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Journal of Power Sources 170 (2007) 401–411
JOURNAL OF POWER SOURCES
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Life-cycle assessment of diesel, natural gas and hydrogen fuel cell bus transportation systems

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Received 12 February 2007; accepted 9 April 2007
Available online 25 April 2007

Abstract

The Sustainable Transport Energy Programme (STEP) is an initiative of the Government of Western Australia, to explore hydrogen fuel cell technology as an alternative to the existing diesel and natural gas public transit infrastructure in Perth. This project includes three buses manufactured by DaimlerChrysler with Ballard fuel cell power sources operating in regular service alongside the existing natural gas and diesel bus fleets. The life-cycle assessment (LCA) of the fuel cell bus trial in Perth 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. The LCAs of the existing diesel and natural gas transportation systems are developed in parallel. The findings show that the trial is competitive with the diesel and natural gas bus systems in terms of global warming potential and eutrophication. Emissions that contribute to acidification and photochemical ozone are greater for the fuel cell buses. Scenario analysis quantifies the improvements that can be expected in future generations of fuel cell vehicles and shows that a reduction of greater than 50% is achievable in the greenhouse gas, photochemical ozone creation and primary energy demand impact categories.

Keywords: Life-cycle assessment; Hydrogen; Fuel cell bus; Diesel; Compressed natural gas; Transportation

1. Introduction

The Sustainable Transport Energy Programme (STEP) is an initiative to examine alternative transport fuels for Western Australia (WA). The project includes three buses manufactured by DaimlerChrysler, which operate with fuel cell engines from Ballard Power Systems, and a raw hydrogen supply provided by the BP Kwinana oil refinery. 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 Global Hydrogen Bus Platform (HyFLEET:CUTE) [1].

Recent work has evaluated the potential for the establishment of a hydrogen economy in Australia [2] and current activities in the field [3]. These studies have presented a qualitative overview. A policy framework for hydrogen has yet to be established. There is a recognized need for detailed quantitative analysis and testing [4].

The Government of Western Australia, through the Department for Planning and Infrastructure (DPI), has commissioned several research projects to develop academic knowledge and expertise from the fuel cell bus trial. The life-cycle assessment (LCA) is one such project, that is aimed at evaluating the hydrogen infrastructure and fuel cell buses in relation to the existing diesel and natural gas transportation systems. Based at Path Transit's Morley Bus Depot in the Malaga suburb of Perth, the fuel cell buses are operating in regular service alongside the conventional Transperth natural gas and diesel bus fleets.

The life-cycle models are designed to be flexible and thereby allow for future scenario analysis that examines 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 the project. Continued efforts to develop and refine these models can identify industry opportunities, as the entire product life-cycle moves towards optimization, and important problems are resolved in the early

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doi:10.1016/j.jpowsour.2007.04.036

stages of the emerging hydrogen economy. The knowledge gained from this research may be used to define the direction of future programmes and policies.

The application of LCA and similar well-to-wheels (WTW) methods to hydrogen fuel cell vehicles has become an active field of research. A precursor and important basis for this study is the research conducted by Faltenbacher et al. [5,6] as part of the CUTE trial evaluation. The preliminary results from the CUTE trial, reported in [5,6], provided a base of methodology for the subsequent LCA work on the CUTE, ECTOS and STEP trials. In a recent literature review [7], several common deficiencies in the hydrogen futures literature were raised. Many studies lack participation from stakeholders and use a top-down theoretical approach with little discussion of the issues experienced by technology on the ground. These issues are categorically addressed by this study through the use of data provided by the participating companies and collected from the field results of the STEP fuel cell bus trial.

Research on the capabilities of hydrogen fuel cell technology in relation to conventional and other alternative transport solutions has been undertaken in the LCA context using a variety of methods. The Comparison of Transport Fuels conducted by Beer et al. [8] referenced the GREET model and examined a very broad range of transport fuel alternatives. The only hydrogen pathway examined was production from steam reforming of natural gas, which is just one of the many possible pathways. Colella et al. [9] evaluated the change in emissions and energy use from an instantaneous change to a hydrogen fuel cell vehicle fleet. Granovskii et al. [10] conducted an LCA of hydrogen fuel cell and gasoline vehicles using a first-principal methodology, which was based on theoretical calculations of the required economic and energetic data. Zamel and Li [11] performed an LCA of fuel cell and internal combustion engine vehicles in Canada, with fuel-cycle calculations carried out using GREET [12] and vehicle cycle data derived from published literature. General Motors conducted two WTW studies [13,14], one based in North America and the other in Europe, of which the latter examined a total of 88 fuel supply pathways including 14 hydrogen-based pathways. The GM studies did not include hydrogen sourced as a by-product of petroleum refining, which is the case in the STEP project. Pehnt [15] made an LCA of fuel cell stacks in accordance with ISO methodology and included discussion of allocation rules regarding Platinum Group Metals (PGM's) and recycling concerns. Ahluwalia et al. [16] and Schäfer et al. [17] have reported performance expectations for future fuel cell vehicles, together with a range of results due to the large uncertainty associated with both this developing technology and the specific boundary conditions chosen for each study.

