A life cycle assessment of Western Australian LNG production and export to the Chinese market

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EXECUTIVE SUMMARY

The use of Liquefied Natural Gas (LNG) can contribute lower greenhouse gas (GHG) emissions (and carbon footprint) than traditional petroleum products. The material and resources consumed in producing LNG from exploration to liquefaction and transport stages however do contribute to global warming impacts.

In reviewing the carbon footprint of the production and transportation of $1m^3$ of LNG to China, this Life cycle assessment (LCA) has confirmed that the production and liquefaction stage generates the most GHG emissions (45.4%), followed by the natural gas exploration and separation stage (39%) and the exportation and transportation stage (15.7%). Within the production and liquefaction stage, energy consumption is the main contributor to GHG emissions.

The utilisation of wind power energy as a replacement of gas fired electricity generation could possibly reduce the ‘energy consumption’ related GHG emissions of LNG production by some 36-51%. Similarly, the utilisation of carbon capture and storage to sequester the GHG emitted during electricity production could potentially reduce ‘energy consumption’ related GHG emissions by 33-45%.

LCA can assist exporters, manufacturers, and suppliers in the LNG supply chain in Australia and China with enhanced environmental supply chain management and the management of a future carbon trading pressures on the LNG industry in Australia.

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1 INTRODUCTION

The first shipment of liquefied natural gas (LNG) was exported from the Australian North West Shelf (NWS) to Japan in 1989. Since then the natural gas industry has shown significant growth in Australia. Roarty (2008) notes that Australian output can be expected to quadruple to over 50 million tonnes of LNG per year. Currently Japan is the greatest importer of LNG in the world, followed by Taiwan, with both obtaining their LNG from south east Asia, Australia, North America and the Middle East. However the growth in exports to China and India are expected to increase and account for around 40 % of the total LNG imports in the Asia Pacific region by 2015. China will then become the third largest LNG export destination (Ball *et al*, 2004).
The first NWS shipment of LNG to the receiving terminal in Dapeng in Guandong Province China was in May 2006. This trade has continued to expand rapidly and currently Australia is supplying the largest volume of bulk LNG to China (Priestley, 2010).

Roarty (2008) states that the greenhouse gas emissions (GHGs) associated with the production of one tonne of LNG ranges between 200 to 400 kg (Roarty, 2008). He projects an associated increase of 10 to 20 Mt of GHG production by 2020 with the increase in Australian production to 50 Mt of LNG (Roarty, 2008). With the passing of the Clean Energy Act (2011) and the Climate Change Authority Act (2011) in which most industries will be taxed on the amount of pollution generated, the Australian production of LNG needs to be scrutinised for mitigating options to improve or sustain competitive factors (CPRS, 2008; CEF, 2011; Dunn, 2011).

With the implementation of Australia’s Clean Energy Act (2011), many industries will be required to pay carbon emission taxes on their GHG production and to consequently reduce the life cycle carbon footprint of their production/process and supply activities (Jaramillo *et al*, 2005; Okamura *et al*, 2007; CPRS, 2008).

A full life cycle carbon footprint calculates the total greenhouse gas emissions involved in a production/process from initial mining of resources through to the final use stages of the product supply chain. Although research has established that the combustion stage of LNG produces significantly less emissions than other existing fossil fuels products, pre-combustion activities, including natural gas production, liquefaction, storage and overseas transport stages, are energy intensive and produce significant CO_2 emissions from energy consumption, flare combustion, venting and equipment construction (Jaramillo *et al*, 2005; Okamura *et al*, 2007).

Life cycle assessment (LCA) assesses the environmental emissions of a product from the initial mining/drilling of the resource to the final disposal/waste management stages of the product/process. LCA compiles and evaluates inputs (e.g., energy and material) and outputs (e.g. CO_2, CH_4 and N_2O) associated with a particular product life cycle (Yoon & Yamada, 2001). Some specific applications of LCA include:

- LCA identifies the hotspots requiring environmental improvement. Once the hotspots have been identified, cleaner production strategies, including technological modification, input substitution, reuse, recycling and good housekeeping, are applied to reduce the supply chain carbon footprint (van Berkel, 2007; Biswas *et al*, 2010).

- LCA also provides information on environmental improvement opportunities to stakeholders in the supply chain, including exporters or miners, processors, manufacturers, retailers, government, research organisations and consumers, to implement appropriate strategies to enhance the supply chain environmental performance (Biswas *et al*., 2011).

The production of LNG has been noted as being energy intensive and this together with fuel intensive transport options required for its exportation suggest an inherent value in both reviewing the carbon footprint of LNG export and the potential methods of mitigating the associated emissions from the production and export process.

The proposed research conducts an LCA assessment that will enable LNG producers and supply chain stakeholders to improve their understanding of the relative contribution of pre-combustion and post-combustion production GHG emissions and undertake mitigation strategies to reduce the carbon footprint associated with LNG production.

2 LITERATURE REVIEW

2.1 Liquefied Natural Gas

Natural gas is an alternative source of fossil fuel predominantly used for power generation applications, with lower global warming impacts than other fossil fuels (NG, 2011). It is extracted from gas fields using existing proprietary technology and passes through a number of stages, including extraction, conditioning, liquefaction and transportation to the point of use (city gas). Natural gas is composed of a mixture of hydrocarbons in different ratios. These typically include methane, ethane, propane and butane, with the composition of natural gas varying across wells in different geographical locations (Kidnay & Parrish, 2006; Petroleum Engineering, Curtin University, David Pack, pers. comm.). Impurities in the form of hydrogen sulphides, carbon dioxide, water and can also be present.

In order to improve fuel efficiency and address storage issues, a liquefaction process is used to convert the natural gas into liquefied natural gas, commonly known as LNG. In the liquefaction process the natural gas is cooled to less than -161°C to allow for the condensation of the gas to form a liquid, typically reducing the volume of the natural gas by a factor of 600. The primary component of the natural gas, namely methane, liquefies at this temperature (Arteconi *et al*., 2010; Barnett, 2010).

LNG is an odourless and colourless gas which is ideal for transportation to export markets. In 2009 the top ten exporters of LNG were Qatar, Indonesia, Algeria, Malaysia, Australia, Trinidad, Nigeria, Egypt, Oman and Brunei; representing approximately 90% of world supply. Regionally 30% of LNG is produced from the

Atlantic Basin, 40% is produced from the Asia Pacific Basin and 30% produced from the Middle East (Ball *et al*, 2004; Barnett, 2010). Australia contributed 16% of the Asia Pacific Basin production in 2009 and in 2010 Western Australia produced approximately 6% of global LNG production (DSD, 2011).

2.2 Environmental Implications of LNG production

Whilst natural gas has been considered as one of the safest and cleanest fossil fuels (Dinca, Rousseaux & Badea, 2007; ConocoPhillips, 2011; NG, 2011) when compared to other fossil fuels like coal and oil in terms of nitrous oxides (NO_x), sulphur dioxides (SO_2) and carbon dioxide (CO_2) emissions, the production and use of natural gas is energy intensive and not free of environmental impacts. Table 1 presents data comparisons from the USA Environmental Protection Agency for natural gas, coal and oil GHG emissions (NG, 2011). There are significant advantages associated with the use of natural gas as the combustion of natural gas emits virtually no ash or particulate matter and produces relatively low levels of carbon monoxide and other reactive hydrocarbons (NG, 2011). However, when natural gas is converted to LNG its impact on the environment is exacerbated. According to Sakmar (2010), the environmental impact and emissions created from the production of LNG from natural gas may nullify the clean-burning benefits experienced from the use of LNG. This is due to the methane emissions that arise from natural gas release and the significant energy requirement for the liquefaction, transportation and regasification of the LNG .

Table 1: Fossil fuel emission levels (pounds per billion Btu of energy input (NG, 2011)

Pollutant	Natural gas	Oil	Coal
Carbon dioxide	117000	164000	208000
Carbon monoxide	40	33	208
Nitrous oxides	92	448	457
Sulphur dioxide	1	1122	2591
Particulates	7	84	2744
Mercury	0	0.007	0.016

During the production, processing, storage, transmission and distribution of natural gas there are associated losses of methane as fugitive gas and similarly during flaring. While methane is a powerful greenhouse gas capable of trapping 21 times more heat effectively than carbon dioxide, research has indicated that the reduction of emissions from the increased use of natural gas outweighs the detrimental effects of the increased methane emissions occurring from the exploration, production and combustion (use) of natural gas (EPA, 2011; NG, 2011).

