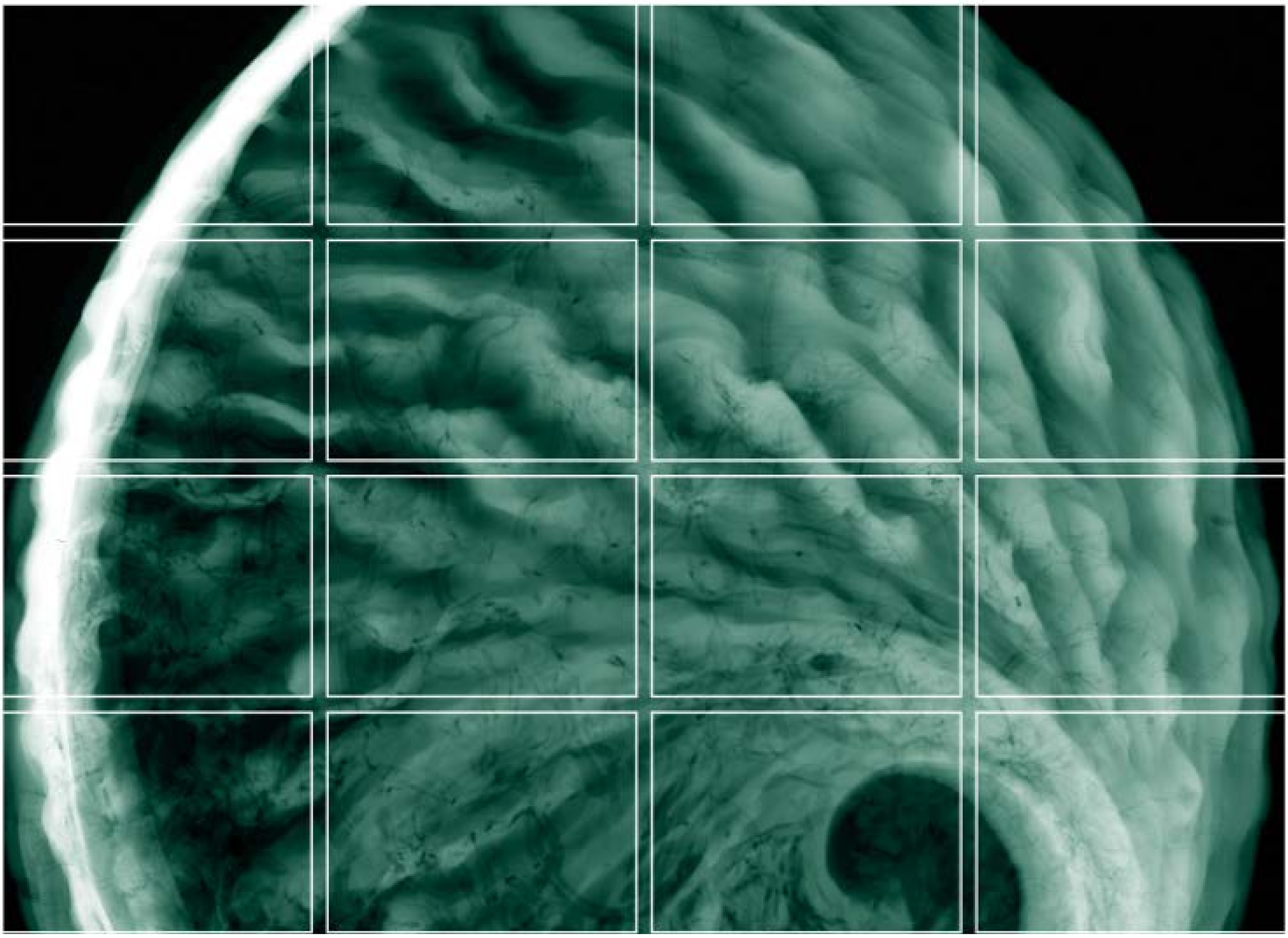

Comparative Life Cycle Assessment: Browse and Scarborough

Comparative Life Cycle Assessment

22 April 2020

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The business of sustainability

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22 April 2020

Comparative Life Cycle Assessment: Browse and Scarborough

Comparative Life Cycle Assessment

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ABBREVIATIONS AND GLOSSARY OF TERMS

Acidification – Potential impact category	Measured in Mol H^+ e This impact category looks at the emissions (SO_2, NO_x, NH_3, HCl, HF) by human activities that could affect the quality of all components of the environment (including air, soils and surface waters) not only in the vicinity of the sources, but also hundreds or even thousands of kilometres from their emitting sources. In the case of the systems under this study, the key acidification components are NO_x and SO_2.
ASEAN	The ASEAN region includes the following ten countries: Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Vietnam
Average mix	Defined as the emissions intensity of a more diversified power market, for all fuels, including fossil, renewables and nuclear.
Climate change – Potential impact category	Measured in kg CO_2e The impact category, climate change, represents the carbon footprint of a product system adding up all greenhouse gas emissions (GHG) taking account of their respective global warming potentials (GWPs). GWPs represent the amount of heat trapped by the gas in the atmosphere over time. All gases are measured relative to carbon dioxide. The most relevant gases to this study are carbon dioxide, methane and nitrous oxide. This impact method does not include the extent to which these emissions cause a change in global temperature as this requires additional modelling of other global emissions and sinks.
Coal only mix	Defined as the emissions intensity of the coal-only section of the power market under study.
CPS	Current Policy Scenario.
Fossil fuel mix	Defined as the emissions intensity of the power market under study, which accounts only for fossil fuel power sources.
FPSO	Floating, Production, Storage and Offloading facilities.
FPU	Floating Production Unit.
IEA	International Energy Agency.
IPCC	Intergovernmental Panel on Climate Change.
ISO14044	International Organization for Standardization Standard 14044, Environmental Management Standard – Life Cycle Assessment, 2006.
KGP	Karratha Gas Plant.
LCA	Life Cycle Assessment.
LNG	Liquefied Natural Gas.
MWh	Megawatt hours.

Particulate matter – Potential impact category	Measured in g $PM_{2.5}$e. This impact category represents the human health impacts from exposure to particulate matter (PM_{10} and $PM_{2.5}$ principally) but also secondary particulates including SO_2 and NH_3. This is one of the highest non-behaviour related risks to human health as identified in the global burden of disease (Vos, Barber et al. 2015).
Photochemical smog – Potential impact category	Measured in g NMVOC e Photochemical smog, also known as photochemical oxidation creation potential, represents the potential of hydrocarbons and nitrogen oxides in the atmosphere to react under the catalytic action of sunlight to produce tropospheric (ground level) ozone, as well as some other chemicals, which has significant respiratory and other health effects. While all impact categories represent potential impacts, this is particularly the case with photochemical smog as the effect only occurs when the appropriate mix of gases are present in sunlight.
SDS	Sustainable Development Scenario.
STEPS	Stated Policy Scenario.
TPED	Total Primary Energy Demand.
WEO	World Energy Outlook.

GUIDE FOR READERS

This document presents a summary of a life-cycle assessment (LCA) for the two proposed Woodside Energy Limited (Woodside) operated gas reservoirs; Browse and Scarborough. The broader report discusses the context and rationale for Liquefied Natural Gas (LNG) in Asia Pacific under various future electricity generation scenarios. The report follows the outline of the structure provided below:

Chapter 1 provides background to the study.

Chapter 2 introduces the International Energy Agency (IEA) scenarios describing future market developments, including the emergence of a lower-carbon world.

Chapter 3 examines a case study for the role of gas in decarbonising the energy system in Europe, the United States and China.

Chapter 4 defines the goal and scope of the study.

Chapter 5 covers the inventory analysis.

Chapter 6 gives an overview of the results of the study relating to greenhouse gas emissions. Chapter 6 also includes comparisons to IEA scenarios, and describes the method used to conduct this analysis.

Chapter 7 provides an interpretation of the LCA results.

Chapter 8 provides a discussion and conclusion to the study.

This document is the second LCA commissioned by Woodside on the sources to end user (gas well to power generation) impacts of the proposed Browse and Scarborough LNG projects. Since the completion of the first study in 2019, a number of changes have occurred, which have warranted the revision of the first LCA study. These changes cover a range of refined and updated input data. As data continues to improve over time, e.g. to extend the data series, the increase in confidence in the conclusions may lead to further revisions.

Changes from the first study include (but are not limited to):

- More accurate quantification of LNG production quantity;
- Updated efficiency of the use of Scarborough and Browse gas over time;
- Correction of how shipping emission factors treat the return journey;
- Inclusion of Woodside's estimates of emissions required to meet the Australian Safeguard Mechanism, as stated in the December 2019 Draft Browse to NWS EIS/ERD and existing Western Australian conditions;
- Updated production and emissions forecasts, including changes due to an uplift in Scarborough reserve volumes of 52% from 7.3 trillion cubic feet (tcf) to 11.1 tcf;
- Updated LNG production efficiency, that has occurred as engineering design has progressed; and
- An update to the IEA scenario data to align with data from the World Energy Outlook published in November 2019.

The LCA is intended for public release and therefore constitutes a comparative assertion which may be disclosed to the public, invoking specific requirement from the ISO 14044 standard including 3rd party review and a data quality assessment. This public release document is the entire report, except for granular production and emissions data for Browse, Scarborough and shipping which has been removed from Appendix B since it is commercially sensitive.

EXECUTIVE SUMMARY

The purpose of this life cycle assessment (LCA) is to analyse the full life-cycle impacts of liquefied natural gas (LNG) production and utilisation from two proposed Woodside Energy Limited (Woodside) operated gas reservoirs; Browse and Scarborough. The main market for LNG from these reservoirs is Asia Pacific, and in particular China, Japan, Southeast Asia (ASEAN) and India.

This study covers LNG, which is the major product from Browse and Scarborough, but other products including domestic gas, condensate and liquid petroleum gases (LPGs) will all be produced. These other products are not in the scope of this report.

Natural gas is a fossil fuel like coal and oil. However, it can be used more efficiently than other fossil fuels and increasing natural gas contributes to lower greenhouse gas (GHG) emissions when it replaces the burning of coal and oil for power generation, as well as combustion for heat. In Europe, the USA and China, increasing consumption of natural gas has substantially contributed to lower GHG emissions than would have been the case. Gas from the Woodside operated Browse and Scarborough projects is expected to play this role in the four markets under consideration.

As the global energy system changes, driven principally by advancing technology and pressure to curb climate change, tracking an accurate path to the future has become ever more difficult. This report considers different scenarios to assess uncertainty, and to test the role for Browse and Scarborough gas under a range of market conditions, some of which look very different to those of today. For this study, the International Energy Agency (IEA) World Energy Outlook (WEO) scenarios provide an appropriate backdrop. IEA WEO scenarios are revised annually and are broadly considered by industry to be a benchmark of energy scenarios. The three scenarios that comprise the WEO cover a sufficient range of policy, technology and climate outcomes to 2040 (the end of the IEA modelled period), allowing a significant portion of the lifetime of the Browse and Scarborough assets to be considered.

The differences between the IEA WEO Sustainable Development Scenario (SDS), the Stated Policies Scenario (STEPS) and Current Policies Scenario (CPS), are a very important consideration in the analysis. As a goal-driven scenario, the SDS works backwards from a set of specific sustainability-related outcomes, including CO_2e emissions, and builds an energy system of the future, consistent with these goals. By contrast, the STEPS and CPS are more akin to forecasts, projecting forward growth in energy demand and sources from today's market conditions.

The study compares the environmental impacts of electricity generated in the four target markets, using Browse and Scarborough LNG as fuel, to the environmental impact of specific electricity grid mixes in the same markets under each future development scenario. This analysis demonstrates how Browse and Scarborough-sourced gas would compare, either on a grid-average basis (which includes nuclear and renewables), directly against coal-fired generation, or against a portfolio of fossil fuel power sources.

A portfolio of fossil fuel power sources is considered the most appropriate comparison for Browse and Scarborough-sourced gas, for several reasons. Direct competition against coal offers the greatest reduction in emissions, but as the world, and specifically Asia Pacific markets, move to decarbonise, the proportion of coal in the energy mix will inevitably decline. Therefore, the assumption that gas will only ever compete with and offset coal should be treated with caution. So too should the assumption that gas will compete directly with renewables.

Renewable power generation is growing at a fast pace, supported by maturing technology and falling capital investment costs. Renewables have a near zero short run marginal cost, so power is delivered to grids whenever the sun shines or the wind blows. Applicable to all of the markets (apart from China) under consideration, and beyond, is that limits to growth of renewables are more likely to be dictated by physical capacity constraints than economics. All of this indicates that renewables will take their place in power markets, leaving the various fossil sources to compete for the remaining market share.

Table 0-1 shows the LCA potential environmental impact assessment indicator results of climate change, particulate matter, photochemical smog potential and acidification potential. These are presented in the form of equivalents as (CO_2e), ($PM_{2.5}$ e), (NMVOC e) and (H^+e) respectively for electricity produced from LNG sourced from Browse and Scarborough for all four regions, under three different policy scenarios, averaged over the 2026-2040 timeframe.

These results present the default case for Browse and Scarborough LNG for these markets, and do not include any sensitivity assessments. **Table 0-1** results indicate that electricity from LNG has significant benefits in reducing photochemical (ground-level) ozone formation, acidification, and particulate matter in all modelled regions, for both the CPS and STEPS. The benefit of LNG sourced electricity for these non-carbon indicators is much smaller when compared to the SDS. This is to be expected for an energy scenario featuring a large and increasing proportion of renewable sources. Note: annual values of the indicators shown in the table change significantly to 2040, particularly in the case of the SDS.

With regard to the LCA potential environmental impact indicator of climate change (represented by CO_2e), the picture is more nuanced, but still positive. From a power sector emissions intensity perspective, Asia Pacific markets are generally characterised as 'high carbon', featuring a large share of coal in the overall mix. Adding gas from Browse or Scarborough to the power mix is expected to lead to a decline in CO_2e emissions intensity in each market under consideration, to at least 2040.

Table 0-1 LCA Environmental Impact Indicator Results for 1 MWh Electricity Generated from Browse and Scarborough LNG Compared to Fossil Grid Scenarios in China, Japan, ASEAN and India

Region	Scenario	Climate Change t CO_2e	Particulate Matter g $PM_{2.5}$e	Photochemical Smog kg NMVOC e	Acidification mol H^+ e
China	CPS	1.00	1146	3.15	5.67
China	STEPS	1.03	1189	3.25	5.87
China	SDS	1.03	1149	3.18	5.70
China	LNG Browse	0.56	36	0.56	0.42
China	LNG Scarborough	0.49	36	0.46	0.40
Japan	CPS	0.70	222	1.68	4.03
Japan	STEPS	0.69	213	1.63	3.82
Japan	SDS	0.57	135	1.12	2.23
Japan	LNG Browse	0.50	24	0.51	0.37
Japan	LNG Scarborough	0.44	23	0.41	0.36
ASEAN	CPS	0.79	669	1.68	4.32
ASEAN	STEPS	0.77	631	1.62	4.10
ASEAN	SDS	0.64	394	1.18	2.71
ASEAN	LNG Browse	0.57	100	0.58	0.44
ASEAN	LNG Scarborough	0.49	100	0.47	0.42
India	CPS	0.96	715	2.65	4.90
India	STEPS	0.99	754	2.77	5.15
India	SDS	0.76	473	1.93	3.42
India	LNG Browse	0.57	37	0.67	0.52
India	LNG Scarborough	0.49	36	0.56	0.50

This study assumes distribution of Browse and Scarborough gas into the target markets of China (31%), Japan (24%), ASEAN (27%), India (19%). Browse and Scarborough gas is assumed to be displacing fossil-generated electricity under all three scenarios. **Table 0-2** shows that Browse and Scarborough gas, if used to generate power in the target markets, will release approximately 913 Mt CO_2e over the 2026 – 2040 period (circa. 595 Mt CO_2e from Browse and 318 Mt CO_2e from Scarborough). Differences in **Table 0-2** between the STEPS and CPS scenarios are due to slightly different implied emissions intensities. This in turn is a result of the different balance of power generation technologies utilised in each scenario.