There is a need for present-day LCA results, which adhere to internationally accepted methodology standards, to indicate the current state of the technology and highlight the issues from an operational trial. The LCA research conducted in Perth aims to address this need and to develop a set of validated models that can be used for scenario and sensitivity analysis.

2. Methodology

The premise for LCA studies is the comprehensive evaluation of all energy and material flows through a product system over its entire life-cycle. A system boundary is defined which encompasses the important processes of the product system and specifies the scope of the study, as shown in Fig. 1. Energy and material flows across the system boundary are accounted for in the LCA, and the processes contained within the LCA are studied in detail. The conservation of mass and energy across the system boundary is one calculation check that can be used to support the validity of the LCA model.

The formulation of an LCA can be a complex task with many possible pathways to reach the desired objectives. The results can be clear and concise or they can be complicated and diverse, as determined by the methods used and the overall design of the LCA. Adherence to accepted international standards helps to ensure the quality of the research and increases confidence in the reliability of the results. The methodology for this study is based on the international standards ISO 14040–14043 [18–21]. 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. In addition, the study must account for the flow of resources and wastes through each life-

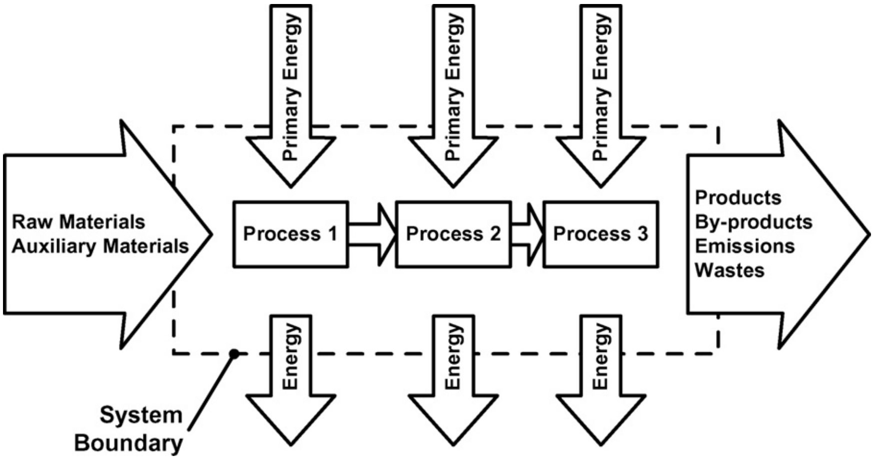

Fig. 1. Generic illustration of LCA process and graphical definition of system boundary.

cycle process, to yield a comprehensive balance of material and energy flows. The ISO 14040 methodology sets out the framework for the LCA by defining four separate phases, namely, goal and scope definition, inventory analysis, impact assessment, and interpretation. The LCA is an iterative process, and requires the practitioner to revisit and refine all phases as the study develops.

3. Goal and scope definition

The objectives for this research are

- evaluation of the environmental impacts and energy demands of the hydrogen fuel cell bus transportation system life-cycle;
- parallel comparative evaluation of the established diesel and natural gas bus transportation systems;
- scenario analysis examining different technologies and the impact of future technological improvements.

These objectives are conducted with an aim to provide input to the strategic decision-making process for future transport energy policy, and to identify key areas of interest for further technology research and development. The target audiences for this study are decision makers in the State and Commonwealth Governments of Australia, and their transport authorities, as well as corporate managers in the energy and infrastructure sectors, the bus industry, and the general automotive industry.

The system boundary for each of the three transportation systems includes the fuel infrastructure, but excludes processes that impact the life-cycle balance by <1% (known as the cut-off criteria). For example, the diesel bus fleet consumes a very small fraction of the oil refinery's total product, and thus construction and dismantling of the oil refinery is of negligible magnitude in the LCA of the diesel bus system.

The study consists of three separate product systems. A system boundary must be specified for each system using the cut-off criteria as a guideline. The system boundary for the hydrogen production process in Perth contains more processes than the diesel and natural gas systems due to the low throughput of fuel. The diesel and natural gas infrastructures are optimized for a large throughput, and thus the construction and dismantling of much of the infrastructure equipment falls well below the 1% cut-off criteria. In the hydrogen infrastructure, much of the compression, purification and transport equipment is designed for low volumes of product hydrogen, and thus construction and dismantling must be accounted for in the LCA. This difference between the well-established conventional fuel infrastructures and the emerging hydrogen infrastructure puts hydrogen at a disadvantage.