Electricity produced from the combustion of gas is said to generate 40 - 60% less CO_2 than electricity generated through the combustion of coal (INPEX, 2011). However the power generation required for gas liquefaction in the LNG production process has been found to be energy intensive. The reduction of CO_2, as well as other GHGs is important in reducing the greenhouse effect and in meeting Australia's climate change targets (NG, 2011). The Natural Gas Supply Association in the United States indicates that the combustion of LNG produces almost 30 % less CO_2 than oil and just under 45 % less CO_2 than coal (NG, 2011). However both the production and export and distribution relevant to LNG production should also be considered in assessing the carbon footprint of LNG production.

Numerous research studies have shown that the energy consumption in the LNG production process contributes most of the carbon footprint associated with LNG production (Dinca, Rousseaux & Badea, 2007; Barnett, 2010). A full environmental assessment of LNG production should scope and evaluate all stages/phases of the production process from extraction at the wellhead, through to preparation, liquefaction, fractionation, storage and loading, shipping, regasification and final use (Dinca, Rousseaux & Badea, 2007). In addition, factors such as land-use change, resource depletion, noise and aesthetics may also present adverse effects as a result of LNG production (Dinca, Rousseaux & Badea, 2007; Curtis, 2009; Chevron, 2010). Furthermore direct, indirect and cumulative impacts should be identified and reported on for each part of the process including SO_2, NO_x, carbon monoxide (CO) and CO_2 emissions and dust, which affect human health and also may impact on adjacent agricultural, forest, freshwater and terrestrial ecosystems (Dinca, Rousseaux & Badea, 2007).

As the demand for natural gas increases more data is required to enhance decision making on its use as a less carbon intensive fuel. The application of Life Cycle Assessment (LCA) to this process is valuable as it enables the researcher to take all polluting stages of the life cycle into account and to identify areas of concern (hotspots) and from there develop appropriate mitigation strategies (Tamura *et al*., 2001; Ball *et al*., 2004).

2.3 Life Cycle Assessment

As awareness of climate change and other environmental threats increase, pressure is being applied to businesses, industries and society as a whole to manage and reduce associated GHG impacts. Manufacturers and consumers are faced with the dilemma of making more intelligent choices which include, amongst others, the selection of raw materials for production, the use of more ecologically sustainable production methods and also the choice of a greener product (Arvanitoyannis, n.d.; Curran, 2006; Finnveden *et al*., 2009). Environmental management systems (EMS), environmental impact assessments (EIA), social impact assessments (SIA) and now more recently life cycle assessments (LCA) have been developed in order to assist in the assessment of production activity associated environmental impacts (Curran, 2006).

Life cycle assessment is seen as an objective process that is used to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment (Grant & Beer, 2006). The assessment may start with the acquisition of the raw material, right through to production and use and end of life management of generated waste (cradle to grave) (Arvanitoyannis, n.d.; Curran, 2006). Life cycle assessments focus on each of the interdependent stages of the production system being studied to identify ways in which the production affects the environment by impacting on ecological well-being, human health and resource depletion. It also assesses the impact of energy and material uses and releases on the environment (Arvanitoyannis, n.d, Finnvedin *et al*., 2006). Environmental impacts not commonly included in other traditional assessments such as raw material extraction, material transportation and ultimate disposal are often examined in LCA, and can therefore provide a more comprehensive view of the environmental impacts of the product or process and a more accurate picture of the true environmental trade-offs in product and process selection (Arvanitoyannis, n.d).

LCA's are also able to pinpoint the environmental impacts in the various stages of the production process (Tamura *et al*, 2001; Curran, 2006) and allow the focussed development of mitigation measures.

LCA does have a number of methodological limitations however, including the accurate and complete definition of the system boundaries, the acquisition of reliable and homogenous data, temporal scope differences and also the choice and definition of the environmental indicators to be used for characterisation and classification of the impacts (Riva, D'Angelosante & Trebeschi, 2006). Whilst LCA does not generate absolute comparative values, it is a useful tool to compare the environmental performance of products doing the same work and to enable policy and environmental planners to identify appropriate mitigation strategies in the relevant production and supply chain.

2.4 Life cycle assessment of LNG

Life cycle assessments have been used by a number of researchers in the assessment of LNG with various results (Tamura *et. al*. 2001; Okamura *et al*., 2007; May & Brennan, 2003,).

Tamura *et al*. (2001) conducted a life cycle analysis of LNG and city gas in Japan, in which the whole life cycle of natural gas from well production through to the final domestic use (combustion) thereof was assessed. Data was obtained from five countries (Indonesia, Malaysia, Brunei, Australia and Alaska) currently exporting LNG to three Japanese city gas[1] suppliers (Tokyo Gas Co. Ltd., Osaka Gas Co. Ltd., and Toho Gas Co. Ltd.) and weighted averages calculated. Thereafter Tamura *et al*. calculated and analysed the GHG emission reduction due to the use of LNG in the

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[1] LNG is regasified at the receiving terminal and then distributed downstream as city gas. City gas is used for domestic, industrial and transportation applications.

city gas chain supply. The GHG emissions from the LNG chain were subsequently summarised into production, liquefaction, transportation and combustion (city gas use). The research found that the use of gas for domestic and industrial purposes was the major contributor of GHG (about 90 %) in the daily supply chain, but when considering the production, liquefaction and transport of the gas the liquefaction stage is the highest emitter of GHGs.

A study by Okamura *et al*. (2007) reviewed the GHG emissions of an LNG and city gas supply chain from Middle Eastern countries (Qatar and Oman) to Japan with similar results to those reported in the Tamura *et al*. (2001) study. The results were summarised into production, liquefaction, transportation, equipment and combustion stages. Analogous to the Tamura *et al*. study the combustion stage contributed the most to GHG emissions, followed by liquefaction. Coal (88.53 g-CO_2/MJ) produced the most GHGs followed by oil (68.33 g-CO_2/MJ), LPG (59.85 g-CO_2/MJ), city gas 13A (51.23 g-CO_2/MJ) and then LNG (49.40 g-CO_2/MJ). Technological improvement and natural gas composition were considered in quantifying the difference in GHG emissions. This study found that the GHG emissions from production and liquefaction in 2003 were lower than those reported by Tamura *et al*., but higher for transportation, with overall emissions 0.9 % lower in the study by Okamura *et al*. These differences could be explained by improvements in liquefaction technology and the use of weighted averages in which the average transportation distances from the Middle East was larger. A further reduction of 1.1–1.2% was forecasted for 2010 and attributed to improved energy efficient technology in the production and liquefaction stages.

In a study by May & Brennan (2003) the environmental impacts of electricity generation for Australia’s three most common generation fuels namely brown coal, black coal and natural gas were quantified using LCA. In Australia natural gas and black coal are mainly used for electricity generation and brown coal and LNG are exported. Using a functional unit of one MWh of high voltage electricity delivered to the substation, the impact of each was determined over a range of impact categories, including climate change, solid waste and production energy. The production systems within each fossil fuel studied were fuel recovery and processing, fuel transport, electricity generation and electricty transmissions. The most significant impact resulting from the life cycle of brown coal was found to be climate change, for black coal it was acidification, eutrophication and solid waste generation, and photochemical smog from natural gas (May & Brennan, 2003).

An LCA on the GHGs resulting from natural gas energy generation using LNG fuel supply and competing coal fired generation options in the USA, was completed by PACE (2009) for the Centre of LNG (CLNG). It was found that for the life cycle of coal versus LNG, coal overall generates 160 % more GHGs than the life cycle of LNG. However when just considering the processing and transportation stages of both fossil fuels, LNG produced more GHGs. In a follow-up sensitivity analysis, in which more recent technology was used for the coal production process, a comparative 70 %, more emissions were quantified in the coal life cycle than in the LNG life cycle (PACE, 2009).