By contrast, if the broad fossil fuel mix forecast by the IEA is used to generate electricity in the target markets, then emissions are much higher. Under the STEPS, the baseline total is 1514 Mt CO_2e (936 Mt CO_2e Browse, 577 Mt CO_2e Scarborough). Under the CPS, the fossil balance of the power grids in the target markets are more biased towards coal relative to the STEPS. Thus, the baseline total under this scenario is 1528 Mt CO_2e from 2026 – 2040 (945 Mt CO_2e Browse, 583 Mt CO_2e Scarborough).

This means that using Browse and Scarborough gas to generate power in the target markets, results in avoided emissions of 601 Mt CO_2e under the STEPS (i.e. 1514 less 913), and 620 Mt CO_2e under the CPS (i.e. 1528 less 908). Of the approximately 913 Mt CO_2e of life cycle emissions associated with Browse and Scarborough gas, around 159 Mt CO_2e is associated with the production of the LNG in Australia. The remainder of the life cycle emissions and all of the avoided emissions will occur in the jurisdiction where the LNG is consumed. The ratio of production emissions in Australia to avoided emissions across the life cycle is 159:601 (STEPS) or 159:620 (CPS), or 1:3.8 and 1:3.9 respectively. In other words for every 1 Mt CO_2e associated with the production of Browse and Scarborough LNG in Australia, approximately 4 Mt CO_2e of net emissions to the global atmosphere would be avoided.

Grids are envisaged to be significantly more progressed in their decarbonisation pathways in the SDS than in the other two scenarios. Therefore, avoided emissions – are 345 Mt CO_2e over the 2026 – 2040 period.

Table 0-2 also takes into account the use of CO_2e offsets for Browse and Scarborough, used to offset the volumes of CO_2 vented at the well. Use of offsets effectively lowers emissions by a further 50 Mt CO_2e for Browse, and 0.2 Mt CO_2e for Scarborough. Avoided emissions are therefore 651 Mt CO_2e compared to the fossil power baseline under the STEPS, and 670 Mt CO_2e compared to the fossil power baseline under the CPS. If the same displacement assumptions were made for the SDS, avoided emissions would be 395 Mt CO_2e over the 2026 – 2040 period.

Table 0-2 Mt CO_2e Emitted / Saved by Browse and Scarborough LNG from 2026 to 2040 Compared to Fossil Grids, under Three Policy Scenarios

Emissions Description	CPS Fossil	STEPS Fossil	SDS Fossil
Emissions from Browse-sourced power	592	595	591
Emissions of baseline scenario (fossil grid)	945	936	771
Browse CO_2e offsets	-50	-50	-50
Browse avoided emissions (no offsets)	***-354***	***-342***	***-181***
Browse avoided emissions (including offsets)	***-404***	***-392***	***-231***
Emissions from Scarborough-sourced power	316	318	316
Emissions of baseline scenario (fossil grid)	583	577	481
Scarborough CO_2e offsets	-0.2	-0.2	-0.2
Scarborough avoided emissions (no offsets)	***-267***	***-259***	***-165***
Scarborough avoided emissions (including offsets)	***-267***	***-259***	***-165***
Total Emissions from Browse and Scarborough-sourced power	**908**	**913**	**907**
Total Emissions of baseline scenario (fossil grid)	**1528**	**1514**	**1252**
Total avoided emissions (no offsets)	***-620***	***-601***	***-345***
Total avoided emissions (including offsets)	***-670***	***-651***	***-395***

The results from the LCA identify that LNG based electricity supply into Asia Pacific will improve air quality outcomes compared to the IEA's assumptions about the fossil grid under all scenarios. Particulate matter emissions are much higher than those from LNG under any of the scenarios assessed.

For climate change, LNG impacts vary through time, and are sensitive to factors such as the relative levels of coal, gas and renewables on power grids.

1. INTRODUCTION

1.1 Background

The twin challenges of decarbonisation and rapidly-maturing alternative technologies have upset the balance of energy commodity markets in recent years. Uncertainty over demand, price, and market landscape is a challenge for energy producers worldwide. Companies are now expected, by capital markets and regulators, to show how current and planned investments perform under a range of future market conditions, some of which are a radical departure from the conditions of today.

The purpose of this report is to assess the life-cycle impacts of LNG production and utilisation from Browse and Scarborough, two proposed gas developments held by different joint ventures where Woodside is the operator. The main market for LNG from these projects is Asia Pacific, and in particular China, Japan, Southeast Asia (ASEAN) and India. The study compares the life cycle CO_2e emissions of electricity generated in these markets from Browse and Scarborough LNG to the CO_2e emissions of specific electricity grid mixes in the same markets. This analysis demonstrates how Browse and Scarborough-sourced gas would compete in the power markets under consideration, either on a grid-average basis, directly against coal-fired generation, or against a portfolio of fossil fuel power sources.

A portfolio of fossil sources is considered the most appropriate comparator for Browse and Scarborough-sourced gas, for several reasons. Direct competition against coal offers the greatest emissions benefits, but as the world (and specific to this analysis, markets in Asia Pacific) move to decarbonise, the proportion of coal in the energy mix will inevitably decline. Therefore, the assumption that gas will only ever compete with coal should be treated with caution. So too should the assumption that gas will compete directly with renewables. The latter form of power generation is growing at a fast pace, supported by maturing technology, falling capital investment costs and, in many regions, a generous subsidy regime. Renewables have a near zero short-run marginal cost, so power is delivered to grids whenever the sun shines or the wind blows. Limits to growth are more likely to be dictated by physical capacity constraints, than economics relative to other energy sources. All of this indicates that renewables will take their place in power markets, leaving the various fossil sources to compete for the remaining market share.

Scenarios used in this assessment are drawn from the International Energy Agency World Energy Outlook (IEA WEO) 2019 and cover a business-as-usual outlook (Current Policies Scenario), a central case (Stated Policies Scenario) and a lower-carbon outlook (Sustainable Development Scenario). Note, these scenarios are not forecasts, but assessments of how global and regional energy markets could look under a range of policy environments.

The study has been undertaken following the requirements of the International Organization for Standardization (ISO) Standard 14044, Environmental Management Standard – Life Cycle Assessment, 2006 (International Organization for Standardization 2006).

1.2 Audience

The primary audience for the study is Woodside Energy Limited (Woodside), with the potential to extend it to licensing and regulation bodies and the public. As released to the public, the study would constitute a public comparative assertion according to ISO 14044.

1.3 Life Cycle Assessment

Life Cycle Assessment (LCA) is a method for assessing the full 'cradle-to-grave' environmental impacts and benefits of products and processes by assessing environmental flows (i.e. impacts) at each stage of the life cycle. LCA aims to include all important environmental impacts for the product system being studied. In doing so, LCA seeks to avoid shifting impacts from one life cycle stage to another, or from one environmental impact to another. The method and guidance for undertaking life cycle assessment follows the international standards ISO 14040:2006 and ISO14044:2006

(International Organization for Standardization 2006). The general structure of the LCA framework is shown in **Figure 1-1**. Each stage of the LCA interacts with other stages.

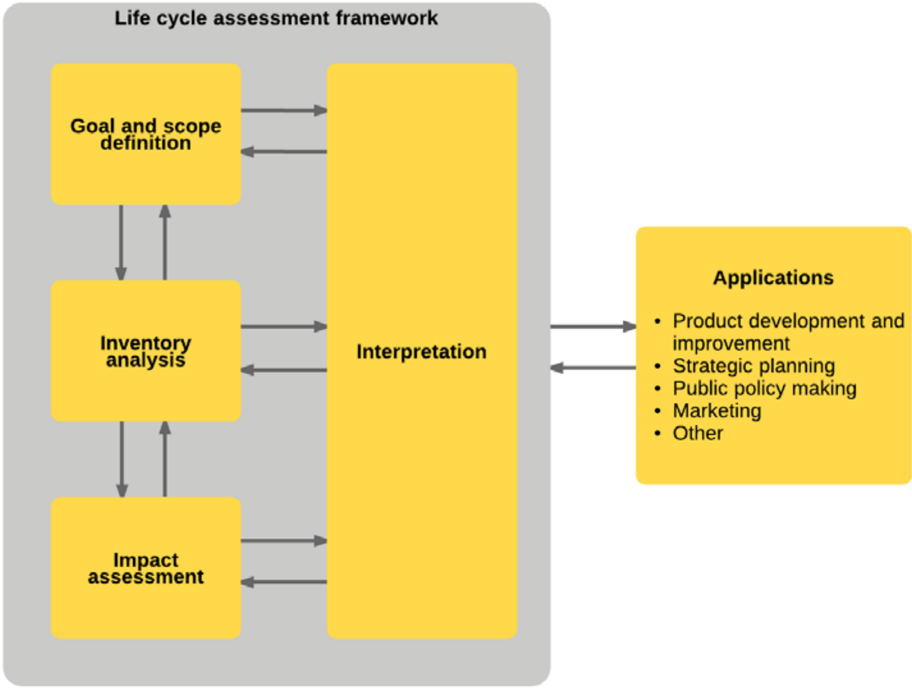


Figure 1-1 Framework for LCA from ISO 14040

The first stage in the LCA framework (goal and scope definition) describes the reasons for the LCA, the scenarios, boundaries and indicators used. The second stage (inventory analysis) builds a model of the production systems involved in each scenario and describes how each stage of the production process interacts with the environment. The third stage (impact assessment) assesses the inventory data against key indicators to produce an environmental profile of each scenario. The final stage (interpretation) analyses the results and undertakes systematic checks of the assumptions and data to ensure robust results.

2. IEA SCENARIOS: ILLUSTRATING A PATH TO DECARBONISATION

As the global energy system changes, driven by advancing technology and pressure to curb climate and other environmental impacts, tracking an accurate path to the future has become ever more difficult. Scenarios are a useful tool to assess uncertainty. They may describe differing economic or demographic or technological futures, but what is critical is that the chosen views of the future illustrate a range of outcomes under which the investments under consideration may be expected to function.

This section provides an overview of the scenarios contained in the 2019 edition of the IEA WEO. These scenarios have been used in this report to test the proposed Browse and Scarborough developments against a range of future market conditions.

For this study, the IEA WEO scenarios provide an appropriate backdrop. IEA WEO scenarios are revised annually, and are broadly considered to be the benchmark of energy scenarios. The three scenarios that comprise the WEO (details below) cover a sufficient range of policy, technology and climate outcomes over the years to 2040, allowing a significant portion of the lifetime of the Browse and Scarborough assets to be considered.

The study uses an energy mix directly drawn from IEA data, and power generation efficiencies calculated from IEA data but not published by them.

2.1 Current Policies Scenario

The Current Policies Scenario (CPS) is the IEA's business as usual outlook. This scenario assumes no change (i.e. no additional) policy from that of today. Energy demand continues to grow through to 2040, and much of this demand growth is met by fossil fuels. Meeting energy demand at lowest cost is a priority, especially in emerging markets, and environmental concerns are secondary. Global CO_2e emissions exceed 40 billion tonnes per year by 2040, and the world is on track for significant global warming.

2.2 Stated Policies Scenario

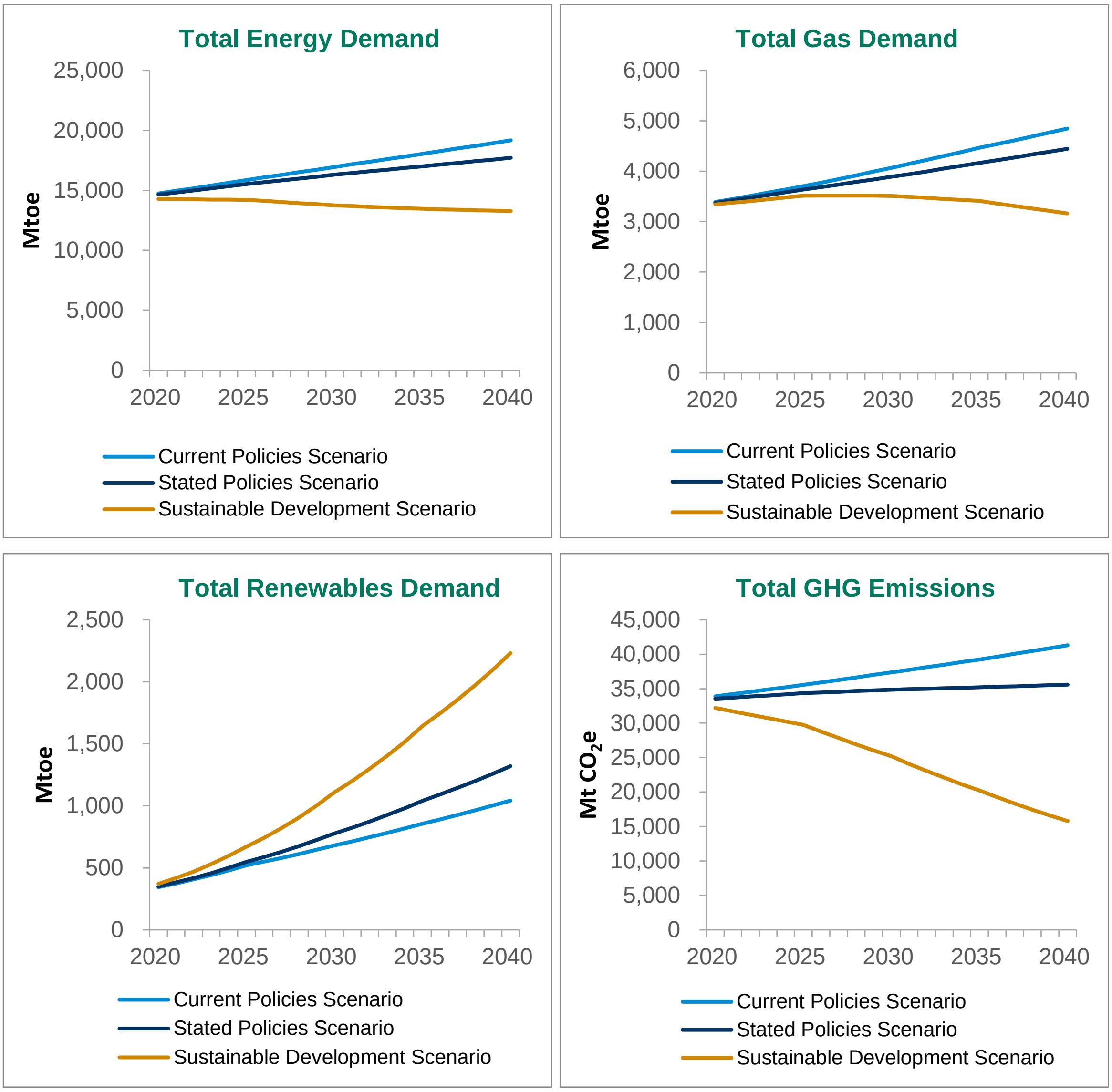
The Stated Policies Scenario (STEPS) is the IEA's central case. The STEPS accounts for policies and measures announced even if they have not yet been enacted by governments. The STEPS delivers a world which is broadly consistent with the aggregated Nationally Determined Contributions (NDCs) under the Paris Agreement. However, these NDCs are not yet strict enough to reverse emissions growth or keep global warming below 2^{o}C. Nevertheless, the STEPS does see additional decarbonisation relative to the CPS, including a shift to greater use of gas and renewables.

2.3 Sustainable Development Scenario

The Sustainable Development Scenario (SDS) envisages a radical change in the supply and consumption of energy, such that global CO_2e emissions peak in 2020 and decline sharply thereafter. The SDS is consistent with the ultimate goals of the Paris Agreement, to keep global warming below 2^{o}C, alleviate energy poverty and improve air quality in line with the UN Sustainable Development Goals. Unlike the CPS and STEPS, the SDS works backwards from these goals, to map a path to that future from the present day.

To achieve this lower-carbon future, the world shifts wholesale to lower carbon energy. The SDS is therefore often a challenging future for fossil fuel demand. This includes gas, demand for which plateaus between 2025 and 2030 before falling into decline. However, markets in Asia Pacific are expected to see demand growth to 2035 even under this lower-carbon scenario. This in turn is expected to be supportive of LNG demand.

Key metrics from the three scenarios are shown in **Figure 2-1.** Energy demand, defined as Total Primary Energy Demand (TPED), is shown in million tonnes of oil equivalent (Mtoe) and GHG emissions are presented in million tonnes (Mt CO_2e).