4. Life-cycle inventory

The collection of data that describes the systems to be examined is termed the life-cycle inventory (LCI). In compiling the LCI, each material and energy flow through each process and across the system boundaries must be carefully enumerated. For complex product systems, this can be an enormous task. PE Europe GmbH has provided the GaBi 4 software system and datasets on material and energy flows, which greatly reduces the data-collection workload for common industrial processes [22].

4.1. South west interconnected system (SWIS)

The production of electrical power is an important process that must be captured within the scope of the LCA. Hydrogen and natural gas compressors are examples of relevant systems that draw significant power from the grid. The establishment of an accurate grid dataset is also important for scenario analysis of alternative technologies, such as hydrogen production from grid-based electrolysis. The cut-off criteria dictate that the system boundary for the electricity grid excludes construction and dismantling of the electricity infrastructure.

The electricity supply networks of Western Australia are separated into the South West Interconnected System (SWIS) and the regional power systems. The SWIS is the largest network in Western Australia, 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 13679.2 GWh of electricity [23]. A peak demand of approximately 3600 MW occurs during the summer months depending on ambient conditions [24]. The fuel supply for the SWIS is primarily coal, but also includes gas, liquids (oil and distillate), and a very small fraction of renewable resources.

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 annual report of Western Power [25], the Australian Greenhouse Office (AGO) [26], and the National Pollutant Inventory (NPI) [27]. Fuel mass quantities for coal, natural gas and fuel oil were converted to units of energy using heating values from ABARE [28]. A simplified illustration of the GaBi model for the SWIS is shown in Fig. 2.

Some aggregated results from the LCA of the SWIS are listed in Table 1. These values are calculated by linearly scaling the input and output flows reported by Western Power to an electrical output of 1 kWh delivered to the customer. The model has been validated by comparison of the primary energy, overall efficiency and key emissions with published figures in the literature.

Table 1
LCI results for SWIS

Flow	Quantity
Primary energy input	4.52 kWh
Electricity output to customer	1 kWh
Global warming potential	1.02 kg CO_2-equivalent
Photochemical ozone creation potential (POCP)	3.8×10^{-4} kg ethene-equivalent
Acidification potential (AP)	7.6×10^{-3} kg SO_2-equivalent
Eutrophication potential (EP)	5.5×10^{-4} phosphate-equivalent

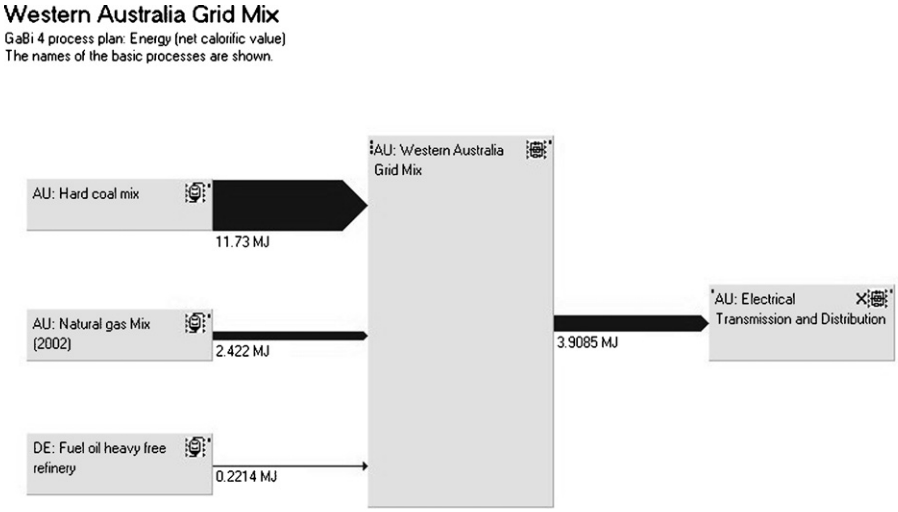

Fig. 2. Simplified illustration of SWIS electricity grid model.

4.2. *Diesel fuel infrastructure*

The diesel fuel supply includes crude oil exploration, extraction, transport, processing, and delivery to the fuelling point at the bus depot. The Transperth bus fleet is currently using ultra-low-sulfur diesel (50 ppm).

The refinery has one main input (crude oil) and several product outputs. It would be incorrect to attribute the entire energy and environmental impact of crude oil extraction to a single refinery product, and thus allocation is necessary. Two allocation rules were applied, namely: (i) the share of crude oil for each refinery product was allocated based on the energy of the product; (ii) 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 petrol (gasoline), would be allocated a large share of the crude oil input and a large share of the energy required for the intermediate processes [29]. The LCI for the diesel supply includes crude oil exploration, extraction, transport, processing and delivery to the fuelling point at the bus depot.