WorleyParsons (2008) conducted a life cycle comparison of greenhouse gas emissions of Australian coal seam gas (CSG/LNG) and Australian black coal from extraction in Australia to combustion in China for power generation. In this study an understanding of the implications of LNG versus black coal production in Australia was researched, and China was chosen as a reference as it imports both LNG and black coal from Australia. China currently imports 3.9 million m^3 of LNG but this has been projected to increase to 12 billion m^3 by 2015. In both the life cycle of LNG and black coal to China the major source of GHGs was found to be the power generation process, attributing 82 % and 93 % of emissions respectively. However the life cycle greenhouse intensity for LNG was found to be approximately 50 % lower than that of black coal. The bulk of the GHG emissions for LNG were generated in Australia, and for coal in China. As Australia is required to reduce GHGs with introduction of the Clean Energy Act (2011) and the Climate Change Authority Act (2011), LNG producers could be penalised more than coal producers based on the volume of national emissions. WorleyParson stated that the additional costs added to LNG production based on national GHG emissions (and not considering global effects) will increase the cost of LNG extraction and production, thus increasing the attractiveness of using coal as an export fuel.

Barnett (2010), as part of his Bachelor in Engineering completed a project entitled: ‘An LCA of LNG and its environmental impact as a low carbon energy source’. Barnett concentrated on LNG produced in Australia with specific reference to the Gorgon project in the NWS. Liquefaction, shipping and regasification formed the scope of the research. In contrasting the results obtained for the Australian liquefaction process he concluded that the Australian LNG plants were 42 % more efficient than those studied by Okamura *et al*. (2007). He attributed this to the use of more efficient LNG processing technology in Australia. Shipping emissions, when compared with those of Okamura *et al*. (2007), were 52 % lower in the study by Barnett (2010) and were attributed to the increasing size and supply efficiency of the tankers. Regasification, although not a significant source of GHGs when compared to liquefaction and transportation, showed a reduction of 58 % in emissions when compared to the study by Okamura *et al*. (2007), due to improved technology. He concluded that liquefaction was the stage in which the most GHGs were generated and should be the focus of future research (Barnett, 2010).

Other researchers have completed LNG related research - Sakmar (2010) investigated the suitability of LNG as a futuristic fuel, Lin *et al*. (2007) investigated the significant investment by the Chinese in LNG infrastructure and Arteconi *et al*. (2010) compared fossil fuels for use in transportation.

At the World Energy Congress in Montreal, Canada in 2010, Sakmar (2010) questioned whether LNG is a fuel for the 21st century. Sakmar identified the three main LNG “regions” as the North American/Atlantic Basin Region, the European Region and Asia/Pacific Region. The Asia/Pacific region however is the greatest market in terms of importing the fuel, and projected to grow an additional 10 % by 2015. Sakmar also confirmed that there is limited independent research that analyses the environmental impact of the entire life-cycle emissions of LNG, and that whilst LNG has a key role to play as a cleaner burning fossil fuel globally, further improvements are necessary to reduce associated GHG production and to improve the cleaner burning reputation of LNG (e.g. increased efficiencies in shipment and power technologies). The research highlighted the hotspots in LNG production and identified appropriate mitigation measures (increased size of tankers, use of updated and more efficient technology) that could increase the efficiency in the production of LNG.

Lin, Zhang & Gu (2007), suggested that LNG was the future of China's energy supply. As a relatively new and booming industry in China, they discussed the neccessity of establishing codes and standards of practice surrounding the LNG market, as well as current and developing infrastructure. Factors that were highlighted included five LNG plants in operation in 2009 and another three being built, three operating receiving terminals obtaining LNG from Australia, Indonesia and Malaysia and another 10 in planning or in construction, two 147 200 m^3 LNG tankers were built in China in 2008 for transportation of LNG, together with satellite LNG stations and ongoing research on LNG vehicles. The research highlighted the effort applied in the construction of new gas terminals and gas distribution infrastructure in China in preparation for the increased importation of gas to satisfy growing energy requirements in China (Lin *et al*., 2007).

A comparison of the GHG emissions between diesel and LNG as fuel, for heavy duty vehicles in Europe was conducted by Arteconi *et al*. (2010). For the LNG scenario the study distinguished between locally (directly at the service station) and globally produced LNG (from the regasification terminal). They found that both LNG solutions afforded a 10% reduction in GHG compared to diesel, given the more efficient combustion phase in the vehicle. The emissions were quantified as kg CO_2-e/km_{truck}, and the stages considered included production, distribution and combustion. Total emissions resulting across the three stages were comparable, with diesel having the highest emissions (1.8563 kg CO_2-e/km_{truck}) , followed by local LNG (1.8055 kg CO2-e/km_{truck}) and then global LNG (1.6642 kg CO_2-e/km_{truck}). When compared to other studies it was stated that the production of LNG and diesel had much the same GHG emission rate but with the LNG delivery and distribution being higher. The authors however forecasted a continuing reduction of GHG emissions for the delivery of LNG due to the expansion of LNG in the European market in the future making delivery and distribution more efficient (Arteconi *et al*. 2010).

In summary when considering current research on the life cycle of LNG from extraction to final combustion, the stage in which the majority of GHGs is emitted is combustion, followed by liquefaction, transportation and finally extraction.

The following LCA assessment includes the production and supply of LNG gas to China from the Western Australian North-West Shelf. The assessment also includes a review of potential cleaner production strategies in improving the carbon footprint of LNG production and distribution.

3 METHODOLOGY

The following LCA reviews the LNG production process from the first stage of natural gas exploration, to liquefaction, fractionation, storage and transport to China.

The methodology used to complete the study is described in the ISO 14040-14043 standard which considers four steps of assessment in LCA- goal and scope definition, life cycle inventory analysis, life cycle impact assessment and the interpretation of the results.

3.1 Goal and scope definition

An LCA commences with the definition of the goal and scope of study. It states why the LCA is being conducted and describes the system being studied (Curran, 2006). The goal of this study was the identification of the carbon footprint of each production stage of LNG and the identification of mitigation measures to reduce the GHG emissions in these problem areas (“hotspots”). In the goal and scope definition a functional unit is also identified which describes the function of the process being studied. This provides a common unit for comparison between the production stages of other similar LCA assessments (Curran, 2006). The functional unit selected for this project is the transportation of 1 m^3 of LNG to China. The functional unit of an LCA analysis has a large bearing on the conclusions drawn and depends on the purpose of the study. When comparing the environmental implications of different fuels to provide the same services (e.g. 1GWh of electricity), the functional unit is an energy unit (Biswas *et al*., 2008). In this study cubic metre (m^3) a volumetric unit was considered because the purpose of the research is to assess the environmental implications of transporting LNG to the Chinese market. All upstream and downstream inputs and outputs of the systems should ideally be included to represent the flows between the environment and the technological system (Tillman *et al*., 1994). The system boundary for the current research includes the initial exploration for natural gas, the liquefaction and fractionation of the LNG and export transportation to China.

3.2 Life cycle inventory

Inventory analysis is a listing of inputs (energy and materials) and outputs (emissions and waste) from each of the processes of the life cycle of a product, their boundaries, and the potential impact of each process and system. The Life Cycle Inventory (LCI) was initiated with the drawing of a flow diagram (Figure 1) in which the boundaries for each of the above mentioned systems was clearly demarcated. The data was collected within these boundaries by making use of specialist reports, journal articles and expert interviews. An inventory list of inputs and outputs was compiled and a mass balance drawn up. Data was collected and analysed for both the production inputs and outputs of the LNG cycle only and excluded all construction and exploration (start-up) phases of the LNG production process. Chemicals, energy and heat were quantified in terms of inputs and outputs. Each of the production stages complete with assumptions made is outlined in the sections below. Appendix A highlights the LCI calculations for heat, electricity and chemical inputs.

3.3 Life cycle impact assessment

The environmental impact assessment of $1m^3$ of LNG transportation to China for extraction, liquefaction and exportation stages involved two steps. The first step classifies the total emissions produced due to the production, transportation and application of these inputs and the second step converts these gases to an equivalent CO_2 value (CO_2-e) for different environmental impact categories, including global warming, photochemical oxidation, eutrophication, carcinogens, land use, water use, solid waste, fossil fuels and mineral depletion.

Step 1: The input and output data from the LCI were entered into Simapro 7.3 (2011) software (PRé Consultants 2011). The software calculated the actual emissions for the different environmental impact categories. The input/output data of the LCI were linked to relevant libraries in Simapro 7.3. The LCA Library is a database that consists of energy consumption, emission and materials data for the production of one unit of a specific product.