Source: IEA WEO 2019

Figure 2-1 Global Energy, Gas and Renewables Demand; Global CO_2e Emissions, IEA Scenarios 2020 – 2040

3. CASE STUDY: NATURAL GAS AS A DECARBONISATION FUEL IN EUROPE, THE USA, AND CHINA

Natural gas has the lowest carbon content of the fossil fuels. When combusted in a power plant, natural gas typically emits around half the amount of carbon dioxide (CO_2) per unit of power generated, compared to coal.[1] When combusted, natural gas also emits around 98% less carbon monoxide (CO), sulphur dioxide (SO_2), nitrous oxide (N_2O), and particulate matter than coal. Increasing natural gas use tends to contribute to lower GHG emissions, as it can replace the burning of coal and oil for power generation. Natural gas is also increasingly used as a substitute for petroleum fuels in petrochemicals.

When considering the role gas from Browse and Scarborough may play in the energy systems of the markets where it will be consumed, it is useful to examine case studies of markets where increasing consumption of gas has contributed to lowering emissions growth. This has occurred in Europe, the USA and China, but at different times, and for different reasons.

In Europe, the USA, and China, gas demand has been increasing steadily since the early 1980s, as shown in **Figure 3-1**. In Europe, gas demand steadily increased from around 1970 to 2008, but it has wavered slightly since then, in part due to the relative low pricing of coal following the near collapse of the EU Emissions Trading Scheme. The USA has always been a large consumer of natural gas (for domestic and industrial use), although demand increased again from around 2006, following the emergence of unconventional gas as a supply source. In China, gas demand has been increasing since the early 2000s, supported by a growing economy, and more recently a drive to improve local air quality.

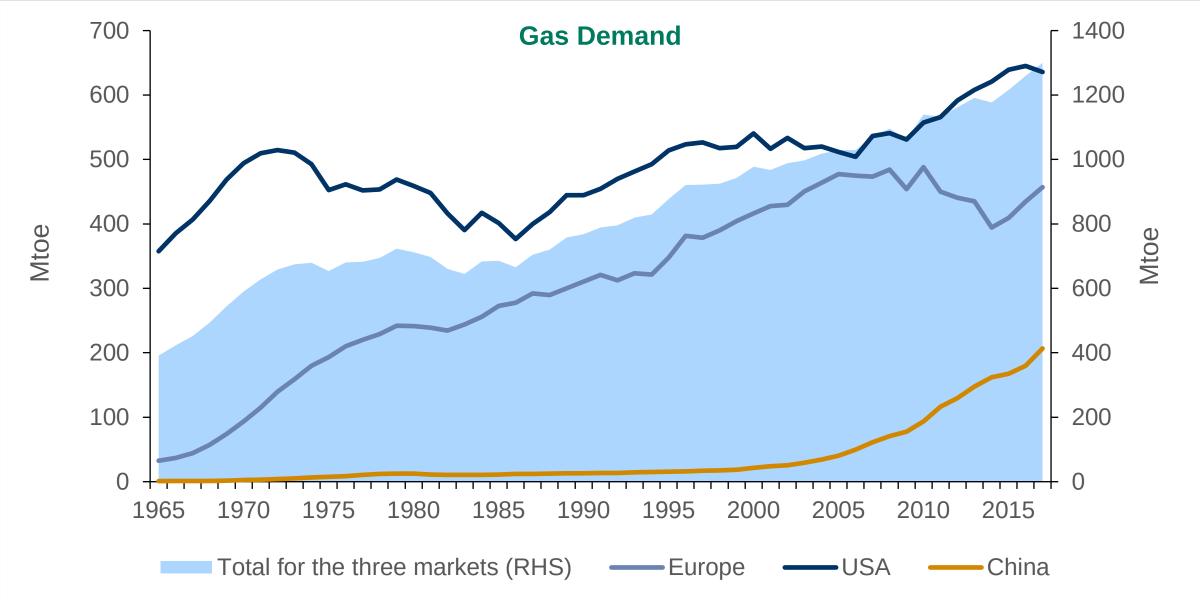


Figure 3-1 Natural Gas Demand in Europe, the USA, and China, 1965 to 2017

(Source: BP Statistical Review of World Energy, 2018)

3.1 Europe

While European gas demand had grown during the 1970s, it was not until the beginning of the 1990s that demand for gas began to be widespread across the continent. Simultaneously, key consumers, including the UK, began a ‘dash for gas’ which almost doubled demand for the fuel in the space of ten years.

[1] In 2017, gas: 0.506 Mt CO_2/TWh; coal: 0.996 Mt CO_2/TWh. Source: IEA World Energy Outlook 2018

The transition of the UK from coal to gas clearly illustrates the effect of increasing gas consumption on GHG emissions. Gas consumption in the UK started to grow from the early 1970s, much in line with the European trend. The initial increase was due to natural gas substitution into homes for both cooking and heating, as well as increasing industrial use.

A second period of increasing consumption occurred from 1990. This ‘dash for gas’ occurred due to several key changes in the UK energy market:

- The UK electricity industry was privatised in 1990, and this led to changing regulation which permitted the use of natural gas as a fuel in power generation;
- Natural gas power stations were smaller and quicker to build than coal and nuclear plants which made them more attractive financially due to the high interest rates at the time;
- Developments in generation technology meant combined cycle gas turbines (CCGTs) were economically attractive due to their higher efficiency and lower capital costs; and
- Wholesale natural gas prices were falling as supply increased, predominantly from the North Sea.

At this point therefore, it was not a climate change policy which encouraged the use of natural gas. Growth in the 1990s was market-led, driven by the electricity sector, this is shown in **Figure 3-2** below. Lines (read from the LH axis) show power generation by fuel, while the shaded area (read from the RH axis) shows sectoral CO_2e emissions.

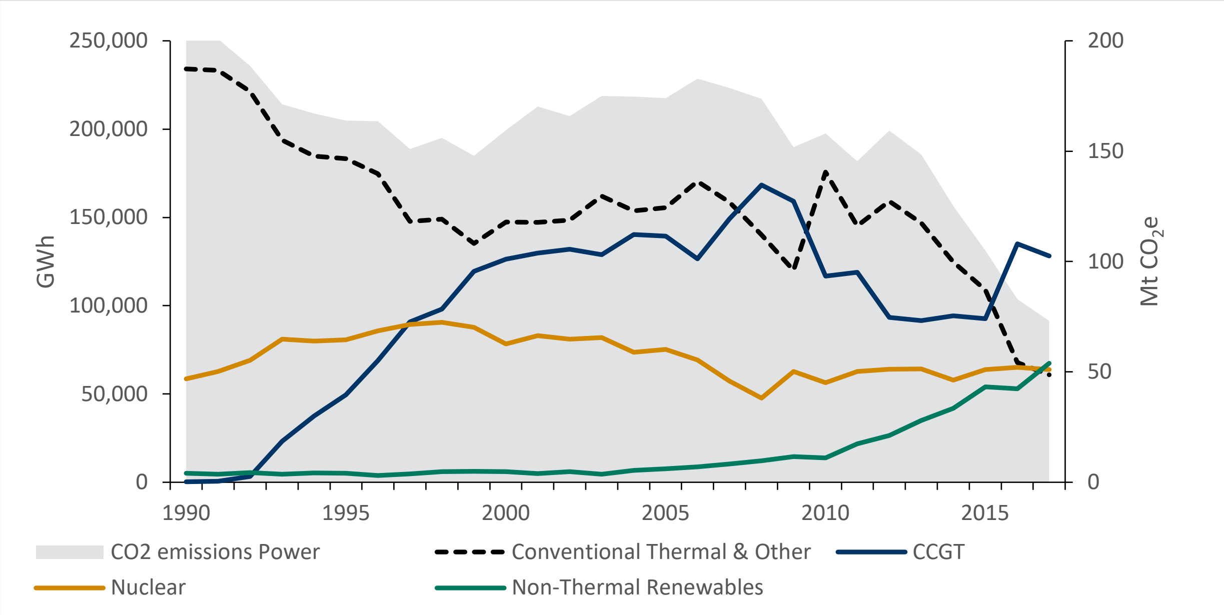


Figure 3-2 UK Power Gen. by Fuel and Sectoral CO_2e Emissions (RHS), 1990 – 2017

(*Source: UK Department for Business, Energy and Industrial Strategy)*

Figure 3-2 also shows the inverse relationship between natural gas (marked on the chart as CCGT) and coal power generation (included on the chart in Conventional Thermal and Other). Natural gas generation increased throughout the 1990s, rising from 1.6% in 1990 to just under 40% of total generation by 2000. This led to a decrease in coal generation of 42% from 1990 to 2000. As **Figure 3-2** shows, power generation from natural gas and coal have largely been in equilibrium since 2000; as one has increased, the other has decreased, often in equal volumes. This change has been mostly driven by profit margin differences between natural gas and coal power generation, known as 'spark spreads' and 'dark spreads'[2], respectively.

Before carbon pricing, coal to natural gas switching was driven by wholesale price differences. Since 2005 however, when the EU Emissions Trading Scheme (ETS) began, power generators have also had to factor in the costs of purchasing carbon allowances under the scheme. This is known as the 'clean spark spread' and the 'clean dark spread' for natural gas and coal, respectively. The carbon cost is proportional to the efficiency of the generation type, meaning natural gas is cheaper in terms of carbon allowances.

The difference between the clean spark spread and the clean dark spread is known as the 'climate spread'. After the global financial crisis issues with the EU ETS (allowances far in excess of demand) meant that carbon prices were not high enough to stimulate coal to natural gas generation switching. Fluctuations in the wholesale costs of natural gas and coal also meant that there have been instances since 2005 when the volume of coal generation has moved back above natural gas. This was most noticeable in the period around 2012 when high natural gas prices favoured coal generation. This often led to a subsequent increase in emissions, which can also be seen in **Figure 3-2**. It is clear, therefore, that since 2000 in the UK, natural gas has played a key role in halting the volume of emissions from coal generation.

Today, gas is playing a new role. Since the oil price crash of 2014, wholesale natural gas prices have been low enough to stimulate lasting coal to natural gas switching. However, a new dynamic is at play: generation from renewables. This has been accelerated by climate change policies and regulatory changes which have facilitated the build out of renewables at massive scale.

Renewables now occupy a 28% share of the UK electricity market, up from less than 5% in 2000. Natural gas is holding on to its 40% share by virtue of providing balancing generation for intermittent renewable generation, such as onshore wind power. Natural gas has excellent suitability for this role because gas generation can be ramped up and down much more easily than coal or nuclear generation. The long-term viability of this is dependent on the type of plant used to generate power from natural gas. But nevertheless, natural gas generation in the UK looks set to become a facilitator for the next wave of emissions reduction which will see coal all but leave the generation mix, replaced by onshore and offshore wind, and photovoltaic solar.

3.2 USA

In the USA, the recent growth of natural gas consumption is a story all about supply. The development of unconventional onshore oil and gas resources since around 2006 has led to a 46% increase in natural gas production to 2017, as shown in **Figure 3-3.** This has had extensive knock-on effects for the domestic energy market.

[2] The 'spark spread' is the gross margin of a gas fired power plant selling one unit of power. The 'dark spread' is the same margin for a coal fired power plant. 'Clean spark' and 'clean dark' spreads are similar margins for the two fuels, but also accounting for costs of carbon allowances.

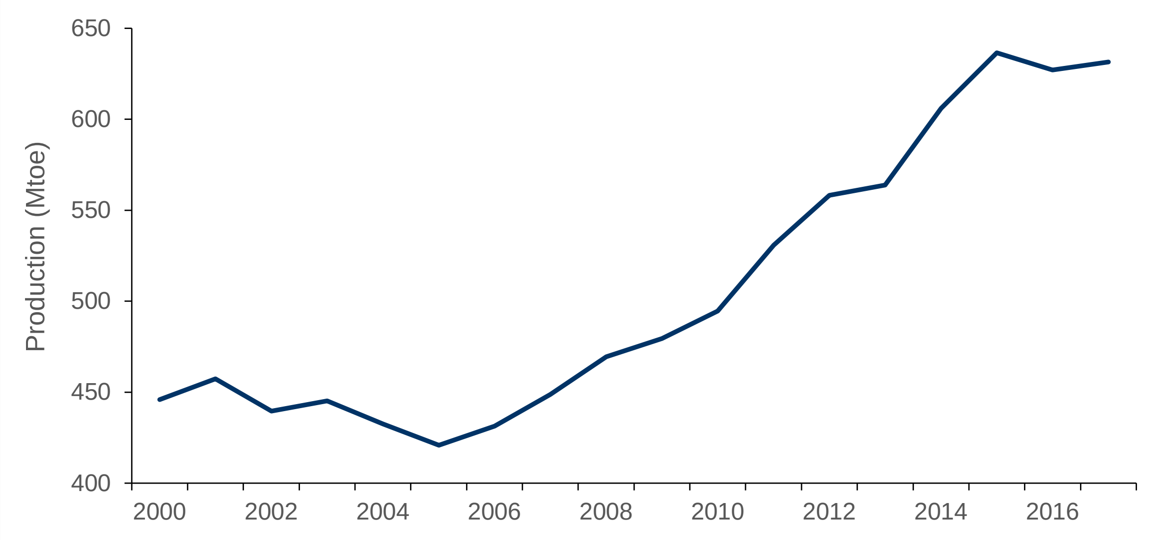


Figure 3-3 Natural Gas Production in the USA from 2000 to 2017

(Source: BP Statistical Review of World Energy, 2018)

Prior to the large-scale development of unconventional resources, the US energy sector had been anticipating an upcoming shortage of natural gas supply. This had led several companies to begin developing LNG regasification plants for import. Cheniere, for example, had begun development of import facilities at Sabine Pass and Corpus Christi on the Gulf Coast. Once the scale of the unconventional natural gas opportunity was realised however, these projects were reconfigured for LNG liquefaction and export.

The availability of natural gas in these volumes meant that prices fell dramatically. This stimulated power generators, faced with a period of relatively high coal costs and impending climate change-related regulations, to begin investing in natural gas. **Figure 3-4** shows the increase in natural gas generation, which, similarly to Europe, has reduced the market share of coal by around 38% since 2007, as well as contributing to power sector GHG emissions which are nearly 30% lower.

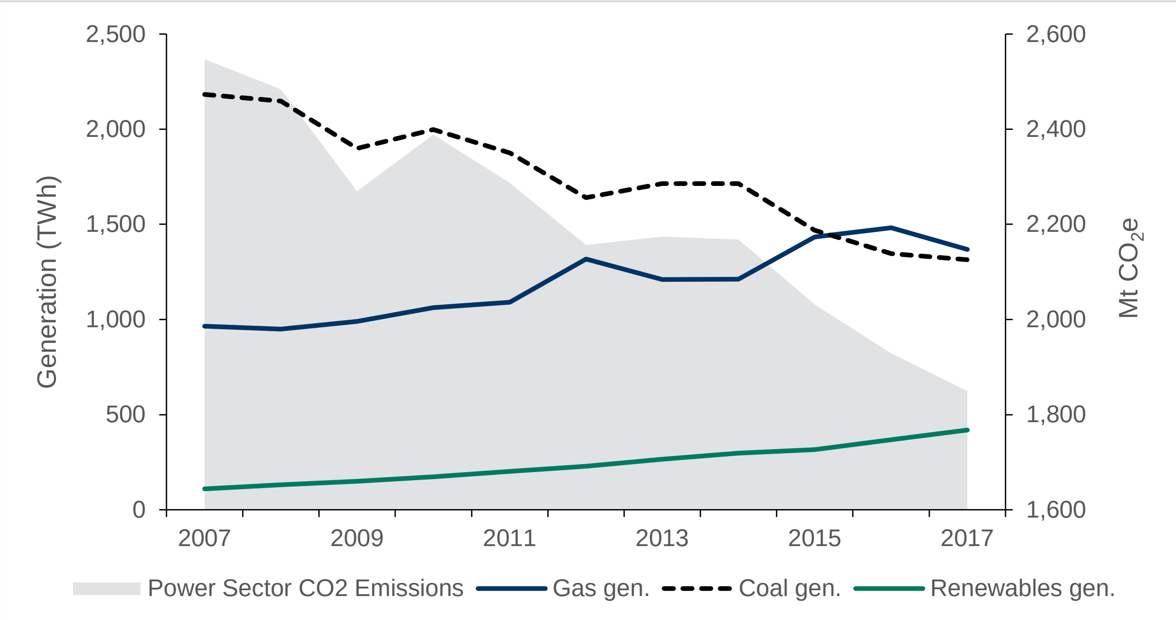


Figure 3-4 USA Power Generation and National Emissions (RHS) from 2007 – 2017

(Source: Generation from BP Statistical Review, 2018; Power sector emissions from the IEA)

Therefore, coal to natural gas switching in the US power sector is mostly a result of commodity prices, although in some state jurisdictions, for example California, there are carbon pricing mechanisms which also play a role. The reduced market share of coal generation has caught the headlines in recent times; with so much cheap natural gas available, the market has struggled to respond to the drive for coal on purely economic terms.