Most of Western Australia'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 optimize for different crude oil compositions, which allows 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% 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 [29].

The detailed LCI for the BP refinery is credited to Ilg [29] who used an existing GaBi refinery template and data provided by personal communication with BP experts in Kwinana. Diesel fuel is transported by pipeline to a distribution centre at Kewdale (approximately 50 km), where it is transferred to trucks for transport to the Malaga bus depot (approximately 20 km). The transportation and pumping efficiencies for diesel fuel are included in the system boundary.

4.3. *Natural gas fuel infrastructure*

Natural gas amounts to 46% of Western Australia'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), with a smaller fraction of production used for domestic consumption in the form of compressed natural gas (CNG) [30]. The CNG fuelling station at the bus depot in Malaga is supplied from the offshore Carnarvon basin.

The natural gas system boundary includes the exploration, processing and pipeline transport to the fuelling station at the bus depot. The main infrastructure data for the Australian natural gas supply was taken from the GaBi database. The gas inlet pressure to the fuelling station is 7 bar; buses are fuelled to a settled pressure of 200 bar (260 bar maximum pressure during filling). A *fast-fill* compressor station fuels the CNG buses at Malaga, using three electrically powered gas compressors with an assumed compression efficiency of 96.6% [31].

4.4. *Hydrogen fuel infrastructure*

The hydrogen source for the STEP project is unique; it originates 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). This process releases hydrogen as a by-product at some 60 tonnes per 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 99.999% pure hydrogen. A

Table 2
General bus specifications

Specification	Diesel OC 500 [45]	CNG OC 500 [45]	FC Citaro [46]
Engine	Mercedes Benz OM 457 hLA	Mercedes Benz M 447 hLAG	Ballard HY-205 fuel cell engine
Chassis	Flat-ladder steel frame	Flat-ladder steel frame	Steel space-frame
Body	Volgren extruded aluminium	Volgren extruded aluminium	
Empty vehicle mass (kg)	11,100	11,950	14,500
Passenger capacity [47]	75	59	59
Engine power (kW)	185	185	205
Maximum torque (Nm)	1,100	1,050	1,050
Approx. range (km) [48]	450	350	250

diaphragm compressor fills a hydrogen trailer to 165 bar for transport to the bus depot. Waste gas from the purification process (known as 'tail gas') is returned to BP via a compressor, as it mainly consists of hydrocarbons with useful calorific value.

The hydrogen trailer travels from the BOC plant in Kwinana to the Malaga bus depot, a distance of approximately 66 km. A refuelling station at the depot compresses the hydrogen from the trailer into 300-bar buffer cylinders, to reduce the time required for bus fuelling. The hydrogen trailer is exchanged when the pressure drops below 80 bar, or approximately every 3 days when the three fuel cell buses are in regular service. When a bus is connected to the refuelling station the buffers are equalized with the bus cylinders in stages, followed by a high-boost stage during which the compressor pressurizes the bus cylinders to the final fill pressure.[1]

The LCA of the production, transport and fuelling of gaseous hydrogen was completed by Ilg [29].

4.5. Vehicle data

The diesel and natural gas buses selected for this study are the Volgren/Mercedes-Benz Diesel OC 500LE and CNG OC 500LE models, respectively. The CNG OC 500 is the latest model delivered to Transperth and is considered representative of current Australian bus design. Transperth is not currently purchasing diesel OC 500's, but the diesel version of the OC 500 is selected for this study to maintain consistency. The fuel cell (FC) buses are commissioned in Germany and are based on a Mercedes-Benz O530 Citaro chassis. General specifications for the three buses are given in Table 2.

IKP at the University of Stuttgart 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 the manufacturing of the diesel, natural gas and fuel cell variants of the O530 Citaro bus have been supplied for the purposes of the present study.

The construction of an Australian OC 500 bus is quite different from the factory-built Citaro bus described above, and thus the LCA models of the diesel and natural gas buses must be modified to represent an Australian bus. The manufacturing of Australian buses begins with an imported 'buggy-chassis', with engine, steering, suspension and brakes. An Australian bus manufacturer extends the chassis to full bus length and builds the body upon it. Volgren Australia is one of the nation's largest bus body manufacturers, and has contributed the data required to model Australian bus construction [32].

Fuel economy data is one of the key parameters in the LCA, and a wide range of estimates exists. For the purposes of this study, the only published information of the actual fuel economy of the Transperth bus fleet is given in [33], and was verified as representative of the buses currently operating in Perth. The fuel economy of the FC buses is determined from the daily operational data compiled over the course of the STEP trial.

5. Life-cycle impact assessment (LCIA)

A main objective of the 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 into a single parameter, known as an 'impact category'. As stated in ISO 14042 [20], if comparative assertions from 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 with a short description of their environmental relevance. Background information and characterization factors have been published by the Leiden University Centre for Environmental Science [34].