Chemical library: In order to make the LCA results more representative for Australia conditions, local databases and libraries have been used. In the absence of Australian databases, European databases were included to carry out the analysis. The Australian libraries for chemicals were sourced from RMIT (2007), to calculate greenhouse gas emissions from the production of chemical inputs, such as Deionised water, liquid nitrogen, and sodium hydroxide. A European database 'Eco-invent' was used to estimate the GHG emissions from Monoethanolamine production (PRé Consultants 2011).

Electricity and heat libraries: Natural gas burned in the gas turbine library has been used to calculate the GHG emissions from electricity generation from natural gas for liquefaction and other plant use purposes. The GHG emissions from the combustion of natural gas for heating purposes were sourced from the Australian database for energy from natural gas. The emission factor for electricity generated by wind (i.e. 9.7 kg CO_2 –e/MWh) was obtained from a report by Lund & Biswas (2008).

Transport library: Simapro database for Transport, liquefied natural gas, freight (RMIT 2007) was chosen to calculate GHG emissions from the transportation of LNG to China.

Step 2: The Australian LCI impact assessment method was used to assess eight impact categories, which included global warming, photochemical oxidation, eutrophication, carcinogens, land use, water use, solid waste, fossil fuels and minerals. Firstly, Simapro 7.3 (PRé Consultants, 2011) software calculated the relevant emissions resulting from the production of LNG, once the inputs and outputs were linked to the relevant libraries. The program then sorted emissions for different impact categories from the selected libraries, and then converted them to CO_2 equivalents for the corresponding impact category.

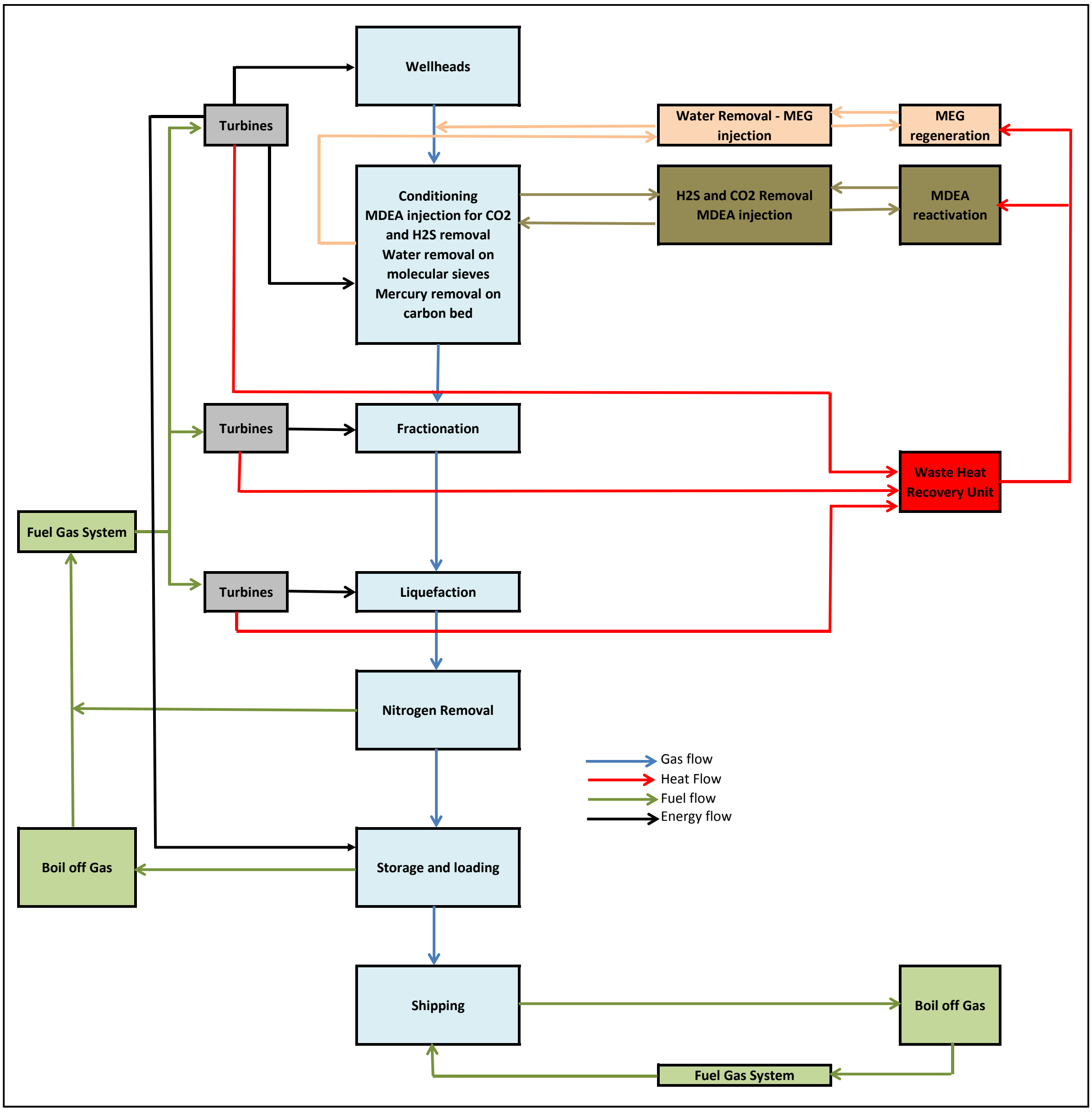

Figure 1: Flow diagram of LNG process

4 RESULTS: CARBON FOOTPRINT OF LNG PRODUCTION IN WESTERN AUSTRALIA

In identifying the carbon footprint and the production hotspots relevant to this research, i.e. gas conditioning, fractionation, nitrogen removal, and liquefaction stages of LNG production were considered individually. A flow sheet presentation and their resulting emission values are found in Appendix B. This flow sheet presents and subsequently identifies the areas of LNG production that have the highest value for GHG emissions, in terms of CO_2 equivalents (CO_2-e).

Table 2 and Figure 2 display the CO_2-e emission values from the production of 1 m^3 of LNG in Western Australia. The liquefaction stage of LNG production emits the highest levels of GHGs (94.5 kg CO_2-e or 54%). These GHGs are largely generated by the burning of natural gas for the turbine electricity generation that liquefies the gas for distribution and export. The gas conditioning phase, which includes the removal of water, CO_2, sour gas and other impurities, produces the second highest levels of GHG emissions, contributing 60.9 kg (35%) of CO_2-e of the total emissions. The electricity generated by gas turbines in the fractionation phase was the third highest emitter of GHGs contributing 15.4 kg (9 %) of CO_2-e and the electricity required for the removal of nitrogen from the LNG was the lowest emitter of CO_2-e at 2.6 kg (1%) CO_2-e. When summarising this section it can be clearly seen that the emissions resulting from the generation of energy to produce the LNG from natural gas is the main GHG contributor.

Table 2: GHG emissions from various stages of NWS LNG production

System	**kg CO_2-e (per 1 m^3 of LNG production only)**	**%**
Liquefaction	94.5	54
Gas conditioning	60.9	35
Fractionation	15.4	9
Nitrogen removal	2.6	1
Total	173.4	100

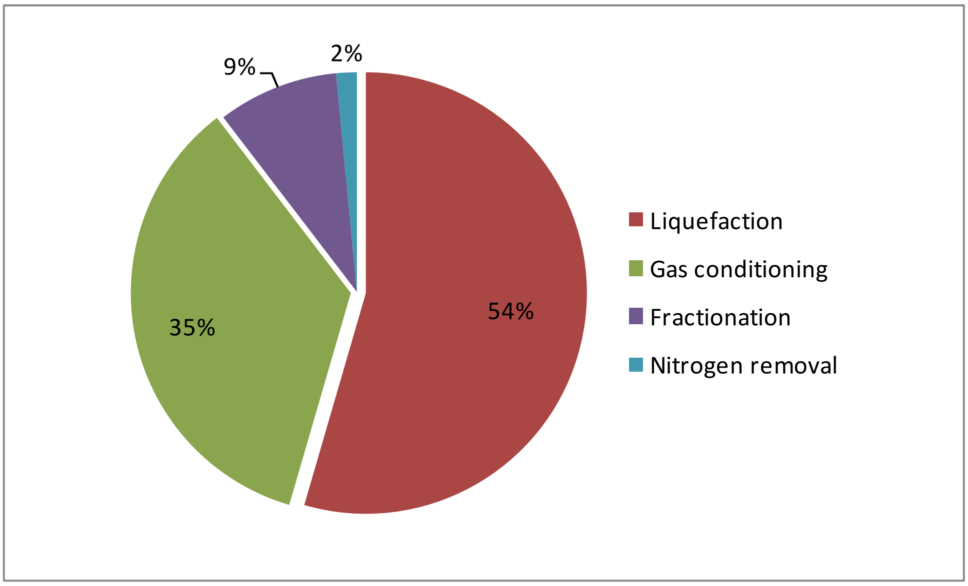

Figure 2: Graphical presentation of CO_2 emissions from various stages of LNG production

