aluminium content effects a change in manufacturing energy and GWP.
7.2 Alternative Hydrogen Production Processes

To further develop the opportunities for sustainable transport, alternative sources of hydrogen production can be incorporated to this LCA using the methodologies and boundary conditions defined during this project. Figure 7.3 is an example of preliminary modeling of other popular hydrogen pathways, and their potential impact on GWP. The only renewable option presented in Figure 7.3 is hydrogen from wind electrolysis.

It has been noted in several publications, that renewable energy would achieve greater reduction of GWP by displacing the existing fossil fuel generation systems [15], rather than using renewables to produce hydrogen. While this is true in the global environmental context, energy independence and local air quality are important concerns that can only be addressed by a
more clean and sustainable transport fuel. Some of the important benefits of hydrogen vehicle technology include a substantial increase in efficiency, and a moderated transition from fossil primary energy sources to renewables. Life Cycle Assessment is a tool that can be used by decision makers to quantify and compare these difficult and sometimes conflicting objectives.

Another finding which can be drawn from Figure 7.3 is that hydrogen produced from the refinery achieves much lower GWP than hydrogen produced from natural gas steam reforming. Considering that the hydrogen produced at the BP Kwinana refinery is a byproduct of the petroleum refining process, and that the three buses in Perth take only 0.2% of the refinery’s hydrogen output, the fuel chain in Perth is a relatively inexpensive and easily-implemented transition stage in the shift to a hydrogen economy. Western Australia is rich in natural gas, and is a net importer of crude oil, but tradeoffs like these will be required to reduce environmental profiles and still provide economical fuel to developing technologies until suitable non-fossil resources are available.

### 7.3 Key parameters for an improved life cycle profile

This project has established a benchmark LCA model, which can be applied to a wide range of scenario and advanced modeling applications. The assessment clearly shows the relative magnitude that each process has on the overall environmental profile, providing feedback to identify the critical processes that need to be addressed.

It has been noted in several publications, that renewable energy would achieve greater reduction of GWP by displacing the existing fossil fuel generation systems, rather than using it to produce hydrogen [15]. While this is true in the global environmental context, energy in-
dependence and local air quality are important concerns that can only be addressed by a clean and sustainable transport fuel. The potential benefits of hydrogen fuel cell technology include a substantial increase in efficiency, and a moderated transition from fossil primary energy sources to renewables. Life Cycle Assessment is a tool that can be used by decision makers to quantify and compare these difficult, and sometimes conflicting, objectives.

It is notable that the STEP project has achieved a GWP profile only slightly greater than the current diesel transportation system, and lower than the CNG transportation system, with a very un-optimised system. In the few years since these buses were built great advances have been made in fuel cell performance and overall engine concepts. The next generation fuel cell bus will bring drastic improvements in fuel economy, which linearly translates to a reduction in energy and environmental impacts.

### 7.3.1 Fuel Cell Durability

As indicated in Section 7.1, fuel cell production contributes significant energy and emissions to the bus manufacturing profile, and thus replacement of the fuel cells over the lifetime of the bus must be accounted for in the LCA. There is a great deal of uncertainty associated with fuel cell manufacturing, and even greater uncertainty associated with fuel cell rework and repair. The stacks removed from the Perth buses were returned for rework, and replacement stacks were typically rebuilt stacks rather than virgin stacks. The actual durability of the fuel cell stacks on the Perth buses is confidential, but Ballard has stated an achieved durability of 2,100 hours [72]. The Ballard, and US Department of Energy (DOE), target for durability is 5,000 hours by 2010. Extrapolating the operation of the Perth buses, the engines will run for approximately 35,000 hours in their lifetime. The most significant contributors to the environmental footprint and energy demand of fuel cell production are the PGM catalysts and the flow field plates, both of which have potential for very high recyclability. Recycling the catalysts can reduce the environmental impact of PGM by factors in the range of 20 to 100 [43]. Future modeling should account for the use and recycling of fuel cell stacks as more detailed information becomes available. In the present model, recovery of the platinum in the original fuel cell stacks is accounted for, but rework and recycling of the fuel cell stacks and flow field plates is not captured.