While there are considerable differences at the state level, the US power sector is in much the same situation as the UK was around 2006. The prominence of renewables is growing, spurred on by nearing cost parity with other generation sources. It's likely that natural gas will continue to take market share from coal, before having a longer term role as backup generation for renewables.

3.3 China

China has only ever had relatively limited natural gas resources. In 2017, China produced 60% of the natural gas it consumed, but natural gas was only 7% of total primary energy consumption, and 3% of power generation. This means that if natural gas consumption is to continue to increase, it is likely that much more natural gas will have to be imported either via pipeline, or in the form of LNG.

A national carbon pricing scheme will come into force in China in 2020. Despite this, the primary reason for China's domestic action on emissions is because of urban air pollution. Policy and regulation have primarily been developed to target this, as opposed to being exclusively climate change related. Nevertheless, the result is the same – a reduction in emissions of GHGs and particulates.

China's urban air pollution problem mainly comes from the dominance of coal in the energy and industrial sectors, although low emissions standards for vehicles is also a contributing factor. In 2017, coal met 60% of China's primary energy needs. However, this is reduced from over 70% a decade ago. Moreover, part of the reason for that decline is due to the growing consumption of natural gas, as well as the mass development of nuclear and hydro power, and, more recently, renewables.

The sheer scale of economic growth that has occurred in China over the last two to three decades has meant China pulling all levers available to meet energy demand. Due to large natural reserves, coal was developed first. Now, China is in a situation where economic growth has slowed, and efforts can be made to address air pollution and climate change goals.

Natural gas consumption in China is not just driven by the power sector; industry and manufacturing will also play a large role. Already, natural gas consumption has increased by more than 870% since 2000, albeit from a low starting point. This trend looks set to continue as natural gas will gradually be favoured over coal for generating not just power, but also heat. **Figure 3-5** shows the ever-increasing role of natural gas, hydro, and renewables in contributing to lowering the emissions intensity of the Chinese economy. The changing balance of the Chinese economy from industry to services is a factor in falling intensity, but the most recent decline (since 2007), coincides with a retrenchment in coal's share of the total energy mix, as other fuels gain in importance.

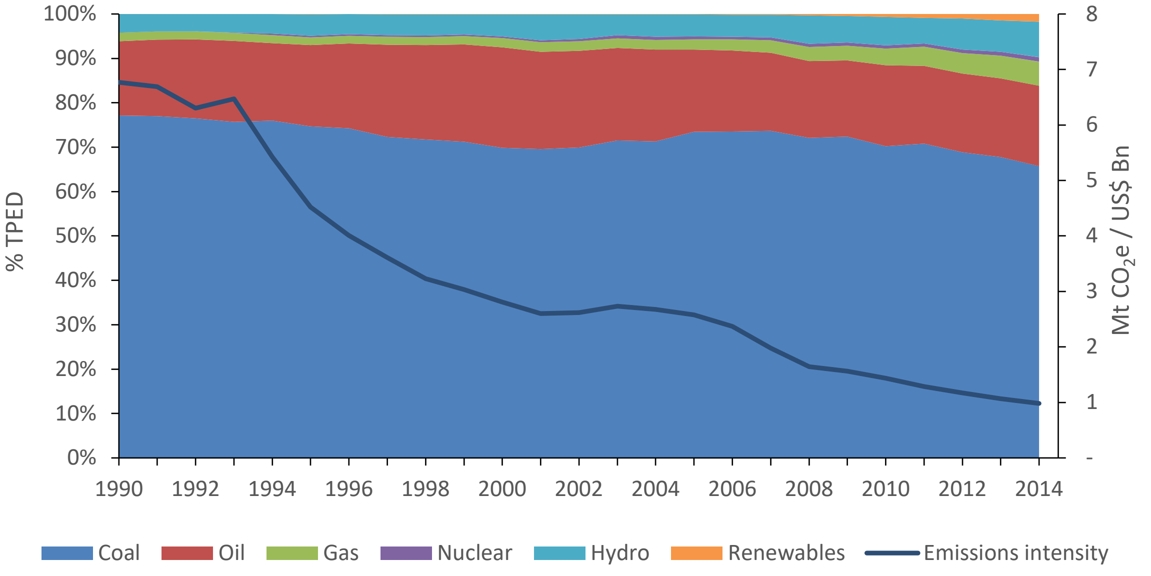


Figure 3-5 Share of Total Primary Energy Demand (TPED) and GHG Emissions Intensity in China, 1990 – 2014

(Source: Generation from BP Statistical Review, 2018; Emissions intensity from the World Bank)

Nevertheless, in 2014, China's economy was still around six times more carbon intensive than Europe's. This means that China still has a considerable carbon burden it needs to shift in order to achieve its climate change goals. Therefore, it is likely that the natural gas story in China has a considerable way yet to run. Upcoming national carbon pricing will also provide a boost to natural gas demand. As China lacks the domestic supply of the USA, this will support demand for imported natural gas.

3.4 Conclusion

Natural gas has played a varying role in the three markets considered, but in all of them it has substantially contributed to decarbonisation as a point of empirical fact. In Europe, natural gas began to displace coal generation from 1990 onwards, driven by changing regulation, growing supply availability, commodity prices, and later climate change policy; all leading to a decline in GHG emissions. Natural gas will now play a role in facilitating the development of renewable generation, further supporting the effort to decarbonise.

In the USA, natural gas demand has grown since the mid-2000s and the advent of readily available, low cost supply from unconventional domestic gas resources. Despite a changing regulatory environment, the USA has followed a similar trend to Europe, with natural gas power generation outcompeting coal on cost, lowering GHG emissions.

China will follow a slightly different pathway, in part due to limited natural resource availability and the timing of its climate change action. Essentially, China has 'early access' to renewable generation, which Europe and the USA were lacking when initial efforts to decarbonise were made. But China is also, by far, the largest energy market in the world, and even at relatively slow rates of annual growth will continue to build phenomenal demand in absolute terms. China's path to decarbonisation must therefore make use of all tools. Coal to gas switching is an essential strategic goal, as the examples of Europe and the USA make clear, and will complement China's ability to build out renewables at scale seen nowhere else in the world. Ultimately, it is the scale of China's emissions problem that will boost demand for natural gas.

4. GOAL AND SCOPE OF THE LCA

4.1 Goal

The goal of this report, as described in Section 1, is to assess the life cycle impacts of LNG production and utilisation from two proposed gas developments; Browse and Scarborough. The main market for LNG from these developments is Asia Pacific, and in particular China, Japan, Southeast Asia (ASEAN) and India. The main use of LNG in these markets is electricity generation, and is the focus of the LCA study. The LCA follows the ISO 14044 requirements, although the structure of the report has been arranged to aid understanding by a non-LCA audience.

The LCA was commissioned by Woodside, undertaken by ERM and Lifecycles and has been critically reviewed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO). The LCA is intended for public release and therefore constitutes a comparative assertion which may be disclosed to the public, invoking specific requirement from the ISO 14044 standard including 3rd party review and a data quality assessment. This public release document is the entire report, except for granular production and emissions data for Browse, Scarborough and shipping which has been removed from Appendix B since it is commercially sensitive.

4.2 Functional Unit

The international standard on LCA describes the functional unit as defining what is being studied, and states that all analysis should be relative to the functional unit. The definition of the functional unit needs to clearly articulate the functionality or service that is under investigation. In this study, the functionality is the supply of electricity in different Asia Pacific markets over the period 2026 -2040.

The functional unit used for this assessment is:

“the supply of 1 MWh of electricity entering the grid from generators in the World, Chinese, Japanese, the ASEAN[3] and Indian markets between 2026 and 2040.”

The scenarios to be assessed are:

- Average, fossil fuel and coal only grid mixes under the IEA Current Policies Scenario (CPS);
- Average, fossil fuel and coal only grid mixes under the IEA Stated Policies Scenario (STEPS);
- Average, fossil fuel and coal only grid mixes under the IEA Sustainable Development Scenario (SDS);
- Electricity supplied from LNG sourced from Scarborough; and
- Electricity supplied from LNG sourced from Browse.
- For analytical purposes a reference unit of 1 gigajoule of delivered gas to market is also used to compare the results from Scarborough and Browse in **Figure 6-8** and **Figure 6-9**.

4.3 System Boundary

The system boundary describes the life cycles, stages and processes included in the LCA; **Figure 4-1** shows the boundary of the system representing the production of LNG from Scarborough used for electricity generation. Note there is one coproduction stream with the production of condensate at the onshore LNG plant. **Figure 4-2** shows the boundary of the system representing electricity produced from LNG sourced at Browse gas field, which has three co-product streams – one offshore being condensate, and two onshore – the first being, propane and butane, with the second co-production between domestic gas and gas used for LNG production and export. **Figure 4-3** represents a generic system diagram for the other electricity sources, both thermal and renewable, used for the comparative scenarios. The analysis uses the same general boundary where applicable for all scenarios, including infrastructure production, fuel extraction, processing and power plant operation.

[3] The IEA state that ASEAN region includes the following ten countries - Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Vietnam

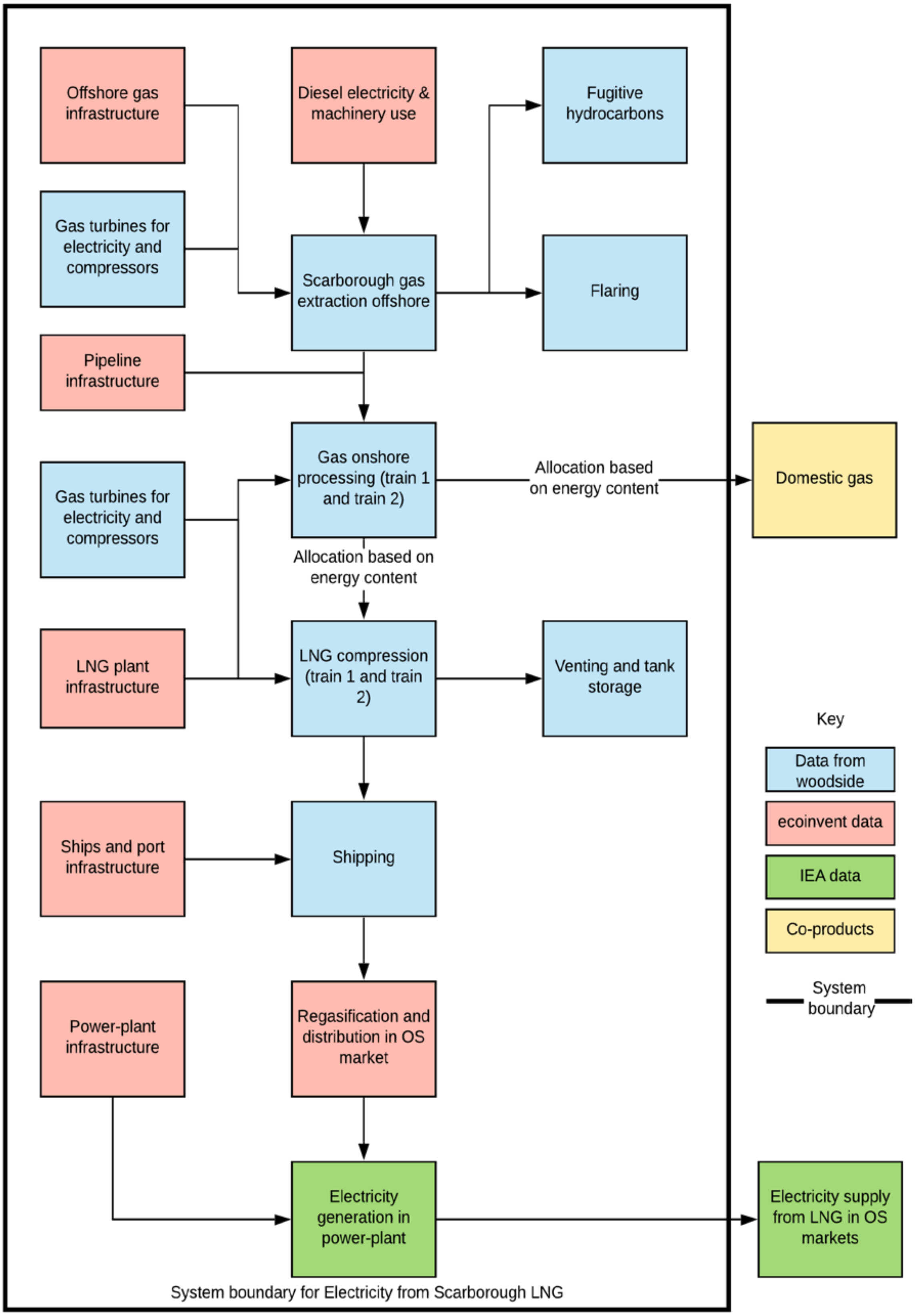


Figure 4-1 System Boundary for the Electricity Production from LNG Sourced from Scarborough Gas Field

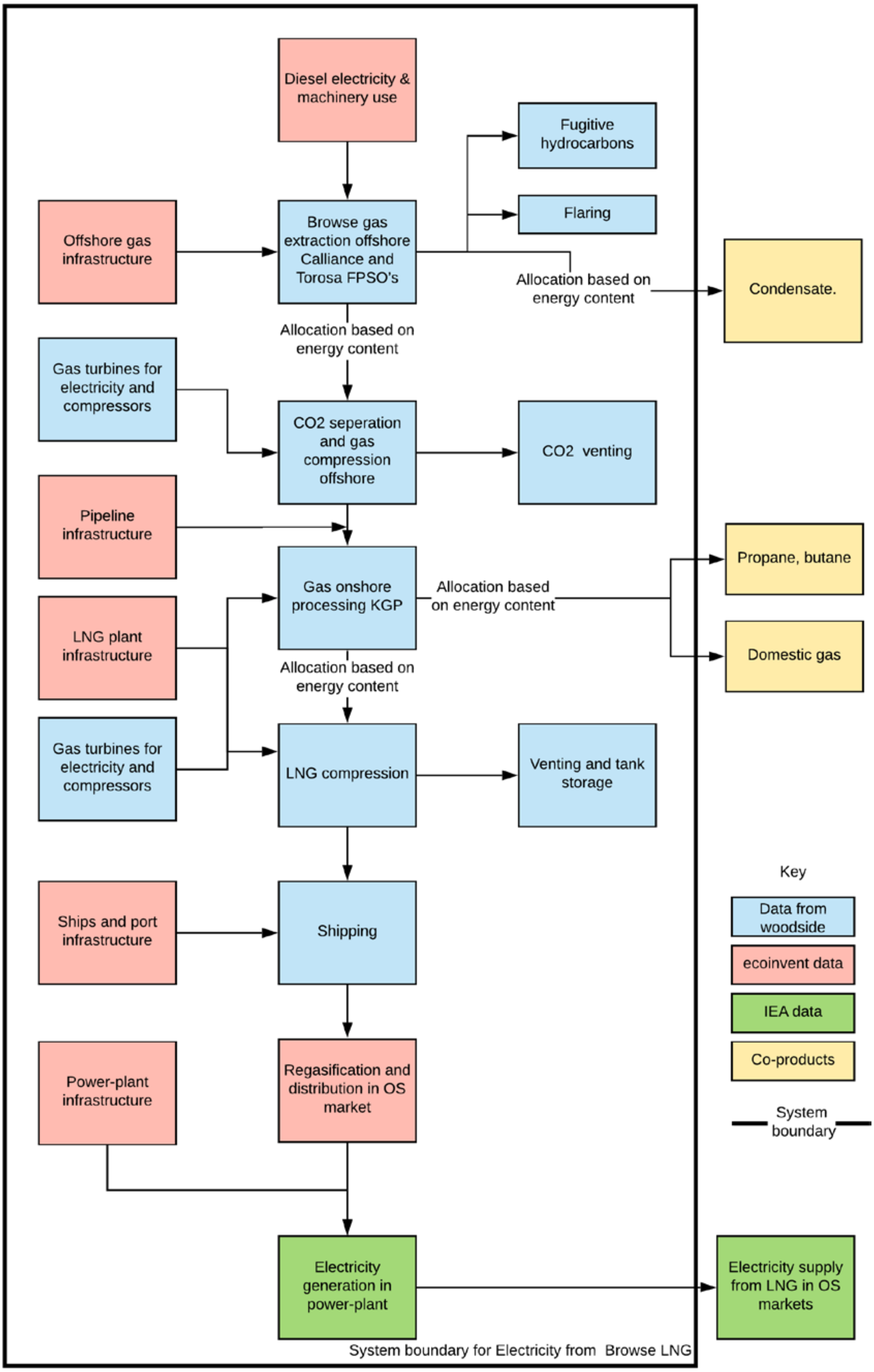


Figure 4-2 System Boundary for the Electricity Production from LNG Sourced from Browse Gas Field