4.1 *Identification of 'hotspots'*

The results obtained show that the liquefaction stage of production (Figure 2) is the highest emitter of GHGs, and these results are consistent with reviewed literature. The reviewed literature also notes the liquefaction phase to be energy and GHG intensive, following the combustion of the gas for domestic and industrial purposes (Tamura *et al*, 2001; Okamura *et al*, 2007; Barnett, 2010). The current study did not explore the regasification, distribution and use of the gas after being despatched in China.

The carbon footprint (kg CO_2 –e) associated with producing and transporting 1 m^3 of LNG to China has been determined in order to identify the "hotspots" or the stages creating the most GHG emissions. Table 3 shows the GHG emissions from the different stages of production including exploration and separation, LNG production process (which includes gas conditioning fractionation, nitrogen removal and refrigeration for liquefaction processes) and the export of LNG to China. Figure 3 is a graphical presentation of the liquefaction, production and transportation stages of LNG production.

The GHG emissions from the LNG production process (173.4 kg CO_2 –e) accounted for nearly half (45.4%) of the total emissions, followed by the greenhouse gas emissions from the exploration and separation process at 149 kg CO_2 –e (39%) and the transportation/export of LNG to China at 59.9 kg CO_2 –e (15.7%).

Table 3: GHG emissions from the main stages of the LNG life cycle

Stages		kg CO_2-e	%
Exploration and separation		149	39.0 %
	Exploration	122	32.0%
	Separation	27	
LNG production process			
	CO_2 removal from raw gas	22.5	5.9 %
	Chemicals	1.8	0.5 %
	Combustion of waste gases in flares	1.5	0.4 %
	Heat recovery for AGRU	35.1	9.2 %
	Electricity - fractionation	15.4	4.0 %
	Electricity - nitrogen removal	2.6	0.7 %
	Electricity - liquefaction	94.5	24.7 %
	Sub-total	173.4	45.4 %
Export to China (LNG tanker)		59.9	15.7%
Totals		382.3	100%

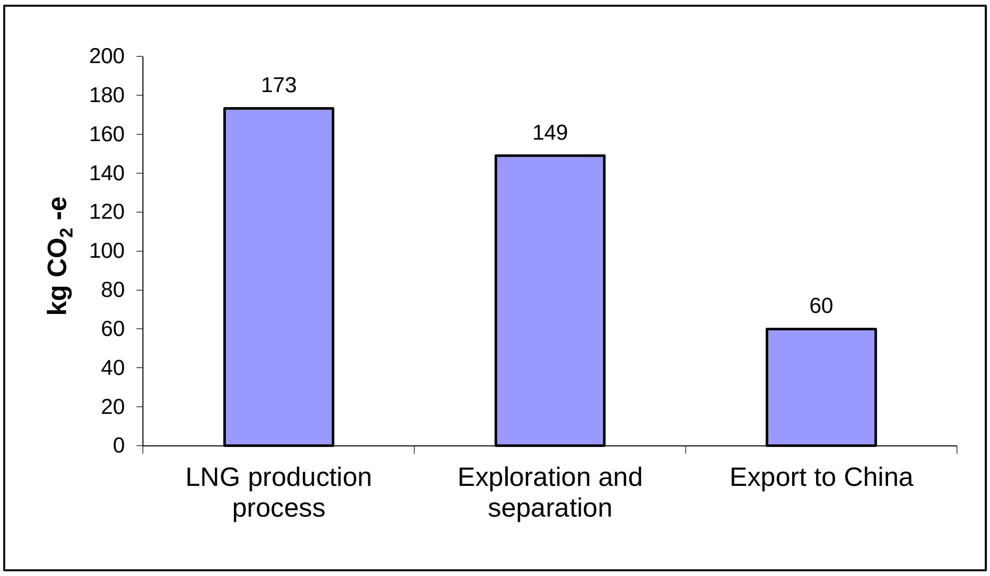

Figure 3: Graphical presentation of kg CO_2-e resulting from exploration, production and transportation of LNG (China)

The emissions from the use of chemicals (MEG, nitrogen liquid, mineralized water etc.) in the LNG production process, (applied for gas drying and impurities removal purposes-CO_2, H_2S), have an insignificant contribution (0.5%) to the total GHG emissions. The thermal energy consumption required for heat treatment in gas conditioning (recovered from the exhaust waste heat of the gas turbine) is equivalent to 9.2% of the total GHG emissions and highlights the value of heat recovery in reducing the overall carbon footprint. The GHG emissions resulting from the combustion of natural gas, have been allocated to two outputs, that of heat in the gas conditioning stage and electricity for powering the whole system. This co-generation system is used in modern LNG plants (Barnett, 2010; Gorgon, 2009). Other sources of greenhouse gas emissions include the combustion of flare gases (0.4 %) and the CO_2 removed during the conditioning process (5.9 %).

GHG emissions from electricity generation are the single largest GHG contributor in LNG production. The GHG emissions from the generation of electricity for converting natural gas to LNG accounted for a total of 29.4 % of the total GHG emissions (24.7 % in the liquefaction stage, 4 % in the fractionation stage and 0.7 % for nitrogen removal). This permits the separation of ethane, butane and propane and the subsequent concentration of methane in LNG.

4.2 Comparison of GHG emissions in the current study with other studies

For this study, the total GHG emissions associated with the $1m^3$ production and transportation to China is 382 kg of CO_2 –e. LCA assessments on LNG production and supply to the Japanese market from Indonesia and the Middle East by Tamura *et al.* (2001) and Okamura *et al*. (2007) reported levels of total GHG emissions from LNG production and transportation at 254 kg CO_2-e/m^3 and 367 kg of CO_2 –e/m^3 respectively (Figure 4). These values are 50% and 4% lower respectively than the current study, because the production of natural gas in Australia emits 5-6 times more GHGs than those produced in Indonesia and other Middle East nations (Tamura *et al*., 2001; Okamura *et al*. 2007; PRé Consultants, 2011). The GHG emissions associated with natural gas production depends on a number of factors, including the composition of natural gas being extracted, the quality of gas produced and the type of well (Arteconi *et al*. 2010). The flow network (Figure 5), which was derived from the Northern Australian natural gas production library of the Simapro software, showed that only one kg of pure natural gas can be separated from 1.32 m^3 (or 1,056 kg) of crude natural gas in Australia. Therefore, the quality of raw natural gas in Australian is likely to be one of the main contributors to the GHG emissions associated with LNG production in this study. However it should also be noted that the system boundary in the Japanese studies for natural gas production are different from this study (see point 2.4 Life cycle assessment of LNG). For example, Venkatesh *et al* (2011) estimated the mean GHG emission factors for different processes of natural gas production to be 54 kg of CO_2-e/m^3 in pre-production, 299 kg CO_2-e/m^3 of natural gas in production; 125 kg CO_2-e/m^3 for processing; 42 CO_2-e/m^3 for transmission and storage; and 24 CO_2-e/m^3 for distribution.