The life-cycle impacts for each of the selected impact categories, as well as the overall energy demand, are shown in Fig. 3.

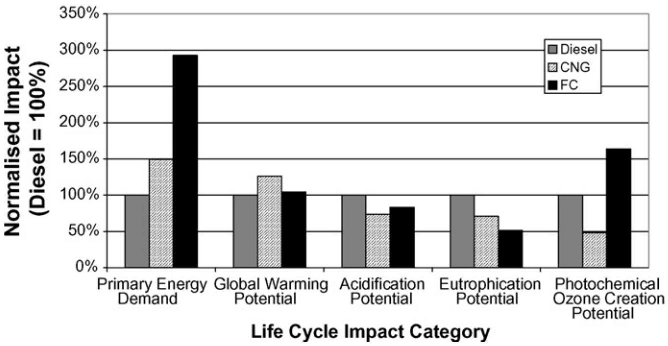

Fig. 3. Life-cycle impact assessment results. Bars normalized to set the reference diesel system at 100%.

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[1] Settled pressure 350 bar at 15 °C. Maximum pressure during fill is 438 bar.

Table 3
Life-cycle impact categories

Impact category	Short description	Examples
Global warming potential (GWP)	Emissions that contribute to global warming	CO_2, CH_4, etc.
Acidification potential (AP)	Emissions that cause acidification of rain, soil and water	SO_2, etc.
Eutrophication potential (EP)	Emissions that change nutrient concentration in lakes, rivers and soil	P and N compounds
Photochemical ozone creation potential (POCP)	Emissions that increase the production of tropospheric ozone	Hydrocarbons, etc.

A more detailed breakdown of the relative magnitude of the life-cycle phases (i.e. effect of manufacturing, operation, disposal) can be found in [35].

6. Interpretation

The life-cycle of each bus transportation system was modelled individually, and the results compared with respect to a functional unit of vehicle kilometres. The average bus in Perth travels 55,000 km annually, with a lifetime of 16 years [33].

The life-cycle impacts for each of the selected impact categories, as well as the overall energy demand, are shown in Fig. 3. 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 system produces higher GWP than the reference diesel bus system due to the lower fuel efficiency observed on the present generation of CNG buses in Perth, as well as fugitive and tailpipe emissions of methane (CH_4) from natural gas systems. The hydrogen production path in Perth also incurs significant GWP, largely due to crude oil extraction and the use of coal-based grid electricity during the processing and compression phases.

6.2. Photochemcial ozone creation potential (POCP)

Photochemical ozone is a main contributor to smog. The CNG system achieves the lowest POCP impact, but it should be noted that the hydrogen production emissions are released from the refinery in Kwinana, therefore effectively displacing these emissions from the city-centre. The diesel emissions at the tailpipe that add to POCP are in the form of NO_x and CO, while fuel production emissions are in the form of non-methane volatile organic compounds (NMVOCs) released during crude oil extraction. The high NMVOCs from crude extraction afflict the hydrogen system as well, in accordance with the allocation rules.

6.3. Acidification potential (AP)

Acidification from mobile sources has not been identified as a primary concern for Western Australia [36], but is an important consideration in evaluating the technologies. The fuel cell 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 extraction of platinum, which is used as an electrocatalyst.

6.4. Eutrophication potential (EP)

The enrichment of nutrients in soil and water is measured by the EP impact category. An increased EP could lead to algal blooms in lakes with reduction in sunlight penetration and other adverse consequences, or similar undesirable effects on soil. The hydrogen bus has already achieved a reduced EP profile due to reduced emission of nitrogen compounds during fuel production, as opposed to the high NO_x emissions that diesel and natural gas vehicles produce during the combustion phase.

6.5. Primary energy demand (PED)

The increased PED of the CNG bus over the diesel is reflected in Fig. 3. Several factors contribute to this efficiency loss including the energy efficiency of the vehicle, as well as the inherently lower energy density of a gaseous fuel, which increases the energy consumed during transport and storage (due to compression losses). The fuel cell system consumes approximately three times the energy of the reference diesel system, but there is significant room for improvement. The current Ballard fuel cell engine was intended to demonstrate a reliable fuel cell vehicle, and design trade-offs were made to achieve high reliability at the expense of energy efficiency. The increased energy demand for hydrogen also includes the significant construction effort required to build a hydrogen infrastructure to supply fuel for only three buses.

6.6. Impact of bus manufacturing

The main difference between the construction of the base European Citaro bus and the Australian Volgren buses lies in the vehicle mass and the aluminium content. The factory-completed Citaro bus is built on a steel space-frame. Australian buses are typically constructed from an imported steel chassis including the powertrain, suspension, steering and other auxiliaries. Domestic body manufacturers, such as Volgren Corporation, complete the bus by building up the body of the bus upon the steel chassis. Volgren uses an aluminium body, and thus the overall aluminium content of the bus is much higher than the European factory-built bus, which results in a reduced vehicle mass.