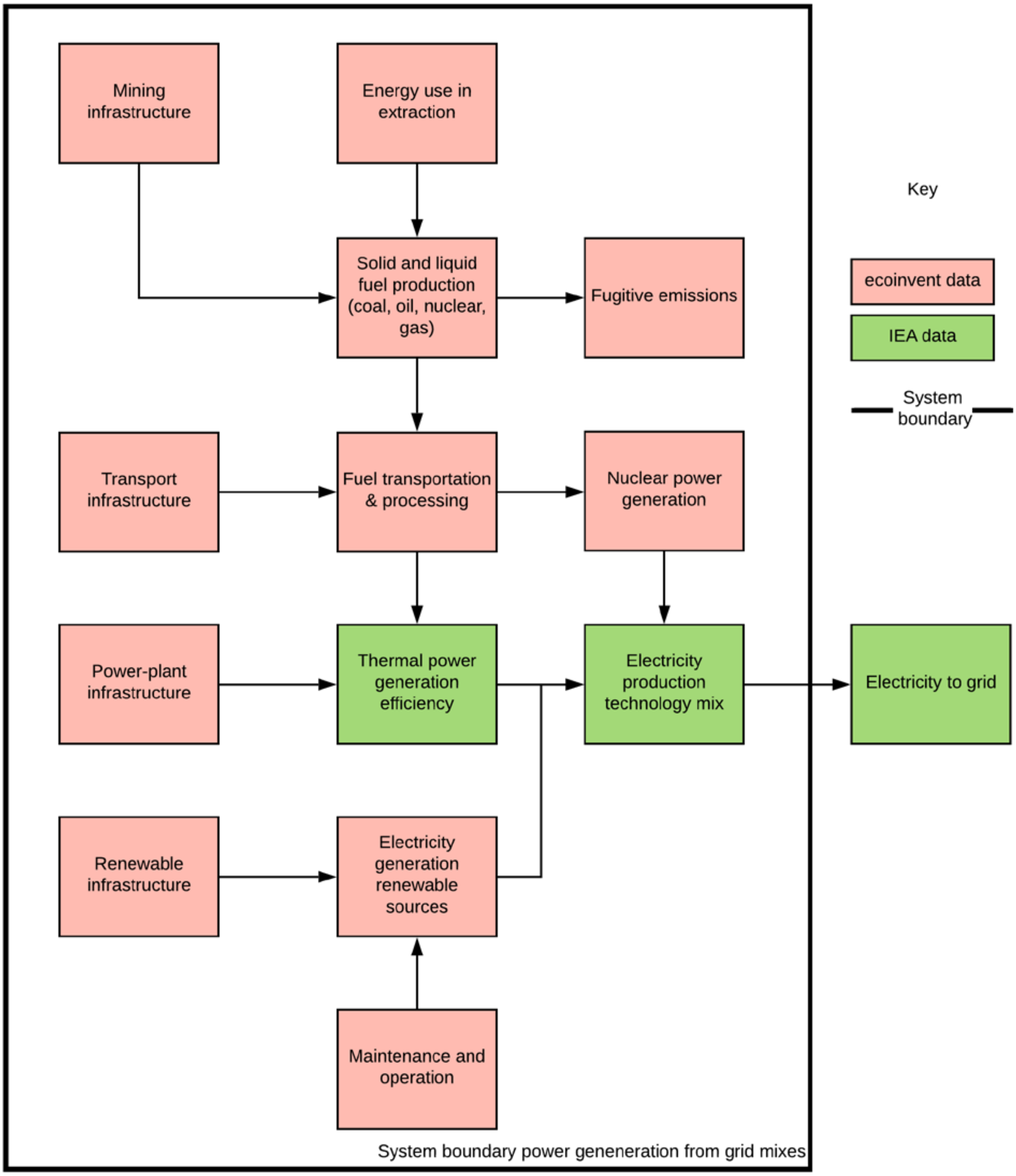


Figure 4-3 System Boundary for the Electricity Production from Other Sources

4.3.2 Included Processes

The assessment included raw gas production from offshore wells, gas treatment (e.g. separation of liquids), and reservoir CO_2 removal where relevant, all extraction processes for natural gas, its transport to shore, further processing in the onshore gas plant and LNG production and storage, LNG shipping to the relevant market, regasification into the local grid and combustion in the power station. Infrastructure elements are included such as drilling rigs, pipes, ships and processing equipment. For electricity supply from other sources, see **Figure 4-3**, the boundary includes fuel extraction, transport and combustion as well as capital equipment.

4.3.3 Cut-off Criteria

ISO standard for LCA allows for the exclusion from the inventory of any flows expected to be less than 1% of any impact category. Small flows such as activated Methyl Diethanol Amine (aMDEA) solvent used in the CO_2 separation, propane refrigerants, machine lubricants, and solid and liquid waste treatment, were not investigated as these were estimated to be well below the 1% mass or impact threshold. Exploration emissions for natural gas, oil and coal as well as research and development of other energy technologies is not included. The climate change impacts of gas exploration in Australia account for 0.26% of total life cycle of gas combustion.

4.4 LCA Methodology and types of Impacts

The choice of environmental indicators has been based on impacts which are strongly linked to power generation. **Table 4-1** describes each of the impact indicators chosen for the LCA and the source of the characterisation factors. Note that LCA impact categories represent **potential** environmental impacts as the different contributions are summed over time and from across the world based on total emission loads. This is different from regulatory reporting of pollutants which is usually concerned with specific locations, timing and concentration of emissions.

Climate change is included due to its high policy relevance, and the links between power generation and greenhouse gas emissions. Photochemical ozone creation potential also known as photochemical smog, is included to incorporate impacts from Non-Methane Volatile Organic Compound (NMVOC) emission from gas processing, as well as the emissions from other power generation technologies especially coal and oil which contribute nitrogen oxides to the atmosphere. Particulate matter is an important indicator to power generation from coal, oil and biomass combustion especially in China where over one million premature deaths per year have been attributed to particulate matter(Lin, Liu et al. 2016). Acidification has been included because of the high contribution of thermal electricity generation technologies and the prevalence of acidification in Asia in particular China (Zhu, De Vries et al. 2016).

We have chosen to exclude abiotic depletion for fossil fuels as fossil fuel depletion is strongly correlated with climate change, with the emerging issue being the ability to deal with the emissions from the combustion of fossil fuels rather than of scarcity of fuel resources. Mineral depletion is important in the renewable energy sector but not in the LNG production, however the models have significant uncertainty so have not been included.

Human and eco toxicity have been excluded due to high uncertainties of these emissions and likely strong correlation to climate change impact linked to coal fired power generation. Ionizing radiation has been excluded as Browse and Scarborough gas is considered most likely to compete against a portfolio of fossil fuel power sources rather than nuclear power generation where this might be significant.

Table 4-1 Impact Assessment Categories and Characterisation Models used in this LCA.

Impact Category	Description	Characterisation Model
Climate change	Measured in kg CO_2e The potential impact category, climate change, represents the carbon footprint of a product system adding up all greenhouse gas emissions taking account of their respective global warming potentials (GWPs). GWPs represent the amount of heat trapped by the gas in the atmosphere over time. All gases are measured relative to carbon dioxide. The most relevant gases to this study are carbon dioxide, methane and nitrous oxide. This impact method does not include the extent to which these emissions cause a change in global temperature as this requires additional modelling of other global emissions and sinks.	IPCC model provided in the fourth assessment report based on the cumulative effect over 100-year timeframe. (IPCC 2007) While updated factors are available from the IPCCs fifth assessment report (IPCC 2013) the report uses the 2007 values which are used by the Australian government and industry for current GHG reporting.
Photochemical smog	Measured in g NMVOC e Photochemical smog, also known as photochemical oxidation creation potential, represents the potential of hydrocarbons and nitrogen oxides in the atmosphere to react under the catalytic action of sunlight to produce tropospheric (ground level) ozone, as well as some other chemicals, which has significant respiratory and other health effects. While all impact categories represent potential impacts, this is particularly the case with photochemical smog as the effect only occurs when the appropriate mix of gases are present in sunlight.	Characterisation factors based on van Zelm et al. (2008) as listed in ILCD method (European Commission JRC IES 2011) documented in SimaPro. Factors are calculated for Europe but are considered applicable to other industrialised regions.
Particulate matter	Measured in g $PM_{2.5}$e This potential impact category represents the human health impacts from exposure to particulate matter (PM_{10} and $PM_{2.5}$ principally) but also secondary particulates including SO_2 and NH_3. This is one of the highest non-behaviour related risks to human health as identified in the global burden of disease (Vos, Barber et al. 2015).	Characterization factors based on Rabl, A. and J. Spadaro (2004) as listed in ILCD method (European Commission JRC IES 2011) documented in SimaPro.
Acidification`	Measured in Mol H^+ e This potential impact category looks at the acid pollutants (SO_2, NO_x, NH_3, HCl, HF) emitted by human activities that could affect the quality of all components of the environment (including air, soils and surface waters) not only in the vicinity of the sources, but also hundreds or even thousands of kilometres from their emitting sources. In the case of the systems under this study, the key acidification components are NO_x and SO_2.	Based on model by Seppälä, Posch et al. (2006) and Posch, Seppälä et al. (2008) as listed in ILCD method (European Commission JRC IES 2011) documented in SimaPro.

4.5 Data Quality Requirements

For a prospective study of future impacts for the extraction and utilisation of LNG for energy in five different regions sourcing data is a challenge. The preference for the study would be to find data projects to future production system in terms of fuel extraction and, electricity generation efficiency.

The key data quality criteria for the study were:

- Data quality
- Time related coverage
- Geographical coverage
- Technology coverage
- Representativeness.

The data quality is assessed using the data quality assessment framework included in **Table 4-2**.

Table 4-2 Data Quality Assessment Framework used in this LCA.

	Poor	Fair	Good	Very good
Reliability	Unqualified estimate	Estimate based on expert judgement	Estimates based on prior measurements	Measured value
Time related coverage	From past production >5 years old	From current production data <5 years old	From future production - singe or unspecified time period	From future production averages from time-period 2026-2040
Geographical coverage	From distinctly dissimilar region	From similar region	From global average	From region of interest
Technology coverage	From old or dissimilar technology	Generic technology average	From technology specific to region	From actual technology used
Representativeness	Unknown coverage	Sample from small part of target region	Sample covers >50% of target region	Representative of entire target region.

4.6 Multi-functionality

Multi-functionality occurs when a single process or group of processes produces more than one usable output, or 'co-product'. ISO defines a co-product as 'any of two or more products coming from the same unit process or product system'. A product is any good or service, so by definition it has some value for the user. This is distinct from a 'waste', which ISO defines as **'**substances or objects which the holder intends or is required to dispose of', and therefore has no value to the user.

As LCA identifies the impacts associated with a discrete product or system, it is necessary to separate the impact of co-products arising from multifunction processes. While there are several coproducts produced in LNG production, almost all products are different forms of fuel, destined for energy markets. The ISO 14044 LCA standard provides a four-step hierarchy for solving the issue of multi-functionality:

1a **Avoid allocation by subdividing systems** – wherever possible, allocation should be avoided by dividing the unit process into sub-processes.

1b **Avoid allocation by system expansion** – expanding the product system to include the additional functions related to the co-products.

2 **Allocation by underlying physical relationships** – the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them.

3 **Allocation between co-products** – the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example, data may be allocated between co-products in proportion to the economic value of the products.

(adapted from text in International Organization for Standardization 2006).

Table 4-3 describes the allocations in the foreground system of this LCA and how they have been handled. The background system of the LCA has used ecoinvent 3.5 which applies economic allocation throughout the database.

Table 4-3 Co-production in the LCA Foreground and Allocation Used

Process	Determining Product	Co-Product	Allocation Approach Used
Gas extraction at well, Browse	Natural gas for pipeline to shore	Condensate	Energy allocation uses as both products represent raw input to energy supply chains.
Natural gas processing at KGP	Natural gas	Propane and Butane	Energy allocation uses as both products represent raw input to energy supply chains.
Natural gas processing at KGP	Liquefied natural gas	Domestic gas	Energy allocation used allocation between LNG and domestic gas
Natural gas processing at Pluto	Liquefied natural gas	Domestic gas	Energy allocation uses as both products represent raw input to energy supply chains.

The background database from ecoinvent contain multi-functionality and by default this is dealt with through economic allocation and in some instances physical allocation. For example, refineries include mostly allocation on energy production in the ecoinvent database. Given the dominance of the foreground results in this study (emissions from power generation technologies) the allocation choices for background databases have insignificant effect on the final results.

5. INVENTORY ANALYSIS

Figure 5-1 shows the different types of flows included in the life cycle inventory. These include flows to and from the environment as well as flows to and from other technical processes (the technosphere). A Life Cycle Assessment model is made up of linked unit processes which deliver the ultimate functional unit.

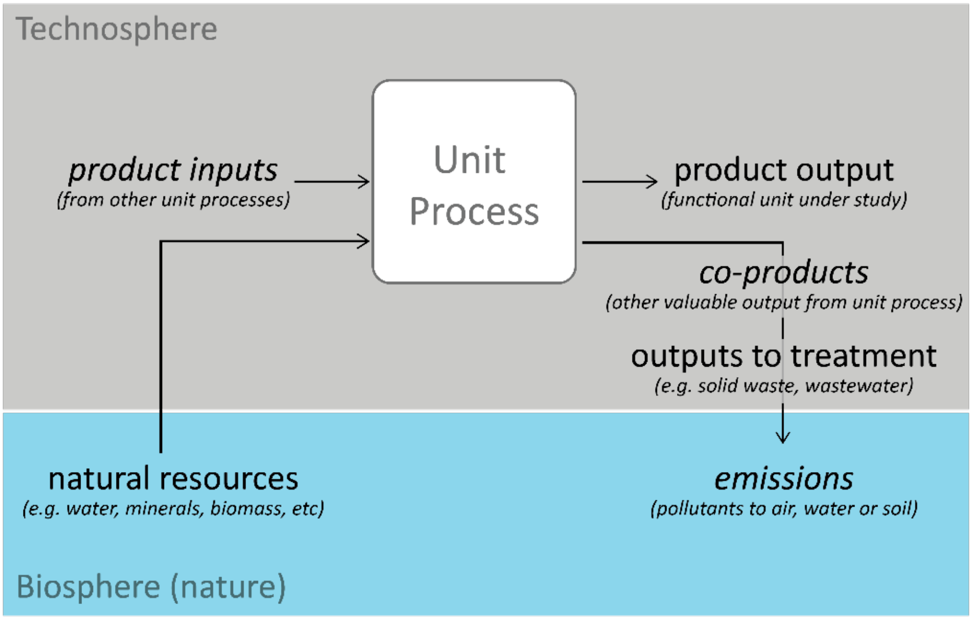


Figure 5-1 Inputs and Outputs of a Unit Process in LCA

The model representing the delivery of the functional unit is broken up into a series of unit processes. Unit processes can be categorised into foreground unit processes and background unit processes:

- Foreground processes are those for which specific data are collected for the study. They may include primary data collected from facilities; however, they can also include secondary data from published papers and modified background processes from LCA databases.
- Background processes are those for which data are typically sourced from pre-existing databases. Background data are either less important to the study outcomes or are already well-characterised in existing data sets and therefore do not warrant specific modelling. In some instances, background unit processes may be modified to better reflect the conditions of the study.