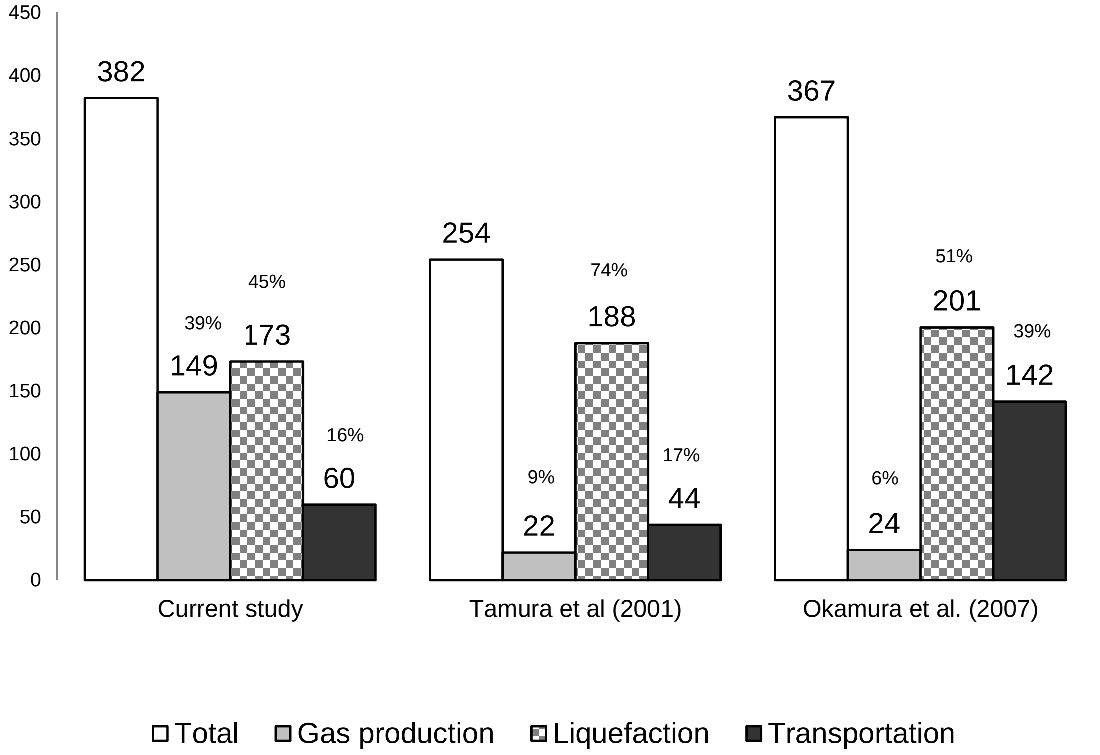

Figure 4: Comparison of current study with other similar studies

There is a small difference in the total GHG emissions from the liquefaction processes in these three studies (Figure 4). This is because all three studies considered the measures for recovering the waste heat from the gas turbine power generation plant through cogeneration systems for gas conditioning purposes. The GHG emissions from the transportation of LNG via tanker in the study by Okamura *et al*. are three to four times higher than this research project and the research reported by Tamura *et al*. This is because Okamura *et al*. used the weighted average of transportation distances of LNG from a variety of LNG exporting countries including Alaska, Indonesia, Quarter, Oman and Australia.

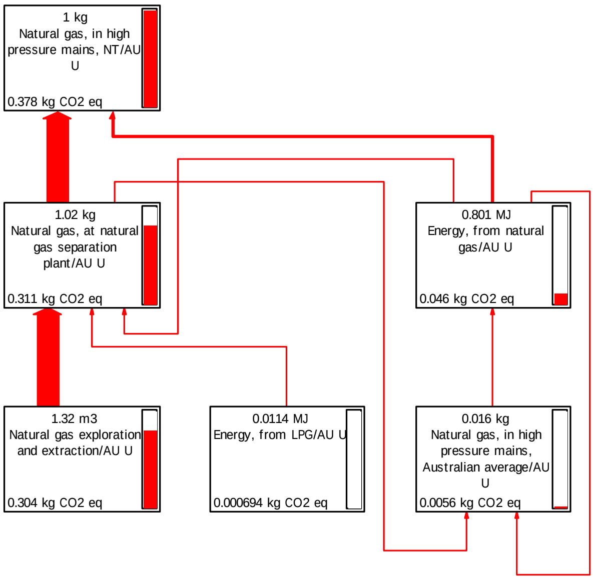

Figure 5: Flow network for 1 kg natural gas extraction and separation

The GHG emissions of the current study have also been compared with other North American (Rosenfeld & Jackson, 2008) and European (Arteconi *et al*., 2010) studies (Figure 6). The GHGs of the study by Rosenfeld & Jackson (2008) of 772 kg CO_2–e /m^3 are higher than the current study, which can be explained by the fact that the natural gas produced in Canada was piped to California for liquefaction processing which significantly increased the overall emissions. As the system boundary of the study by Rosenfeld & Jackson include the distribution and combustion of the LNG, whereas this current study terminates at the receiving terminal in China increased emissions can also be expected

Arteconi *et al*. (2010) found that 1038 kg of CO_2 –e/m^3 of GHGs could be produced in European countries. This higher value may result from the transportation of natural gas that comes from a mix of sources in Europe and from imports of natural gas (WEI, 2008). In addition to LNG tankers, 26 tonne trucks are used as LNG carriers for interstate LNG transport in European countries. The combustion of diesel in these trucks may have added additional GHG emissions into the production life cycle.

Finally, a comparison was made with a local Australian study where Beer *et al*. (2002) assessed the fuel cycle GHG emissions from alternative fuels in Australian heavy vehicles. The study showed that the total GHG emissions from the production of LNG to be 452 kg CO_2-e, which is 29% higher than the GHG value of LNG production (322 kg CO_2 –e) of the current study. Such a variation in results may be due the fact that the data considered in Beer's study came from previous studies in the US Alternative Fuels Data Center, whilst the current study used local data for LNG production processes (Beer *et al*. 2002, as cited in Arteconi *et al*., 2010).

Whilst the current study at 382 kg CO_2 –e/m^3 sits mid-range between 254 kg CO_2 –e/m^3 and 1,038 kg CO_2 –e/m^3, in comparative studies on the carbon footprint of LNG production, it is important to note the boundaries utilised in the comparable LCA assessment and the data sources in order to objectively compare the results.

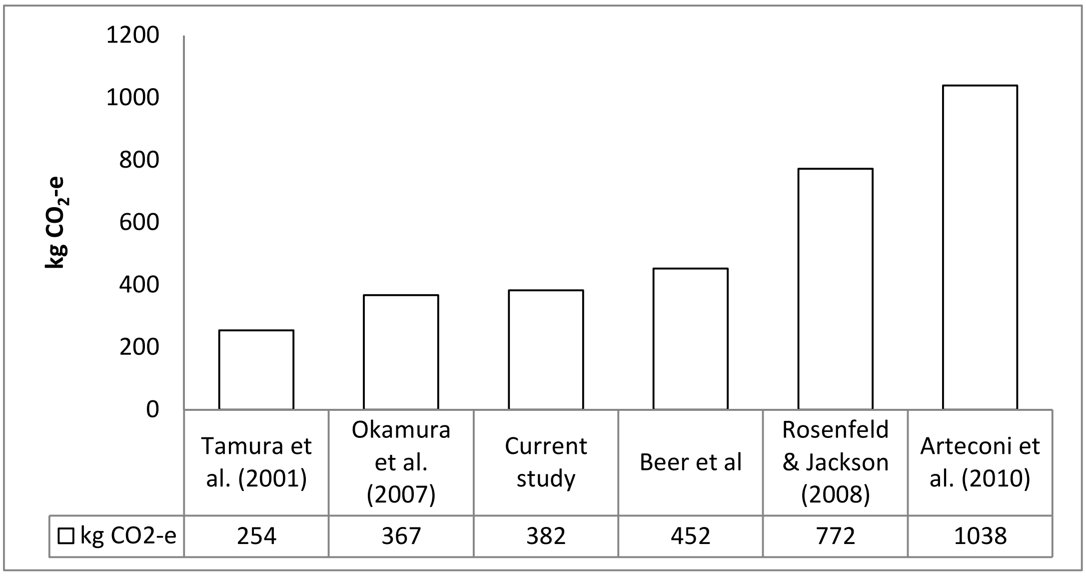

Figure 6: GHG comparative GHG emission graph[2]

5 MITIGATION STRATEGIES FOR REDUCING CARBON FOOTPRINT IN THE LNG PRODUCTION AND SUPPLY CHAIN

A number of 'cleaner production' (CP) strategies can be suggested to mitigate the CO_2 arising from LNG production. Cleaner production improvements are typically focussed on material input management, equipment and technology substitution, product design and the management of waste outputs (van Berkel, 2007). When analysing the GHG emission contribution of inputs in this research, it appears that the emissions from power generation from the gas turbine accounted for 112.5 kg (29.4 %) of CO_2-e of the total GHG emissions and is considered a "hotspot" within LNG production and the one most able to be managed. Whilst LNG exploration and separation (including embodied energy in infrastructure and equipment and fugitive emissins) accounted for a very significant portion of the overall GHG contributions (39 %) we have not discussed potential CP strategies for this production stage in this report.