The significant increase in energy and emissions to manufacture a fuel cell bus can be attributed to a number of factors, all of which can be mitigated with continued research and engineering efforts. The fuel cell engine includes many new components that have not been optimized for weight or material usage. Future generations will use different design concepts that will make many of the present components obsolete and dramatically improve energy efficiency. The 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 a PGM catalyst. The specific energy and performance of fuel cells are advancing rapidly, and cost is decreasing. Background information and future prospects for fuel cell stack manufacturing and PGM loading are discussed in the LCA of fuel cell stacks that was conducted by Pehnt [15].

7. 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 scenarios and advanced modelling applications. The assessment clearly shows the relative magnitude that each process has on the overall environmental profile and thus provides feedback to identify the critical processes that need to be addressed.

It has been noted in several publications that renewable energy would achieve a greater reduction in GWP by displacing existing fossil-fuel generation systems, rather than by using it to produce hydrogen [37]. 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 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-fuel 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 that is only slightly greater than the current diesel transportation system, and lower than the CNG transportation system, with a very un-optimized 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 will linearly translate to a reduction in energy and environmental impacts.

7.1. Fuel cell durability

As indicated in Section 6.6, 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 2100 h [38]. The Ballard, and US Department of Environment (DOE), target for durability is 5000 h by 2010. Extrapolating the operation of the Perth buses, the engines will run for approximately 35,000 h in their lifetime.

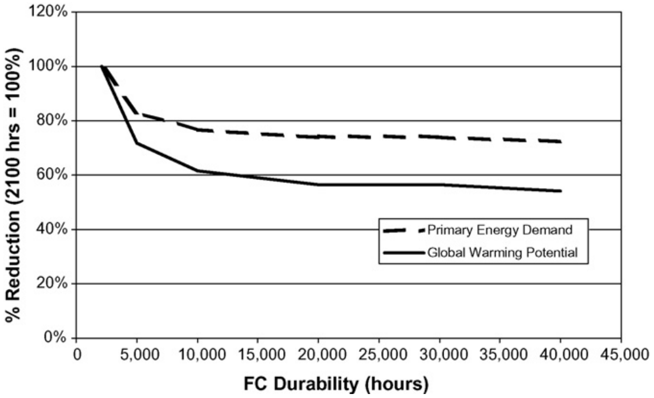

Fig. 4. Effect of fuel cell durability on primary energy demand (PED) and global warming potential (GWP). Current stated fuel cell durability = 2100 h, defined as reference 100%. Improvement in fuel cell durability to 10,000 h would result in a reduction in overall PED by 20%, and a 40% reduction in GWP. Beyond 10,000 h durability the life-cycle improvement is minor.

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 recycleability. Recycling the catalysts can reduce the environmental impact of PGM by factors in the range of 20–100 [15]. Future modelling 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. The change in primary energy demand and global warming potential as a function of fuel cell durability is shown in Fig. 4. The slope change indicates that a 10,000 h 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 h.

7.2. Alternative primary energy sources

To develop further the opportunities for sustainable transport, alternative sources of hydrogen production can be incorporated in the LCA using the methodologies and boundary conditions previously defined. The data in Fig. 5 are an example of some popular hydrogen pathways and their potential impact on GWP relative to the diesel, CNG and hydrogen FC bus results that were presented previously in Fig. 3. Approximated hydrogen sources were modelled by keeping all other phases of the life-cycle constant, except for the hydrogen infrastructure. The alternatives explored in Fig. 5 are hydrogen from on-site steam reforming of methane, hydrogen from electrolysis using electricity supplied by the SWIS, and hydrogen from electrolysis using electricity supplied by wind turbines. Generic datasets on steam reform-

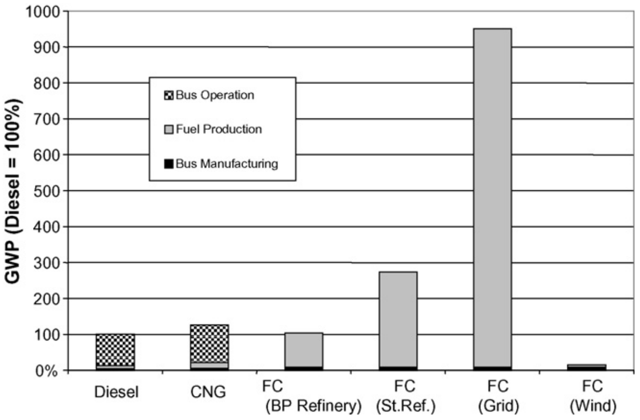

Fig. 5. Effect of different hydrogen sources on GWP of STEP program. Diesel, natural gas and fuel cell bus with hydrogen supplied by BP Kwinana refinery are shown for reference. Scenario analysis explores the same hydrogen consumption produced by on-site steam reforming of natural gas, electrolysis using electricity from the SWIS grid, and electrolysis using hydrogen from renewable wind power.

ing, electrolysis and wind power were derived from research conducted by IKP at the University of Stuttgart on the European CUTE fuel cell bus trial.