5.1 Foreground Data

The data for Woodside operations have been sourced from a mix of predictive internal technoeconomic models. This applies to extraction impacts, flares and fugitive emissions at the two new fields; historic operational data for LNG processing at Pluto and KGP (the existing processing plants which will be used for the new fields) and for shipping operations. All this data are projections for future production – with the existing facility operations being adjusted to align with the specific feedstocks from Browse and Scarborough. There is no technology adjustment into the future to account for improvements in LNG production technology. For Browse, there is a small ramp up at the start of the 2026 to 2040 period, while Scarborough has the same annual production throughout the 15 years of the analysis period.

5.1.1 Browse

The Browse development includes two Floating, Production, Storage and Offloading (FPSO) facilities (Calliance and Torosa), connected to the Browse reservoir subsea production wells via the Browse subsea raw gas gathering manifolds, flowlines and risers.

The FPSOs will process the raw well fluids into:

- condensate that will be stored on each facility and exported from there, and
- treated (dry) gas, which, for the two FPSOs following partial removal of reservoir CO_2, will be compressed and exported via a common for the two FPSOs subsea pipeline to the Karratha Gas Plant (KGP), located on the Burrup Peninsula.

Part of the raw gas, following treatment, will be used at the FPSOs as fuel for the export compressor gas turbines and the gas turbine generators, used for electricity generation.

Following arrival at the KGP, Browse gas will be split into two main streams:

- feedstock for domestic gas, and
- feedstock for the LNG Trains 4 and 5.

The LNG feedstock stream is additionally treated to remove residual reservoir CO_2 (acid gas), mercury and water and further processed to produce:

- liquefied natural gas (LNG),
- liquefied petroleum gas (LPG) and fuel gas for the LNG compressor gas turbines and gas turbine electricity generators.
- Acid gas, dominated by reservoir CO_2, but also containing residual quantities of CH_4, BTEX and H_2S is either vented or combusted into the KGP Thermal Oxidiser (TO).

Small quantities of processed gas from various parts of the processing plants, both offshore and onshore, are periodically flared following process upset events or preparation for maintenance through the FPSOs' and the KGP's flares.

A high-level Browse gas processing and energy flow diagram relevant to this study is summarised in **Figure 5-2**. The boxes on the left of the page represent the offshore FPSOs, whilst the box on the right represents the KGP.

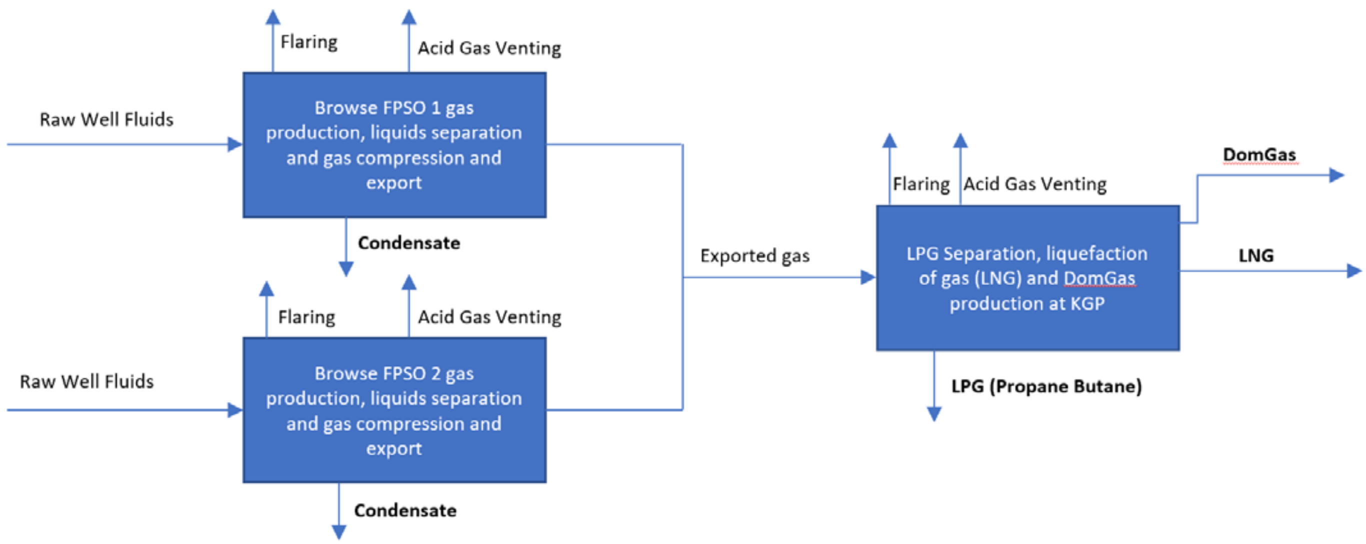


Figure 5-2 Structure of Browse LNG Production Process

The inputs and emission for production of gas at the Browse FPSOs gas field and processing at KGP are provided in Appendix B.

5.1.2 Scarborough

The Scarborough development will involve subsea, high-rate gas wells, tied back to a semi-submersible floating production unit (FPU). The raw gas, containing very small quantities of hydrocarbon liquids, will be treated to separate those liquids and produced water at the FPU and then compressed and transported along an approximately 430 km long pipeline to the Pluto LNG Plant on the Burrup Peninsula.

The production capacity of the Pluto LNG Plant, currently representing a single 5 Mtpa LNG train, will be expanded with a future 5 Mtpa LNG train, dedicated primarily to processing the exported gas stream from the Scarborough FPU. A gas equivalent of 1.65 Mtpa LNG will be processed through the existing Train 1 of the Pluto LNG Plant, whilst a gas equivalent of 4.85 Mtpa LNG will be processed through the future Train 2.

Scarborough gas will also be used to produce the equivalent of 1 Mtpa domestic gas (domgas), which will be processed to achieve the required export specification for the Dampier to Bunbury Natural Gas Pipeline.

Figure 5-3 presents a high-level gas processing and energy flow diagram for the Scarborough gas, showing the offshore FPU facility to the left and the two Pluto LNG Trains to the right. Pluto Train 1 and Train 2 are shown as two separate processing facilities due to their different emissions intensities / energy efficiencies.

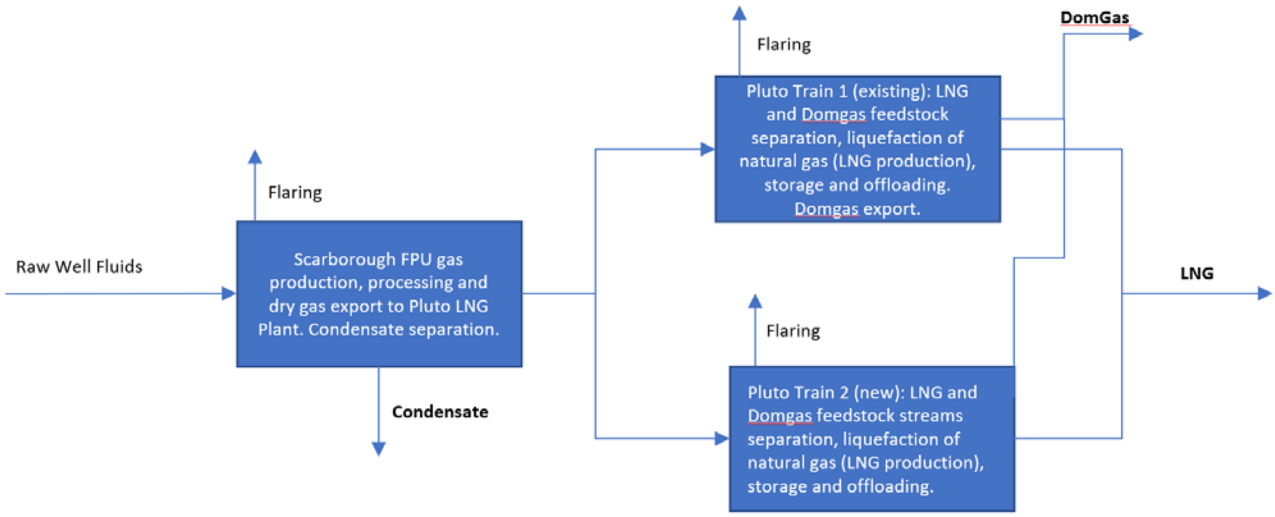


Figure 5-3 Structure of Scarborough LNG Production Process

The inputs and emissions for production of gas at the Scarborough gas field and processing at Pluto gas processing plant are provided in Appendix B.

5.1.3 Gas Compression and Gas Turbine Electricity Generation

The majority of energy inputs to processing gas offshore and onshore is through the use of the available natural gas being combusted in gas turbines to drive both gas compressors and electricity generation.

Specific facility data have been used for Nitrogen oxides, Sulphur oxides, Non-methanic volatile organic compounds (NMVOC) and particulate matter are all sourced from equipment specifications provided by Woodside.

The CO_2 emissions are based on emission factors specific to Browse and Scarborough gas based on gas composition. Methane and nitrous oxide emissions are default values from the National Greenhouse Accounts Factors (2019). The emissions associated with the materials and manufacture of the equipment are based on ecoinvent data[4]. The emissions from compressors and electricity generation for onshore and offshore processes are detailed Appendix B.

5.1.4 LNG shipping

LNG shipping is operated by third party from Woodside. A complete fuel and emissions data set has been provided which has been used to calculate the impacts of shipping. The shipping data is converted into freight task unit: “tonne kilometer” and then multiplied by the distance of the trip and the mass of LNG being transported. The detailed emissions data for shipping are listed in Appendix B

5.1.5 Regasification

Regasification is the process of converting liquefied natural gas into gaseous form in the distribution network of the importing country. The regasification data have been sourced from ecoinvent global databases 3.5 (Weidema, Bauer et al. 2018) and is based on data for regasification in Japan. This has been used for all regions, as no other data are available for the other regions being assessed. Appendix B lists the specific inputs and emissions data for regasification

5.1.6 Gas Transmission

Gas Transmission is assumed to be high pressure transport of gas, and not include lower pressure distribution networks.

The data have been sourced from ecoinvent global databases 3.5 (Weidema, Bauer et al. 2018) and data from Japan have been used for all regions as specific data for other regions assessed is not available.

5.1.7 Electricity Generation

Electricity generation technologies are well represented in LCA database having been studied for many years and often representing the majority of impact in any LCA study. For this study we stop at the generation point for all fuels and don’t include transmission and distribution of electricity to end users.

The majority of background data was sourced from ecoinvent 3.5. This source includes datasets for natural gas and electricity in each of the following regions - Japan, China, India as well as for global supply of electricity. For ASEAN region, not all countries are represented so Indonesian processes were used as a proxy for ASEAN region after adjusting the thermal efficiency of each technology to figures published by IEA. The only exception was for hard coal in ASEAN region where the process was based on the ecoinvent process for electricity from Malaysian hard coal, adjusting the thermal efficiency to match the IEA data for ASEAN region. **Table 5-1** lists the ecoinvent inventory processes used for thermal electricity generation processes. Appendix C lists all generation processes used in the grid mixes for each country / region.

The data for electricity generation from LNG are the same as the data used for other natural gas because once LNG is regasified into the local transmission networks, there is no discernible difference between LNG sources natural gas and other sources. For countries where the energy generation data are broken down into regions (China and India) each generation technology was assessed across all regions for climate change impact, and the median region was selected.

[4] Electricity, medium voltage [DE}| natural gas, burned in gas turbine, for compressor station | APOS, U

For the global model a generation process was selected for coal oil and gas, based on the median climate change impact of all available generation processes in ecoinvent. Note that this may be a poor representation of average technology for the non-greenhouse gas emissions, but was considered acceptable considering that the global model used in calculating the overall benefits of LNG exports.

Table 5-1 Ecoinvent Inventories Selected for Fossil Fuel Power Generation for each Country/Region

Region	Fuel	Unit Process Name in Simapro Ecoinvent APOS Library
ASEAN	Hard coal	Electricity, high voltage [MY}| electricity production, hard coal | APOS, U
China	Hard coal	Electricity, high voltage {CN-GZ}| electricity production, hard coal | APOS, U
Global	Hard coal	Electricity, high voltage [CN-GS}| electricity production, hard coal | APOS, U
India	Hard coal	Electricity, high voltage [IN-MP}| electricity production, hard coal | APOS, U
Japan	Hard coal	Electricity, high voltage [JP}| electricity production, hard coal | APOS, U
ASEAN	Natural gas	Electricity, high voltage [ID}| electricity production, natural gas, combined cycle power plant | APOS, U
China	Natural gas	Electricity, high voltage [CN-GX}| electricity production, natural gas, combined cycle power plant | APOS, U
Global	Natural gas	Electricity, high voltage [IN-GJ}| electricity production, natural gas, combined cycle power plant | APOS, U
India	Natural gas	Electricity, high voltage [IN-KL}| electricity production, natural gas, conventional power plant | APOS, U
Japan	Natural gas	Electricity, high voltage [JP}| electricity production, natural gas, combined cycle power plant | APOS, U
ASEAN	Oil	Electricity, high voltage [ID}| electricity production, oil | APOS, U
China	Oil	Electricity, high voltage [CN-GZ}| electricity production, oil | APOS, U
Global	Oil	Electricity, high voltage [CA-QC}| electricity production, oil | APOS, U - GLO
India	Oil	Electricity, high voltage [IN-TN}| electricity production, oil | APOS, U
Japan	Oil	Electricity, high voltage [JP}| electricity production, oil | APOS, U

5.1.8 Generation Efficiencies

The thermal efficiency of power generation from natural gas was adjusted to reflect the energy efficiency values derived from IEA data for each year and each region. For natural gas, this efficiency value was representative of all natural gas power generation which would include a mix of gas turbines and combine cycle gas turbine power plants. Therefore, the inventory represented a mix of natural gas electricity generation technologies defined by the overall thermal efficiency. This efficiency changed over the study period (2026-2040), and this change was included in the calculation of the year by year impacts of power generation. A similar, technology-specific change in efficiency over time was also used for coal and oil-based electricity generation in each region.

Table 5-2 shows the original efficiency of the selected inventories and the efficiency range used in the LCA study. Some of the inventories, such as Chinese natural gas, have lower efficiencies than the range quoted by IEA. This may be because of the difference of approximately 10 years from when the inventory data were collected and the start of the study period. There is a similar discrepancy with coal-based electricity in India which currently is listed to have a very low efficiency compared with the IEA range. This may reflect an expected investment in more efficient power plants and India over the coming 20 years.

The IEA quoted efficiency for electricity from oil is very low, however the amount of electricity from oil in China in these years is insignificant and this does not materially affect the results.

Power generation from LNG is based on the natural gas power generation inventories adjusted to account for slight differences in energy content of gas from LNG compared to the gas reported in the ecoinvent inventory.

Emission control from power generation processes was not modified beyond the changes to overall efficiency of the power plant. Unfortunately the IEA datasets do not project emission control equipment and the effects of that equipment into the future.

The remaining energy technologies such as renewables and nuclear were based on current production with no change in efficiency with time. The overall impact of these technologies are influenced more by the impacts from capital equipment and typically have much lower impacts per kWh than fossil-based power generation systems.

Table 5-2 Original Thermal Efficiency, Efficiency Range in Study and Energy Content of Selected Fossil Fuel Power Generation Inventories

Region	Fuel	Original Efficiency	Efficiency Range in Study Based on IEA Data	Energy Content LHV[1]
ASEAN	Hard Coal	31.50%	36%-38%	22.8
China	Hard Coal	33.00%	35%-38%	22.8
Global	Hard Coal	33.00%	35%-38%	22.8
India	Hard Coal	23.70%	38%-40%	19.3
Japan	Hard Coal	39.80%	37%-44%	24.1
ASEAN	Natural Gas	42.70%	46%-52%	39
China	Natural Gas	33.00%	42%-51%	39
Global	Natural Gas	46.50%	44%-48%	33.1
India	Natural Gas	33.00%	47%-55%	33.1
Japan	Natural Gas	56.40%	52%-59%	39
ASEAN	Oil	28.40%	28%-34%	38.5
China	Oil	33.00%	1%-10%	38.5
Global	Oil	32.30%	27%-33%	38.5
India	Oil	25.80%	26%-28%	31.3
Japan	Oil	40.10%	43%-47%	31.7

1 Energy content is in MJ/m^3 for natural gas, and MJ/kg for oil and hard coal and all are source from ecoinvent database version 3.5 (Weidema, Bauer et al. 2018) documentation.