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[2] Boundaries of each study include:
Tamura *et al*: production, liquefaction, export transportation, regasification, distribution, combustion, equipment construction
Okamura *et* al: production, liquefaction, export transportation, regasification, distribution, combustion, equipment construction
Current study: production, liquefaction, export transportation
Beer *et al*: production, liquefaction. Export transportation, regasification, distribution, combustion
Rosenfeld & Jackson: production, liquefaction, export transportation, regasification, distribution, combustion
Arteconi *et al*: production, liquefaction, export transportation, regasification, distribution, combustion

The following discussion is based on mitigation strategies for offsetting the GHG emissions associated with gas turbine electricity generation ('energy consumption') for the production and liquefaction/fractionation processes only.

Two CP strategies have been investigated- one involving carbon capture and storage (CSS) and the second involving renewable energy technology (wind power) substitution. The option for CO_2 sequestration opportunities has previously been proposed in a Gorgon LNG project review in sequestering fugitive emission associated with the exploration and separation process (Gorgon, 2009). In terms of renewable energy technology substitution, the option of replacing mains electricity generation with the use of wind energy was proposed by the Snøhvit LNG project in Norway (Bomstad & Nordland, 2009). Both these CP options are examined separately and as a joint mitigation option to provide five separate mitigation strategy scenarios (Figure 7).

<u>CCS</u> : During the gas conditioning phase of LNG production, all acid gas is removed in the acid gas removal unit (AGRU), to prevent the natural gas from freezing at low temperatures in the cryogenic sections of the plant and to meet the LNG product CO_2 and sulphur specifications (Gorgon, 2009) (Appendix A). In typical LNG production, the CO_2 and H_2S are removed and vented to the atmosphere. Recent research suggests that it is viable to geo-sequestrate the CO_2 generated during these processes and re-inject the gas into geological formations deep within the earth (Gorgon, 2009; Barnett, 2010). A CO_2 sequestration of 80 % by volume into these formations has been recommended with 20 % venting into the atmosphere for the Gorgon/Jansz feed gas project (Gorgon, 2009). This will achieve an estimated reduction in CO_2 emissions of 3.5 million tonnes per annum (MTPA) (Gorgon, 2009; Shell, 2009).

It should be noted that the feasibility analysis for CSS, both at basin and regional scales, must be assessed on geological, geothermal, hydrodynamic, basin maturity, economic and societal evaluation criteria (Bachu, 2002).

Whilst there is currently no available information on the potential capacity for carbon capture and storage (CCS) in the exploration and separation phases of LNG production, a theoretical sensitivity analysis was carried out to determine the changes in greenhouse emissions associated with the potential sequestration from energy consumption (gas turbine generated electricity) and process impurities related GHG emissions of the LNG production process. The sensitivity analysis suggests that around 33- 45 % (Table 4) of current LNG production greenhouse gas emissions could be reduced with the geo-sequestration of between 50-100% of the GHG emissions from the electricity consumption associated with the LNG production process (Figure 7).

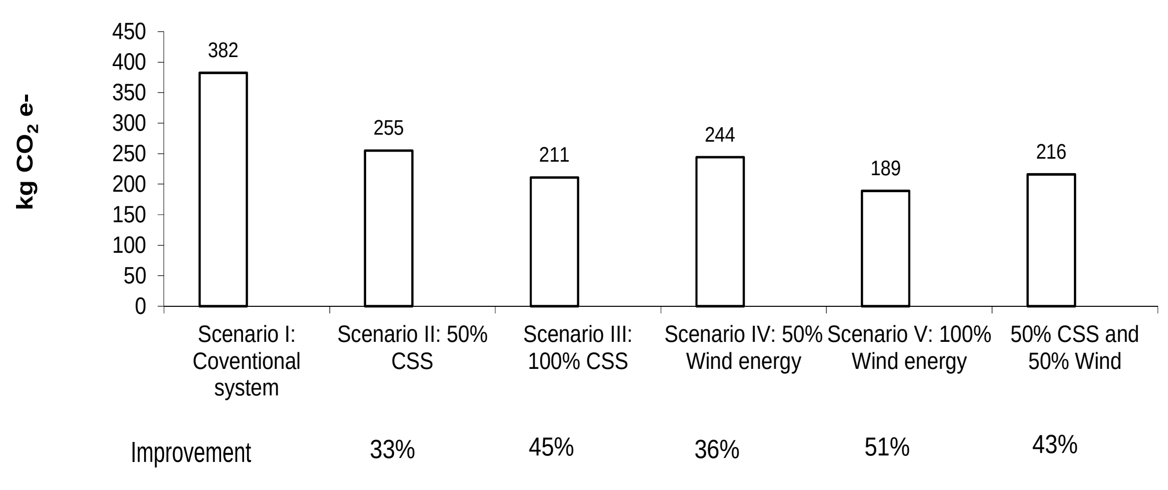

Figure 7: GHG emission mitigation scenarios

Wind power: Wind is a low-cost and fast growing source of renewable energy. Wind energy can be generated by converting wind currents into electrical energy using turbines. Australia has some of the best wind resources in the world, with 1052 wind turbines currently working on 52 operating wind farms in Australia. These wind farms generate a total of 5 000 GWh of electricity per year (CAR, 2011). In Western Australia most of the electricity generated by renewable energy comes from wind energy. The state has 12 wind farms, mostly along the coastal area, with a total of 198 MW of installed generation capacity, which accounts for 63 % of WA's electricity from renewable resources (WWA, 2011). The Snøhvit LNG production facility in Norway (Bomstad & Nordland, 2009) successfully uses wind energy for the generation of electricity and a comparative assessment replacing gas fired turbine electricity generation with wind energy is included in this analysis.

Figure 7 highlights the changes in greenhouse gas emissions associated with a 50 % and 100 % replacement of national grid electricity with wind energy. Between 36-51% (Table 4) less greenhouse gas emissions can be achieved with the substitution of gas turbine generated electricity with wind generated electricity.

Table 4: Sensitivity analyses and % improvement

Scenario	kg CO2-e	% Improvement
Scenario I - Conventional system	382	-
Scenario II – 50 % CSS	224	33.24
Scenario III – 100 % CSS	211	44.76
Scenario IV – 50% wind energy	197	36.13
Scenario V – 100% wind energy	189	50.52
50 % CSS and 50 % wind	216	43.46

6 CONCLUSION

LCA provides the opportunity to assess the environmental performance of LNG as a less carbon intensive fuel in reviewing both the environmental impacts of each stage of production as well as in the development of mitigation strategies.

The carbon footprint of NWS LNG production largely revolves around two major GHG producing functions. Firstly the LNG production and liquefaction stage involving high energy use in the liquefaction and fractionation process and secondly in the GHG emissions (methane) associated with the exploration and separation of the gases prior to LNG production.

This study has only focussed on potential mitigation strategies for the LNG production and liquefaction processes associated with LNG production.

In reviewing the carbon footprint of the production and transportation of 1m^3 of LNG to China, this LCA has confirmed that the production and liquefaction stage generates the most GHG emissions (45.4%), followed by the natural gas exploration and separation stage (39%) and the exportation and transportation stage (15.7%).

The exploration phase of production is the single highest contributor to the GHG emissions associated with LNG production (32%). Secondly the electricity generation required for the liquefaction process generates the next highest level of GHG (24.7%), followed by the heat recovery associated with the AGRU process (9.2%) and CO_2 removal from the natural gas (5.9%).

The GHG emissions from electricity generation required to process the LNG are the single largest contributor to total GHG emissions in the LNG production process (29.4%) and comparable to the GHG emissions associated with the exploration phase of production (32%) .