Another significant finding in Fig. 5 is that hydrogen produced from the refinery achieves a much lower GWP than hydrogen produced from natural gas steam reforming. Considering that the refinery hydrogen is a by-product 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 transport fuel, but trade-offs like these will be required to reduce environmental profiles while still providing economical fuel to developing technologies until suitable non-fossil resources are readily available.

7.3. 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 be greatly reduced with an increased throughput to fuel a larger fleet of vehicles.

The current hydrogen infrastructure suffers a problem typical of many pilot-scale projects, namely, 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 fuelling station. Hydrogen leaks from the compressor and associated piping have occurred since the equipment was commissioned, occasionally triggering the very-sensitive internal hydrogen leak sensors. Additional hydrogen is lost at the fuelling 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% [39], while the mass balance at the BOC purification and compression plant shows no measurable hydrogen loss [40]. The largest hydrogen loss to the atmosphere occurs at the bus depot refuelling 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 refuelling stations of the CUTE trial reported a higher hydrogen loss, typically in the range of 5–10% [41].

7.4. Energy efficiency

As can be seen in Fig. 5, bus operation is the most significant contributor to the GWP profile of diesel and CNG systems, and fuel production is the largest contributor to the fuel cell bus. For diesel, CNG and FC vehicles alike, the energy efficiency of the vehicle is the key parameter that must be optimized in working towards a better life-cycle profile. The fuel cell drivetrain tends to offers much greater prospects compared with 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 optimized 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 [42]. A reduction of the greenhouse gas carbon dioxide 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 the fuel cell engine installed in the Perth FC buses is the Ballard/Xcellsis HY-205, which was first delivered 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 Perth FC buses 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 could). Many of the auxiliary components necessary in a typical bus were taken from the existing diesel industry to simplify the design process and increase the reliability.[2] In addition to the minimum idle speed,

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[2] Auxiliaries such as the chassis air compressor, power steering pump, air-conditioning compressor, and alternators, are powered via a gearcase and belt drive coupled to the main traction motor.

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 and therefore subjects the stacks to power and pressure transients.

A next-generation fuel cell engine, based on knowledge 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 stable optimum design points and thus alleviate the strains of transient direct drive operation, and eliminate the need for a minimum current. These improvements in fuel cell operating conditions would improve overall efficiency and ultimately extend the service life of the fuel cell.

The clear questions are what magnitude of fuel efficiency improvement can be expected 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 simulations based on engineering estimates of realistic component performance.

Ahluwalia et al. [16] studied the fuel economy of light-duty vehicles powered by fuel cells in comparison with conventional gasoline internal combustion vehicles. The investigation was based on the modelling of a theoretical fuel cell engine, with energy efficiency estimations taken from the literature of possible component suppliers. It was concluded that hydrogen-fuelled fuel cell compact, mid-size and sports utility vehicles would achieve 2.7, 2.7 and 2.5 times the fuel economy of conventional gasoline-fuelled vehicles, respectively.[3]

Colella et al. [9] 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, it was noted that this should be considered a low estimate because no account was taken of other future vehicle improvements such as weight reduction using advanced materials, and aerodynamic drag reduction.

The North American [13] and European [14] studies undertaken by GM used a theoretical simulation to estimate the fuel consumption of a wide range of alternative propulsion systems in comparison with the benchmark gasoline internal combustion engine. The vehicle platform was kept constant with alternative powertrains modelled to meet the same performance criteria of acceleration, range, top speed, and gradeability. The modelling software was proprietary and used a database of component performance maps to calculate the power and energy flow through the vehicle, accounting for all inefficiencies and losses. It was claimed that the models had been validated against several conventional and hybrid powertrains, as well as electric vehicle concept cars, with a fuel economy error within 1% of the test results. The GM North American study used a full-size pickup truck for the vehicle platform, and the European study employed an Opel Zafira minivan. It was found that a fuel cell hybrid vehicle would be 2.4 times more efficient than a conventional gasoline vehicle.