5.1.9 IPCC Emission Factors compared with Ecoinvent

Developed from broad studies of available scientific literature, the Intergovernmental Panel on Climate Change (IPCC) assessments of emission intensities for different energy sources remain a reliable open-source benchmark. In 2014, the IPCC updated its findings as part of the Working Group III contribution to the IPCC Fifth Assessment Report, published the same year. While IPCC is a respected source, its published numbers are not sufficiently disaggregated to model electricity generation in each country with all the nuances of fuel type, supply chains for fuel import and processes and technology types.

For the purposes of this study, using ecoinvent emission intensities provides for more accurate analysis. Ecoinvent uses the same emission factors, or more likely the same underpinning sources as the IPCC, but does it on a per MJ fuel basis, rather than per kWh of electricity generated. This enables the modelling approach to account for efficiency differences, etc. Comparing the underlying factors in ecoinvent for direct emissions from coal, they are very close to the IPCC values. The ecoinvent number is a weighted average of a selection of countries and technologies which may affect particularly the non-CO_2 emissions. **Table 5-3** shows the comparison of ecoinvent and IPCC coal emission factors, and demonstrates a high level of consistency between the two sources. A similar consistency across other fuel emission factors can be observed between ecoinvent and IPCC factors.

Table 5-3 Comparison of Ecoinvent and IPCC Coal Emission Factors

	Ecoinvent	IPCC
CO_2	95.5 kg/ GJ	95.8 kg/ GJ
CH_4	0.902 g/ GJ	0.73 g/ GJ
N_2O	1.1 g/GJ	1.32 g/ GJ
Total	95.9 kg CO_2e	96.2 kg CO_2e

5.1.10 Electricity Grids

Each electricity grid modelled for the different scenarios is based on data from the IEA policy scenarios (International Energy Agency 2018). The ecoinvent database version 3.5 was also used to model each individual technology which make up the average country grid. For each region, ecoinvent supplies data for the most common electricity production processes such as coal, oil and gas. However, there is not a dataset for every energy generation type for every region. In this case, proxies have been used when a country was not covered in ecoinvent.

Technology mixes in renewable energy systems (for example between small- and large-scale wind power) were maintained in current ratios to each other. The IEA forecast grid data were disaggregated by region/country and by year, between 2026-2040. Each annual grid mix was calculated and matched to the efficiency values mentioned in the last section. The results from each set of annual data were summed to produce average results across the 15-year timeframe from 2026-2040.

5.2 Background Data

5.2.1 Infrastructure

Infrastructure is required at every point of the gas production process. The infrastructure included material impacts, transport of materials to site, installation, maintenance and eventual disposal. The infrastructure has a long lifetime, is sometimes reused from prior operations and may be used after the project timeframe for future operations. Because of this, infrastructure inputs have not been developed from the Browse or Scarborough project proposals but have used background models on oil and gas infrastructure models supplied with the ecoinvent database (ecoinvent 3.5, allocation at the point of substitution version).

The three processes used include:

- Natural gas processing plant production (Pluto, KGP, Regasification plant);
- Offshore platform production, natural gas (Browse, Scarborough);

- Pipeline construction, natural gas, long distance, high capacity, offshore (Pipelines from Browse to KGP and Scarborough to Pluto).

Table 5-4 shows the characteristics of the infrastructure models from ecoinvent. The plant data are apportioned to Woodside processes on a per GJ of gas production equivalent to the scale of the original processes. For the pipeline process based on the length of the pipeline so this is modelled directly to the required pipeline distance used and then annualised by dividing the pipeline length but the assumed life of the pipeline which is 45 years.

Table 5-4 Infrastructure Models used from Ecoinvent Data

Process	Assumed Life	Size of Facility	Origin
Natural gas processing plant	60	4.23 billion Nm^3 per year	Gas treatment plants in Norway
Pipeline construction, natural gas, long distance, high capacity, offshore	45	1.6 Mio. Nm^3 gas per hour, 1000 metre diameter, steel 25mm, concrete 100mm.	Average Norwegian North Sea pipeline
Offshore platform production, natural gas	11	27.7 Mrd. Nm^3 natural gas per year	Platform Odin, which belonged to Esso Norway.

6. STUDY RESULTS AND ANALYSIS: CLIMATE CHANGE

6.1 Climate Change Results

6.1.1 Comparison against IEA Scenarios

The IEA scenarios consider energy used in all its forms, e.g. in power generation, heating (e.g. residential domestic gas supply), automotive power etc. This study examines the role of LNG as a competitor to other forms of energy in the power generation sector in the four target markets.

From a power sector emissions intensity perspective, Asia Pacific markets are generally 'high carbon', featuring a large share of coal in the overall fuel mix. Under the IEA STEPS outlook, adding gas from Browse or Scarborough to the power mix is expected to lead to a decline in CO_2e emissions intensity in each market under consideration, to at least 2040.

Under very low carbon scenarios (IEA's SDS), Browse and Scarborough gas may play a significant role in the target markets, supporting the shift away from coal, and the build-out of intermittent renewable generation. Under the SDS, total gas demand in the target markets grows by over 60% between 2020 and 2040, while the emissions intensity of total primary energy demand (TPED) falls by more than half over the same period. Therefore, the success of achieving a lower-carbon outcome as described by the SDS is in fact predicated on the increased use of gas in the target markets. The proximity of Browse and Scarborough to these markets represents a competitive advantage versus LNG from, for example, the Middle East or the US Gulf Coast.

6.1.2 Comparative Emissions under Specific Grid Mixes

To demonstrate how Browse and Scarborough-sourced gas would compare to other sources of generation in the power markets under consideration, it is necessary to show climate change impacts under three specific grid mixes:

- **Fossil fuel mix.** Defined as the emissions intensity of the power market under study, which accounts only for fossil fuel power sources. This comparator is considered the baseline for this study, and has been applied for all three IEA scenarios, reflecting most realistically how gas will compete in the target markets. Gas-on-renewables competition is considered to be limited, due to policy support and falling costs for renewables under the STEPS and especially the SDS, and the limited presence of renewables under the CPS. Imported fossil energy remains essential to satisfy growing demand; gas-on-gas competition is implicit in this comparison.
- **Average mix.** This is defined as the average emissions intensity of a more diversified power market, which includes all fuels, including fossil, renewables and nuclear. This comparator demonstrates the impact of the changing balance of power generating sources through time, which will tend to reduce overall grid intensity as lower-carbon power grows in market share.
- **Coal only mix.** The emissions intensity of the coal-only section of the power market under study. This comparator is included to represent direct gas-to-coal competition. New gas fired generation has competed directly with coal in Europe and the USA, and switching from coal to gas is one of the most robust methods to reduce the emissions intensity of power generation.

6.1.3 Regional Trends over Time

The trends in climate change impacts over time are shown in **Figure 6-1** for electricity produced from LNG sourced from Browse and Scarborough and delivered to China, as well as the results for average, fossil fuel, and coal only grid mixes in China, as described by the IEA policy scenarios between 2025 and 2040. These results are shown**,** Japan in **Figure 6-2**, the ASEAN region in **Figure 6-3,** for India in **Figure 6-4** and globally in **Figure 6-5.**

6.1.3.1 China

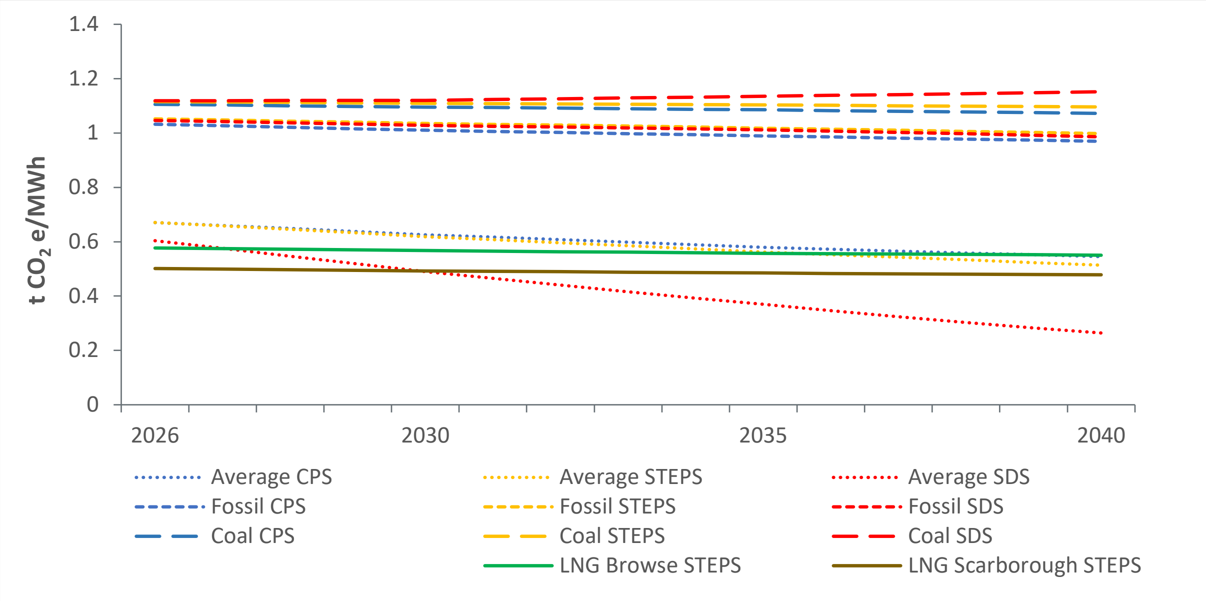


Figure 6-1 Climate Change Comparison of Electricity from LNG and IEA Energy Scenarios in China[5]

The data illustrates the as-yet relatively undifferentiated nature of the Chinese power market. Unsurprisingly, coal only emissions intensity is highest, and trends down only marginally through time as plants become more efficient.

China's fossil fuel emissions intensity is marginally lower than the coal only trend. This shows that diversification within the fossil component of the power fleet is at an early stage – gas generation has a lot of upside and opportunity to take market share from coal. China's fossil power emissions intensity is also approximately double that of gas from Browse or Scarborough indicating LNG from the two developments will provide an emissions intensity benefit when competing with coal, or China's fossil mix, under any scenario.

The average grid mix tells a different story. Here, China's build-out of nuclear, hydro, gas and renewable power is evident in pulling down the emissions intensity of the grid to below 0.7 tCO_2e / MWh by 2026 under the CPS and STEPS scenarios. By this time, a rapid push for clean energy has pushed the SDS average grid emissions intensity to below 0.6 t CO_2e / MWh. Browse and Scarborough-derived power nevertheless undercuts China's average emissions intensity until the mid-2030s, under the CPS and STEPS scenarios. Beyond this point, while the emissions intensity of gas is above the average, it continues to have displacement potential for higher emissions intensity fuels still present in the mix. In the SDS, a goal-driven scenario, which is consistent with a <2^oC climate outcome, gas necessarily occupies a significant portion of the energy mix in order to minimise the overall power grid emissions intensity.

[5] For LNG from Browse and Scarborough only the STEPS scenario is shown as the changes under different scenarios are very small for LNG electricity making it not practical to represent them on these graphs. Results were calculated under CPS and SDS scenarios which we use for calculating the overall avoided emissions for each policy scenario.

6.1.3.2 Japan

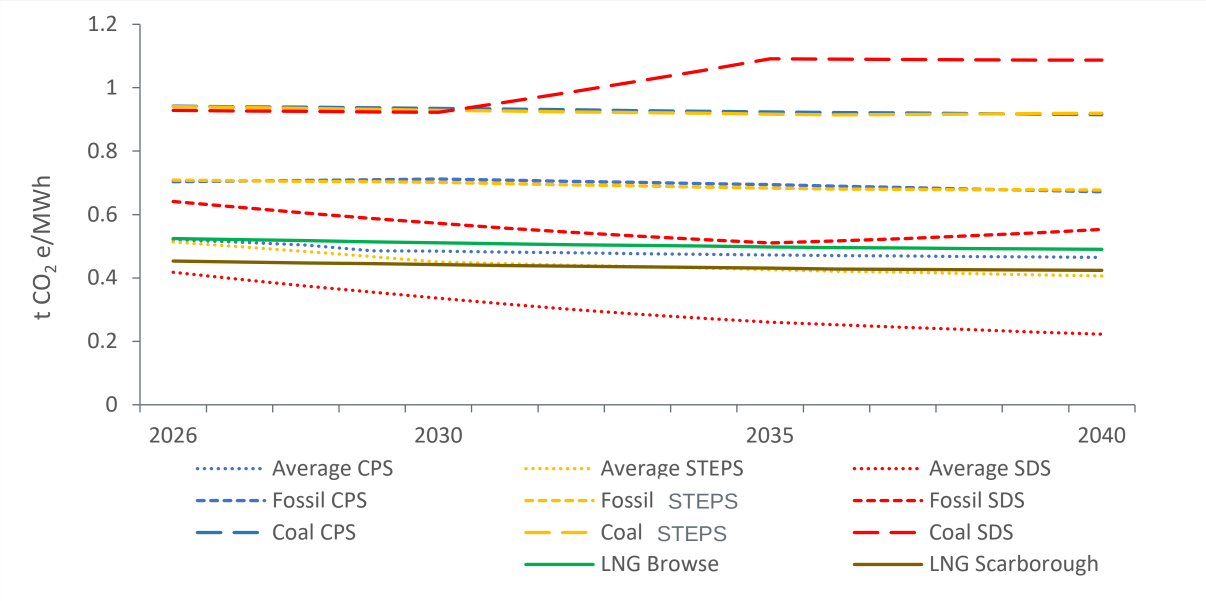


Figure 6-2 Climate Change Comparison of Electricity from LNG and IEA Energy Scenarios in Japan

Results for Japan **Figure 6-2** show again the split between intensities for coal only and fossil fuel generation. The kink in the SDS coal line is an artefact of IEA data inconsistencies[6].

Under the SDS, coal-fired generation is at its lowest across all scenarios in 2040 in absolute terms, but its share of the fossil mix does increase between 2035 and 2040, from 7% to 13%. This explains the differing trajectories of the SDS and STEPS/CPS fossil fuel intensities, and the rebound shown in the chart between 2035 and 2040 for the SDS line. As coal increases its relative share in the fossil mix under the SDS, the emissions intensity of that mix also increases.

Market peculiarities aside, the chart illustrates that Browse and Scarborough gas compete favourably on emissions intensity on a coal only or fossil fuel basis. At first glance, the existence of oil in the power mix may suggest headroom for gas which no longer exists in other developed power markets. But Japan is a low-growth market overall, and any new market entrants will almost certainly be competing directly against existing gas.

By the mid-2020s some of Japan's nuclear fleet will have come back on line post Fukushima. This, and along with significant growth in renewable energy, is stark under the SDS, where gas-fired power drops by half in the years to 2040.

[6] In the Sustainable Development Scenario for Japan, CO_2 emissions for coal-fired power drop off much more sharply than the fall in coal-fired power output. In the case of Japan, emissions fall from 66 million tonnes to 2 million tonnes over 5 years, while power output drops from 17 to 4 TWh. This pulls down the CO_2 emissions intensity of combustion. But the data represented in the charts for Japan and China also include emissions from extraction, processing, shipping, etc. As coal demand falls, this 'upstream' share of the emissions burden becomes proportionally much larger than the combustion share (the reverse is true under normal circumstances). This then acts to drive up coal's emissions intensity, in this scenario only.