In the LNG production process the possible alternatives for improving carbon efficiency can include measures like the recovery of waste heat, the introduction of co-generation systems and improvements in liquefaction technologies. However, given the significant energy requirement of the production process, more substantial impact options were assessed – that of renewable energy and a sequestration mitigation.

The utilisation of wind power energy as a replacement for gas fired electricity generation could possibly reduce the 'energy consumption' related GHG emissions of LNG production by some 36-51%. Similarly, the utilisation of carbon capture and storage to sequester the GHG emitted during electricity production could potentially reduce 'energy consumption' related GHG emissions by 33-45%.

Whilst the literature reviewed highlights the numerous studies that have been conducted on the LCA assessment of LNG production, direct comparison and benchmarking is made difficult by the variety of reference scenarios and associated production boundaries. However, most research, including this study, highlight the significance of the liquefaction process in total LNG production GHG emissions.
Increasing policy focus on GHG reductions through emission taxes and or clean energy investment incentives could all play a role in supporting the introduction of more carbon reduction strategies in the LNG industry.

Although not discussed in detail in this report, carbon efficiency improvements in LNG exploration and extraction will also contribute to the overall reduction in the footprint of LNG production.

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APPENDIX A: NATURAL GAS LIQUEFACTION

Natural gas reception

At this stage of the production process the NG is received in the pipeline after extraction from the wellheads and is separated at the slugcatchers into three separate phases (gaseous, condensate and aqueous phases) (Gorgon, 2009). Typically natural gas is made up of methane, ethane, propane, butane, carbon dioxide and water and other impurities in different ratios according to the gas field. A typical composition for Australia is tabulated below (Table A-1).

Table A-1: Typical mol % composition for natural gas in Australia (Pack, 2011)

Component	**Gas (y) in mol %**
Methane	78.74
Ethane	6.94
Propane	4.23
i-Butane	0.83
n-Butane	1.44
i-Pentane	0.46
n-Pentane	0.46
Hexane	0.59
Heptane +	0.76
Carbon dioxide	2.66
Nitrogen	2.89

After the reception and separation into the three phases (aqueous, gaseous and condensate) the aqueous phase (hereafter referred to as natural gas) is treated with a hydrate inhibitor such as Mono-ethylene Glycol (MEG) which removes the water and salts from the gas feed. Further upstream the MEG is recovered, regenerated and routed back to the wellheads for re-use (Gorgon, 2009). The energy requirement for the pumping of the gas, MEG injection and other utilities (which include gas conditioning, storage and loading etc.) are assumed to be provided by five frame 9 gas turbines running at a 75 % capacity and delivering 116 MW of energy each. The total operating hours for per annum are assumed to be 8170 hours (Gorgon, 2009, Barnett, 2010). The water removed during the dehydration process is assumed to be routed back to the ocean.

Natural gas conditioning

After dehydration the condensate is further treated in the NG conditioning phase. The gas conditioning phase consists of an acid gas removal unit (AGRU) and a dehydration unit. In the AGRU the carbon dioxide (CO_2) and the hydrogen sulphide (H_2S) (collectively known as acid or sour gas) present in the NG is removed using activated Methyl Di-ethanol Amine (a-MDEA) technology. The addition of a-MDEA is approximately 50% by weight of the NG, it is re-activated downstream and re-used (Gorgon, 2009). MDEA make-up, due to losses, is 1.5 kg per ton of CO_2 removed (Singh, Strømman & Hertwich, 2011). All acid gas is removed to prevent the NG from freezing out at low temperatures in the cryogenic sections of the plant and to meet the LNG product CO_2 and sulphur specifications (Gorgon, 2009). The CO_2 and H_2S that is removed are assumed to be vented to the atmosphere. The heat requirements for the operation of the AGRU is acquired from the waste heat recovery units (WHRU) which obtain heat from the gas turbines in both the initial energy generation and liquefaction phases of the process (Gorgon, 2009).

From the AGRU the sweetened gas undergoes dehydration and mercury removal. All excess water is removed to prevent hydrate formation, by making use of molecular sieves. The mercury is removed to prevent corrosion of the heat exchanger tubes in the Main Cryogenic Heat Exchanger (MCHE) (Gorgon, 2009, Barnett, 2011). The technology used incorporates the use of carbon beds for the removal of the mercury and all energy and heat required is supplied by the frame 9 gas turbines as specified previously.

Fractionation

Fractionation is the removal of the heavier hydrocarbons which will freeze during the cooler liquefaction phase of the process. The dry treated gas from gas conditioning is pre-cooled and fed into a scrub column where the composition of the NG is altered as the heavier components are removed, to comply with the composition standards of the LNG. These heavier components are routed to a storage tank and later converted to Liquid Petroleum Gas (LPG) (Gorgon, 2009; Barnett, 2010). During fractionation the energy requirement is assumed to be met by two Frame 6 gas turbines with a collective output of 65 MW when operating at a 75% capacity (Barnett, 2011; Alabdulkarem, 201; Mortazavi, 2011). Heat from these turbines is collected in the WHRU's for use in the process. The lighter component of the NG is routed to the liquefaction part of the production process.

NG Liquefaction

Liquefaction commences as the NG enters the cryogenic units and is the main component of the LNG production train. During liquefaction the stream of NG is cooled to a temperature of less than minus 161 °C (< -161°C) to allow for liquefaction of the gas of specific composition. The typical composition of Australian LNG is subsequently tabulated (Table A-2).

Table A-2: Typical composition of Australian LNG (Pack, 2011)

Typical LNG Composition for NWS	Gas in mol %
Methane	87.95
Ethane	8.00
Propane	3.15
i-Butane	0.35
n-Butane	0.45
i-Pentane	0.01
Nitrogen	0.09

A variety of proprietary technologies have been developed for the liquefaction of NG, the most popular being the Air Products and Chemicals International (APCI) propane pre-cooled mixed refrigerant process (MCR^{TM}), Phillips optimised cascade process, Black and Veatch PRICO^{TM} process, Statoil/Linde mixed fluid cascade process (MFCP), Axens Liquefin^{TM} process and Shell double mixed refrigerant process (DMR). Of these the APCI MCR^{TM} is used the most often (Barnett, 2010; Alabdulkarem, 2011), and was assumed to be used for this research.

In the APCI MCR^{TM} technology the NG after conditioning is separated into a gaseous and condensate phase at temperature -30°C. The condensate is sent to the fractionation unit, which uses a propane cooling cycle to remove the heavier hydrocarbons and the gaseous phase is liquefied in a mixed refrigerant cycle (MCR) (Barnett, 2010; Alabdulkarem *et al*., 2011).

Energy was generated by making use of six Frame 7 gas turbines, generating an average total of 194 MW based on an efficiency of 75 %. The fuel requirements for the turbines totalled an average of 9.8 % of the feed gas per LNG train of approximately 5 million tonnes per annum (MTPA). Heat from these turbines are captured and stored in the WHRU for usage in utilities as specified previously (Meher-Homji, 2008; Barnett, 2010).

After liquefaction the LNG is cooled further in the Nitrogen Reboiler Column to facilitate with the removal of excess nitrogen. The nitrogen is then routed to the fuel gas storage tanks where a portion of it is used as fuel and that remaining is vented to the atmosphere. After nitrogen removal the LNG is stored in storage tanks.

LNG storage, loading and transportation

After liquefaction and prior to the transportation of the LNG the gas is stored in storage tanks. During storage some of the LNG evaporates and is routed to the fuel system to be used as fuel. The storage of the LNG acts as an intermediary between the production and transportation of the gas (Gorgon, 2009; Shell, 2009; Chevron, 2010). The energy required for the storage and loading is assumed to be obtained from the initial power supply.

The capacity of the LNG tankers is assumed to be 137 500 m^3 (61 875 kg of LNG at a density of 450 kg/m^3). The boil of gas (BOG) produced during transportation is reused as a fuel in the tanker at a rate of 11 g per kilogram of LNG transported. The oil requirement for the transportation of this amount of LNG is 6 g of fuel oil per kilogram of LNG transported (Hakes, 1997; Barnett, 2010, Ferc, n.d.). The distance travelled is assumed to be an average of 6177 km (average of distance between Darwin and Shenzhen and Karratha and Shenzhen) with the tanker travelling at an average speed of 20 knots (37.04 km/hr).

APPENDIX B: FLOWSHEET OF LNG PRODUCTION EMISSIONS