A sensitivity analysis was conducted to explore the influence of fuel cell durability on the LCA results. Figure 7.4 shows the change in Primary Energy Demand and GWP as a function of fuel cell durability. The slope change in Figure 7.4 indicates that a 10,000 hour durability will achieve a substantial improvement, with a > 20% reduction in PED, and a > 40% reduction in GWP. A flattening of the curves illustrates diminishing returns for fuel cell durability exceeding 10,000 hours.
7.3.2 Hydrogen Infrastructure Considerations

The LCA model for the hydrogen fuel chain includes the construction and disposal of all purification, processing, transport, and compression systems. The energy and emissions from construction of this equipment is calculated on a per-unit of hydrogen basis, and would diminish with an increased throughput to fuel a larger fleet of vehicles.

The current hydrogen infrastructure suffers a problem typical of many pilot-scale projects, of not being properly sized. Purification equipment, compressors, and even transport trailers, operate on an intermittent 'as-needed' basis. This leads to problems due to the frequent start/stop operation and long periods where equipment is sitting idle.

Fugitive losses of hydrogen are negligible in the raw hydrogen supply and purification phases, but are significant at the depot’s hydrogen fueling station. Hydrogen leaks from the compressor and associated piping have existed since the equipment was commissioned, occasionally triggering the very-sensitive internal hydrogen leak sensors. Additional hydrogen is lost at the fueling station due to the required purge cycles that must take place before and after any part of the hydrogen system is dismantled for maintenance or repair. The hydrogen mass balance at the BP Kwinana refinery yields a loss of less than 0.3% [73], and the mass balance at the BOC purification and compression plant shows no measurable hydrogen loss [74]. The largest hydrogen loss to atmosphere occurs at the bus depot refueling facility where a loss of 2.4% has been observed over a period of 3 months, and includes hydrogen leaks as well as purging for maintenance purposes. The refueling stations of the CUTE trial reported a slightly higher hydrogen loss, typically in the range of 5-10% [6].
7.3.3 Energy efficiency

As can be seen in Figure 7.3, Bus Operation is the most significant contributor to the GWP profile of diesel and CNG systems, and fuel production is largest contributor for the FC bus. For diesel, CNG, and FC vehicles alike, the energy efficiency of the vehicle is the key parameter that must be optimised in working towards a better life cycle profile. The fuel cell drivetrain tends to offer a much greater reduction potential than that of diesel or CNG buses, mainly because the fuel cell reaction is thermodynamically more efficient than the combustion of liquid or gaseous fuels. Qualitatively, the diesel and CNG technologies have already been optimised over many years of development, whereas fuel cell technology is in its infancy and is developing at a rapid pace. Improvements in heavy-duty diesel include a reduction in toxic emissions through technologies such as exhaust gas aftertreatment - technologies which may have a negative impact on fuel economy and engine performance [75]. A reduction of the greenhouse gas CO2 can only be achieved by an improvement in fuel economy.

This contrasts with hydrogen fuel cell vehicles where an improvement in energy efficiency translates to a uniform reduction in all emissions, local pollutants and greenhouse gases alike.

The current generation of fuel cell engine installed in the Ecobuses is the Ballard/Xcelsis HY-205, which began delivery to customers in 2003. The HY-205 has established a track record of reliability and public acceptance, but is no longer representative of the performance capabilities of a state-of-the-art fuel cell propulsion system. This engine was built to demonstrate reliability rather than efficiency, as it was deemed more important for the bus to prove that fuel cells can provide a consistent and reliable power source on board an operational vehicle. As such, the Ecobuses are not hybrids, have no regenerative braking, and maintain a minimum idle speed (as opposed to stopping the engine when the vehicle is at idle, as a hybrid vehicle would). Many auxiliary components necessary in a typical bus were taken from the existing diesel industry to simplify the design process and increase the reliability. In addition to the minimum idle speed, a minimum current is employed to improve the performance and lifetime of the fuel cell stacks. The power demand on the fuel cell stacks is directly linked to the torque requested by the driver, therefore subjecting the stacks to power and pressure transients.