Schäfer et al. [17] used a Matlab Simulink program to back-calculate[4] the fuel efficiency for theoretical light-duty vehicles using petrol, diesel, and hydrogen fuel-cell drivetrain technology representative of the year 2020. It was estimated that an advanced fuel cell hybrid vehicle would be 4.2 times more efficient than today's conventional gasoline vehicle, although the estimate could be considered optimistic as it included many advances in technology throughout the vehicle.[5]

Having proven through the CUTE, STEP and ECTOS trials that a fuel-cell drivetrain is sufficiently reliable, the next generation can focus on optimization of energy efficiency. The efficiency of the 27 buses that made up the CUTE programme is reported in the CUTE final report [41] and has an average of 24.8 kg H_2 per 100 km. Stockholm found that the ratio of the efficiencies of the fuel cell and diesel buses was 0.67 [43], while Porto observed a ratio of 0.76 [44]. Data from the Perth trial gave a ratio of 0.79 in comparison with the Diesel Euro 2 buses currently operated by Transperth.[6] These values are significantly lower than the estimates stated above, thus it can be concluded that a next-generation fuel cell bus will likely achieve a substantial improvement in energy efficiency.

Although the 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 the consensus among a number of prominent institutions and companies is a 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. The energy efficiency of the current diesel, CNG and fuel cell bus, as well as that of a future fuel cell bus, is presented in Fig. 6.

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 reductions in life-cycle emissions and energy demand are dramatic. The effect of a change in vehicle efficiency is reported in Fig. 7 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 Fig. 7 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 realized in future generations of diesel or CNG buses. The bus procurement contract of the Government of Western Australia ensures that the incumbent conventional

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[3] Based on the lower heating value (LHV) of gasoline and hydrogen.

[4] A driving cycle is input as an array of vehicle velocity versus time, and the calculation determines the power required due to drag, tyre resistance, and inertial force. Power is converted to torque, which is then converted to 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.

[5] Schäfer et al. [17] include 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.

[6] Calculated using actual data from the STEP fuel cell buses; and diesel bus consumption of 43 l per 100 km.

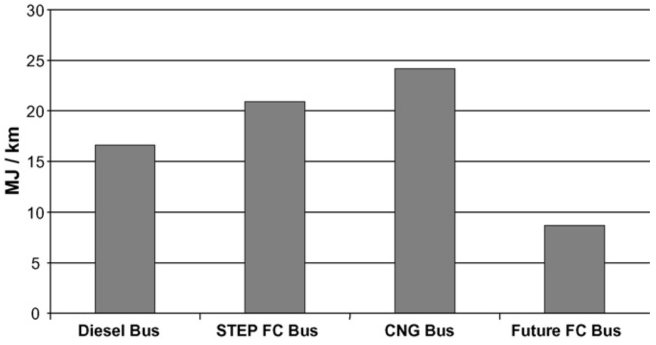

Fig. 6. Comparison of vehicle energy efficiency for diesel, natural gas, hydrogen fuel cell, and future hydrogen fuel cell buses.

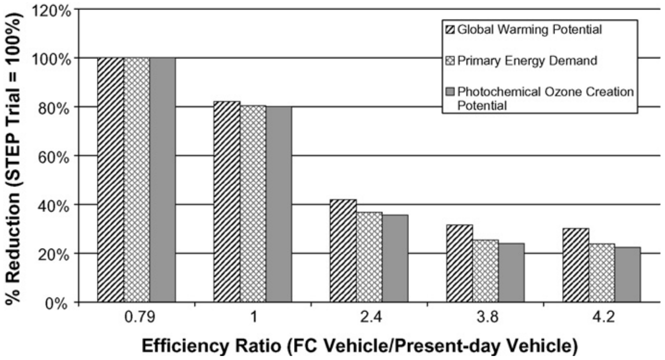

Fig. 7. Effect of energy efficiency on LCA profile, assuming hydrogen produced from BP Kwinana refinery. Current STEP implementation set to reference 100%. The scale of the *x*-axis is energy efficiency, expressed as efficiency ratio of a fuel cell bus to a standard diesel bus.

technology will retain 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.

8. Conclusions

The hydrogen infrastructure implemented in Perth provides a measure of the current state of technology, and a benchmark that can be used to measure future progress. The LCA results highlight the key areas for future research, and a realistic scenario analysis has shown how technological developments can affect the overall life-cycle profile of the transportation system.

This research can be used for strategic decision-making on the future of transport energy policy, and can also be developed further to account for a wider range of alternatives and technological advances. A more detailed inventory of fuel cell stack manufacturing and recycling, next-generation hydrogen vehicles and an expanded hydrogen infrastructure can form a basis of understanding to support the development of a path forward.

Acknowledgements

The authors acknowledge the support of the Department for Planning and Infrastructure of the Government of Western Australia, Ballard Power Systems, BOC Gases, Linde, BP and Path Transit. Valuable contributions were also made by Marc Allen, Alan Bray, Paul Burke, Colin Cockroft, Brendan Davis, Michael Faltenbacher, Geoff Grenda, Glen Head, Christine Howland, Robert Ilg, Ian Kerr, John Lambert, Brian Marsden, Manfred Schuckert, Emma Vanderstaay, Simon Whitehouse, and Tim Woolerson.

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