A next generation fuel cell engine, based on the learning of the current generation, will be another leap forward in technology as more components are designed specifically for fuel cell propulsion. A series hybrid powertrain would allow the fuel cell to operate at a stable optimum design point, alleviating the strains of transient direct drive operation, and eliminating the need for a minimum current. These improvements in fuel cell operating conditions improve overall efficiency and ultimately extend the service life of the fuel cell.

The clear question then is what magnitude of fuel efficiency improvement can we expect in the near term, and what impact will this have on the LCA results? A great deal of work has been done on the subject, with many studies using numerical simulation based on engineering estimates of realistic component performance.
Ahluwalia et al. [46] studied the fuel economy of fuel cell light-duty vehicles in comparison to conventional gasoline internal combustion vehicles. The study is based on the modeling of a theoretical fuel cell engine, with energy efficiency estimations taken from the literature of possible component suppliers. Ahluwalia et al. conclude that a hydrogen fueled fuel cell compact, mid-size, and sport utility vehicle, would achieve 2.7, 2.7, and 2.5 times the fuel economy of conventional gasoline fueled vehicles.

Colella et al. [18] conducted an extensive literature review of fuel efficiency estimations and test results, and concluded that the efficiency ratio of future fuel cell vehicles over today’s conventional vehicles will be 2.9. In addition, Colella et al. note that these should be considered low estimates because they do not account for other future vehicle improvements such as weight reduction using advanced materials, and aerodynamic drag reduction.

The GM North American [33] and European [34] studies use a theoretical simulation to estimate the fuel consumption of a wide range of alternative propulsion systems in comparison to the benchmark petrol ICE. The vehicle platform is kept constant with alternative powertrains modeled to meet the same performance criteria of acceleration, range, top speed, and gradeability. The modeling software is proprietary and uses a database of component performance maps to calculate the power and energy flow through the vehicle, accounting for all inefficiencies and losses. They claim the models have been validated against several conventional and hybrid powertrains, as well as electric vehicle concept cars, with a fuel economy error within 1% of test results. The GM North American study uses a full size pickup truck for the vehicle platform, and the European study uses an Opel Zafira minivan. They find a fuel cell hybrid vehicle will be 2.4 times more efficient than a conventional petrol ICE vehicle.

Schfer et al. [27] use a Matlab Simulink program to back-calculate the fuel efficiency for theoretical light-duty vehicles using petrol, diesel, and hydrogen FC drivetrain technology representative of the year 2020. They estimate an advanced FC hybrid vehicle will be 4.2 times more efficient than today’s conventional petrol ICE, although their estimate can be considered optimistic as it includes many advances in technology throughout the vehicle.

Having proven through the CUTE, STEP, and ECTOS trials that a fuel cell drivetrain is sufficiently reliable, the next generation can focus on optimisation of energy efficiency. The efficiency of the 27 buses that made up the CUTE program is reported in the CUTE final report [6], with an average of 24.8 kg H2/100km. Stockholm found the ratio of FC Bus efficiency to Diesel bus efficiency to be 0.67 [22], and Porto found a ratio of 0.76 [47]. Data from the Perth trial shows a ratio of 0.79 in comparison to the Diesel Euro 2 buses currently operated by Transperth. These ratios are significantly lower than the estimates stated above, thus one can conclude that a next-generation fuel cell bus will likely achieve a substantial improvement in energy efficiency.

Although these ratios are based on the comparison of light-duty vehicles, they can roughly be assumed to be representative of the heavy-duty scenario as well. Indeed, the large range of data indicates the uncertainty on this topic, but a consensus among a number of prominent
institutions and companies is the ratio of 2.4. This value is assumed to be representative of what a future fuel cell bus will likely achieve in terms of energy efficiency over the present-day diesel bus. Figure 7.5 compares the energy efficiency of the current diesel, CNG and FC bus, as well as the efficiency of a future fuel cell bus.

![Figure 7.5: Comparison of energy efficiency for conventional bus technologies, the EcoBus, and a future fuel cell bus](image)

When the vehicle fuel economy parameter in the life cycle models is changed to reflect 2.4, as opposed to the value measured on the Perth buses of 0.79, the reduction in life cycle emissions and energy demand is dramatic. The effect of a change in vehicle efficiency is reported in Figure 7.6 as a function of the energy ratio. A fuel efficiency 2.4 times that of a present-day diesel bus effects a reduction in the life cycle greenhouse gas emission, primary energy demand, and POCP, by greater than 50% from present-day levels. Note the data in Figure 7.6 is a comparison against the conventional bus fleet on the road in Perth today, and does not account for efficiency or emissions improvements that may be realised in future generations of diesel or CNG buses. The Government of WA’s bus procurement contract ensures that the incumbent conventional technology will remain the status quo until at least the year 2011, thus the data captured from the fleet on the road in Perth today is a valid basis for near-term comparison.

### 7.4 Conclusions

The findings from this study are far-reaching and do not indicate any clear winner in the search for the ideal transport fuel. The results from the LCI and LCIA can be taken and applied to a
7.5. Recommendations

Hydrogen production processes are evolving, and the models should be updated in the future to reflect the capabilities of emerging technology. One fuel supply pathway which was beyond the scope of this study is hydrogen produced from coal gasification. Despite the inherent carbon

range of applications, or used as justification for further research.

It must be noted that the STEP project has achieved nearly the same GWP profile as the current diesel infrastructure, and a significant reduction in eutrophication, with a very un-optimised system. In the few years since these buses were built, great advances have been made in fuel cell performance (efficiency, power density), engine concept (STEP buses are not hybrids), hydrogen storage (currently 350 bar, future vehicles could use 700 bar), and vehicle layout (the fuel cell system was made to fit a diesel bus chassis). The next generation fuel cell bus will bring drastic improvements in fuel economy which linearly translates to a reduction in energy and environmental impacts.

Also to be noted is that the current LCA model for the hydrogen fuel chain includes the construction and dismantling of all purification, processing, distribution and compression systems. The energy and emissions from the construction and dismantling of this equipment is calculated per-unit of hydrogen output, and would be greatly reduced with increased flow rates to fuel a larger fleet.

Figure 7.6: Scenario analysis examining effect of bus efficiency on GWP, PED and POCP
emissions, coal-to-hydrogen technology has gained significant popularity. Comparative LCA results for coal-to-hydrogen could be an important inclusion in future LCA studies.

The current EcoBuses are not hybrids and therefore have no traction batteries on board. Very little LCA data exists on the lifecycle of different battery technologies. If Perth were to engage in a next-generation hydrogen bus fleet, the new buses would likely be hybrids and the relationships which would be formed with battery suppliers could be leveraged to obtain the detailed production data that is necessary for a complete Life Cycle Inventory. Such a study would be one of the first publications of its kind.

An arguable assumption made during the STEP LCA was to exclude the replacement of fuel cell stacks. Ballard has stated an achieved durability of 2,100 hours [72]. The Ballard, and US Department of Energy, target for durability is 5,000 hours by 2010. Extrapolating the operating hours of an average Perth bus, the engines will run for approximately 35,000 hours in their lifetime. The most significant contributors to the environmental footprint and energy demand of fuel cell production are the PGM catalysts and the flow field plates, and both have potential for high recyclability. Recycling the catalysts can reduce the environmental impact of PGM by factors in the range of 20 to 100 [43]. Future modeling should account for the use and recycling of fuel cell stacks as more detailed information becomes available.

By developing and refining these models, industry opportunities can be recognised and the entire product life cycle can be optimised at the very early stages of development. Important problems can be resolved while production volumes are low, and before economies of scale transform small oversights into significant issues.

It was decided at an early stage of the project that costs should be excluded from the scope of the study, as stakeholders were resistive to the communication of financial data along with their material and energy flows. Costs for next-generation bus and fueling technologies may be more readily available if data exchange agreements are included in the initial contracts with equipment suppliers. Access to financial data allows researchers to make the transition from Life Cycle Assessment to Life Cycle Engineering (LCE), by including a broad scope of social and economic parameters in the evaluation of existing and proposed technologies.

The LCA expertise and GaBi software systems which have been established at Murdoch University can also be applied to many other transport and stationary applications. Much of the data inventory is applicable to a wide range of existing and future technologies, and additional databases can be purchased from PE Europe to supplement any gaps. The Research Institute for Sustainable Energy at Murdoch is now in a position to become a leading Australian authority on the methodology and application of LCA to existing and emerging technologies.
Bibliography