6.1.3.3 ASEAN

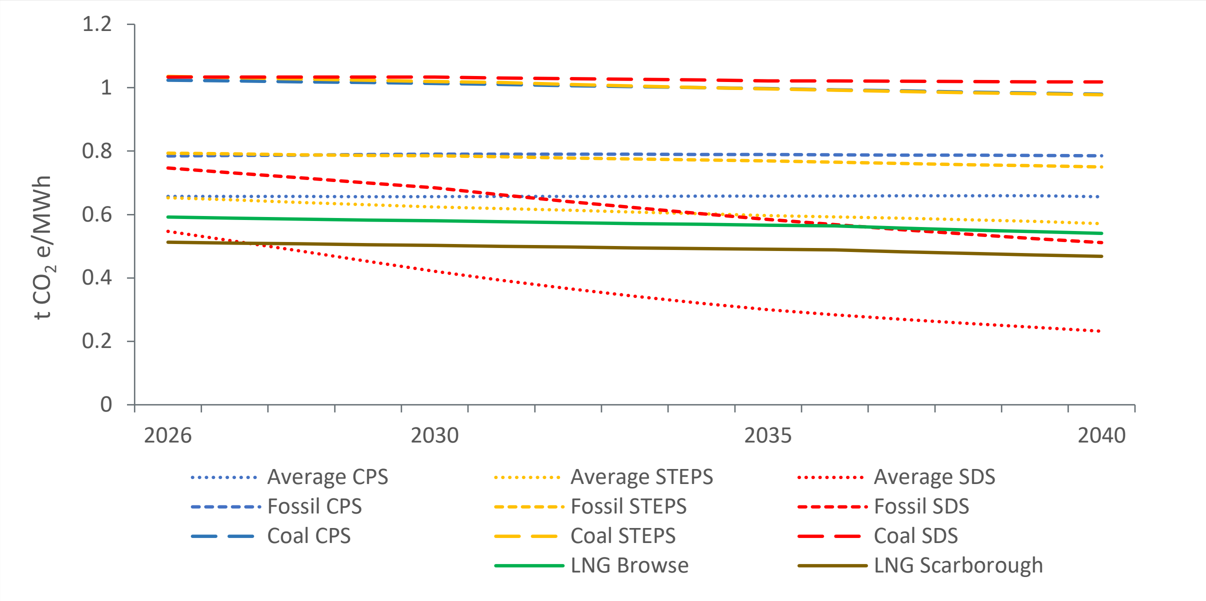


Figure 6-3 Climate Change Comparison of Electricity from LNG and IEA Energy Scenarios in ASEAN Region

Collectively, the ASEAN markets[7] **Figure 6-3** follow a path very similar to that illustrated by India (**Figure 6-4**). Coal to gas switching is dramatic under the SDS, with a commensurate effect on the emissions intensity of the power sector. In fact, this is a sufficient switch from coal to gas to push the emissions intensity of the SDS fossil grid below that of Browse LNG before 2040.

Coal emissions intensity is high and stable throughout all three scenarios. From a fossil fuel mix perspective, differences between the CPS and STEPS scenarios are relatively small. Coal and gas demand grow from 2026 to 2040, and, as in India, the final share of the fuels in the power mix is broadly similar across the two scenarios.

Under the SDS, power sector coal demand is less than one tenth of 2040 demand under the CPS, and gas demand is at approximate parity across the scenarios, in absolute terms. Again, as in India, fossil fuel emissions intensity falls dramatically in this scenario, dropping even below the average emissions intensity under the STEPS and CPS scenarios.

6.1.3.4 India

As in other markets, coal emissions intensity in India is high throughout all three scenarios, **Figure 6-4**. From a fossil fuel mix perspective, differences between the CPS and STEPS scenarios are relatively small. Coal demand grows from 2026 to 2040, as does gas, but the final share of the fuels in the power mix is approximately the same across the two scenarios, explaining the close parallel emissions intensity trajectories.

Under the SDS, 2040 coal demand in India's power sector is pushed down to approximately one tenth of CPS demand. Meanwhile, 2040 SDS gas demand is approximately double the CPS, in absolute terms. As a result, fossil fuel emissions intensity falls dramatically under the SDS, dropping even below the grid average emissions intensity under the CPS.

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[7] The ASEAN region includes the following ten countries: Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Vietnam

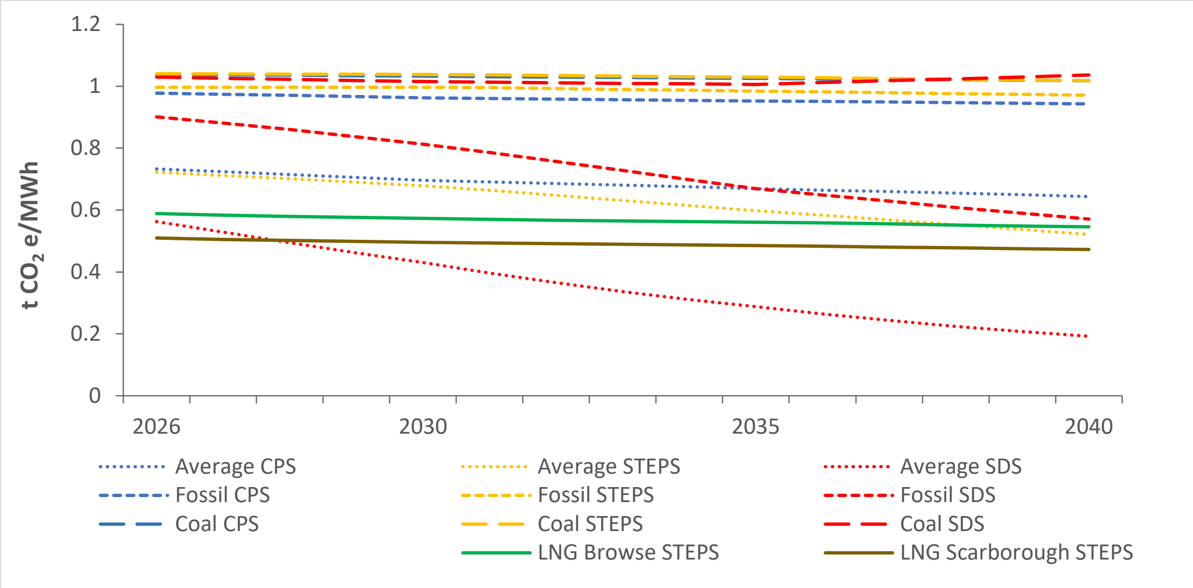


Figure 6-4 Climate Change Comparison of Electricity from LNG and IEA Energy Scenarios in India

On an average grid basis, this opportunity remains clear, under the CPS and STEPS scenarios at least: Browse and Scarborough gas will help to reduce emissions through to 2040. It is only under the SDS – where the sharp drop in coal is accompanied by a booming renewables market – that average emissions intensity falls below that of gas-fired power before 2030. But given that Browse and Scarborough-sourced power is likely to compete against the broad fossil mix, or directly with coal, there is a compelling case for its place in India's electricity mix.

6.1.3.5 Global

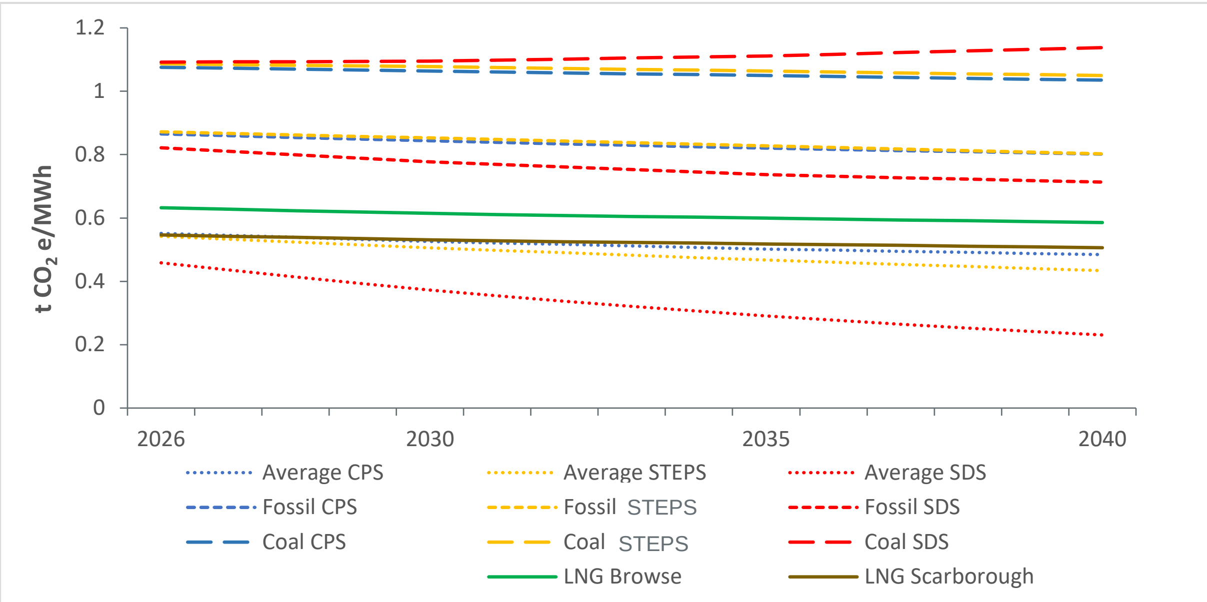


Figure 6-5 Climate Change Comparison of Electricity from LNG and IEA Global Energy Scenarios

Clearly, the idea of a 'global' market is somewhat misleading in terms of where Browse and Scarborough-sourced power will compete. However, the analysis **Figure 6-5** allows consideration of where the various Asia Pacific markets place in terms of the global average, and by implication describes some features of the European and American power markets.

On a coal only basis, emissions intensity is unsurprisingly high. In fact, the trajectories of the coal only lines are very similar to those seen in China, as a result of the predominance of that country in the global coal-fired power fleet.

The fossil fuel mix demonstrates the importance of gas in reducing the burden of emissions from coal. Compared to all other Asia Pacific markets except China, the emissions intensity of the global fossil mix in 2040 is within a close range, indicating a likely global convergence in terms of coal / gas balance in power markets towards the end of the outlook period.

For the grid average, however, global emission intensities are lower than all Asia Pacific markets, except Japan. This would suggest a higher penetration of renewables in the European and American power systems. Grid emission intensities in these markets are likely to be among the lowest in the world.

6.1.3.6 Long-term Average Emission Intensities

Comparison of Long-term Average Emission Intensities is shown in **Table 6-1** and describes the emission intensities of electricity produced from Browse and Scarborough LNG in each region compared to the grid-average, fossil fuel and coal only grids under the three different IEA scenarios. The data show that power sourced from fossil fuels – the baseline comparator – has a greater emissions intensity than power derived from Browse and Scarborough LNG, for all scenarios in all regions. Power sourced from coal still has a greater emissions intensity.

Compared to average grids, which factor in lower-carbon power sources including renewables and nuclear as well as gas, power derived from Browse and Scarborough LNG retains its emissions advantage over the 15 year average in China, Japan, ASEAN and India for the CPS and STEPS scenarios. The average grid under the SDS shows a lower emissions intensity (and therefore emissions output) than power sourced from Browse or Scarborough LNG.

Table 6-1 Emission Intensities in t CO_2e/MWh Averaged from 2026 to 2040 for Different Markets and under Three Policy Scenarios

	CPS Av.	STEPS Av.	SDS Av.	CPS Fossil	STEPS Fossil	SDS Fossil	CPS Coal	STEPS Coal	SDS Coal	Browse	Scarb.
China	0.60	0.59	0.42	1.00	1.03	1.03	1.09	1.11	1.13	0.56	0.49
Japan	0.48	0.44	0.30	0.70	0.69	0.57	0.93	0.92	1.01	0.50	0.44
ASEAN	0.66	0.61	0.36	0.79	0.77	0.64	1.00	1.01	1.03	0.57	0.49
India	0.68	0.63	0.35	0.96	0.99	0.76	1.03	1.03	1.02	0.57	0.49
Global	0.51	0.48	0.33	0.83	0.84	0.77	1.06	1.07	1.11	0.61	0.52

6.1.4 Avoided Emissions – 2026 to 2040

It is possible to assess the potential impact Browse and Scarborough gas would have on the global total emissions burden over the 2026 to 2040 time period, should the gas be used to generate electricity in the target markets. The following assumptions are factored into this assessment:

- Gas volumes from both Woodside developments are delivered to China (31% of total), Japan (24%), ASEAN (27%) and India (19%), from 2026 to 2040. This distribution of trade is based on IEA net import projections for the target markets in 2040, taken from the 2019 WEO, since it is uncertain where the gas will actually be sold. This export split is not an indication of where the gas will be sold, or of the contracting strategy of Woodside or its Joint Venture Partners.

- Delivered gas volumes account for energy lost in the value chain between reservoir and power plant.
- Emission intensities account for non-combustion fossil CO_2 emissions e.g. from venting reservoir CO_2 and fugitive emissions during the LNG production process.
- Gas is used to generate electricity, with plant efficiency identical to the gas fleet average for the relevant market under each scenario.
- Each MWh of gas sourced from Browse or Scarborough displaces 1 MWh of fossil fuel-generated power from the markets under consideration.
- This fossil fuel-generated MWh is regarded as the baseline, with substitution benefits measured against this.
- The IEA's STEPS is regarded as the central case.

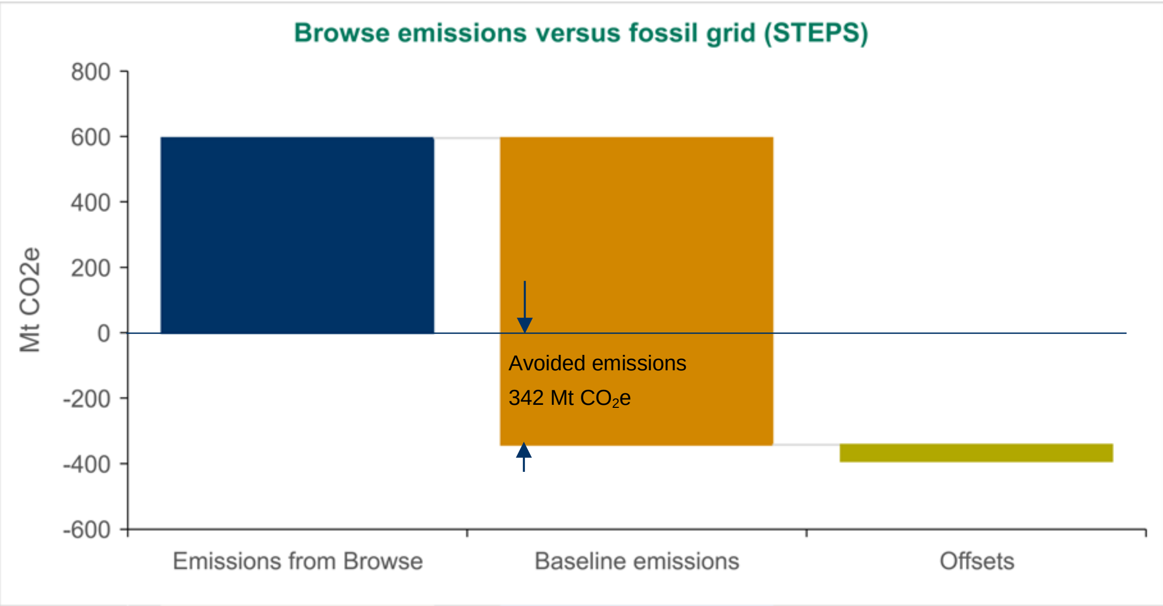
Figure 6-6 shows that Browse gas, if it is used to generate power in the target markets, will release between 591 Mt CO_2e and 595 Mt CO_2e over the 2026 – 2040 period, depending on the IEA power generation scenario.

If fossil fuels are used to generate power under STEPS, then emissions are much higher: 936 Mt CO_2e over the 2026 – 2040 period. Therefore, if Browse gas is used to generate power, then avoided emissions are 936 – 594 = 342 Mt CO_2e.

Under the CPS, the fossil balance of the power grids in the target markets is more biased towards coal relative to the STEPS. This is reflected in the emissions total: 945 Mt CO_2e from 2026 – 2040. If Browse sourced power displaces fossil power under the CPS, then avoided emissions are 354 Mt CO_2e.

The SDS shows a fossil grid with less coal than either of the other two scenarios. The SDS is a goal-driven scenario, meaning that the idea of gas 'competing' is not strictly valid, as gas is required to deliver emissions savings from coal and other high-emitting fuels. Nevertheless, should the same analysis be conducted as for the STEPS and CPS above, avoided emissions under the SDS are approximately 181 Mt CO_2e.

Figure 6-6 also takes into account the use of CO_2e offsets for Browse, which is Woodside's expectation of Browse's compliance obligations under the Australian Safeguard Mechanism Rules, as stated in the December 2019 Draft Browse to NWS EIS/ERD. Use of offsets effectively reduces emissions versus the baseline by a further 50 Mt CO_2e. Avoided emissions are therefore 392 Mt CO_2e under the STEPS, and 404 Mt CO_2e under the CPS. Should the same analysis be conducted for the SDS, avoided emissions would be 231 Mt CO_2e.



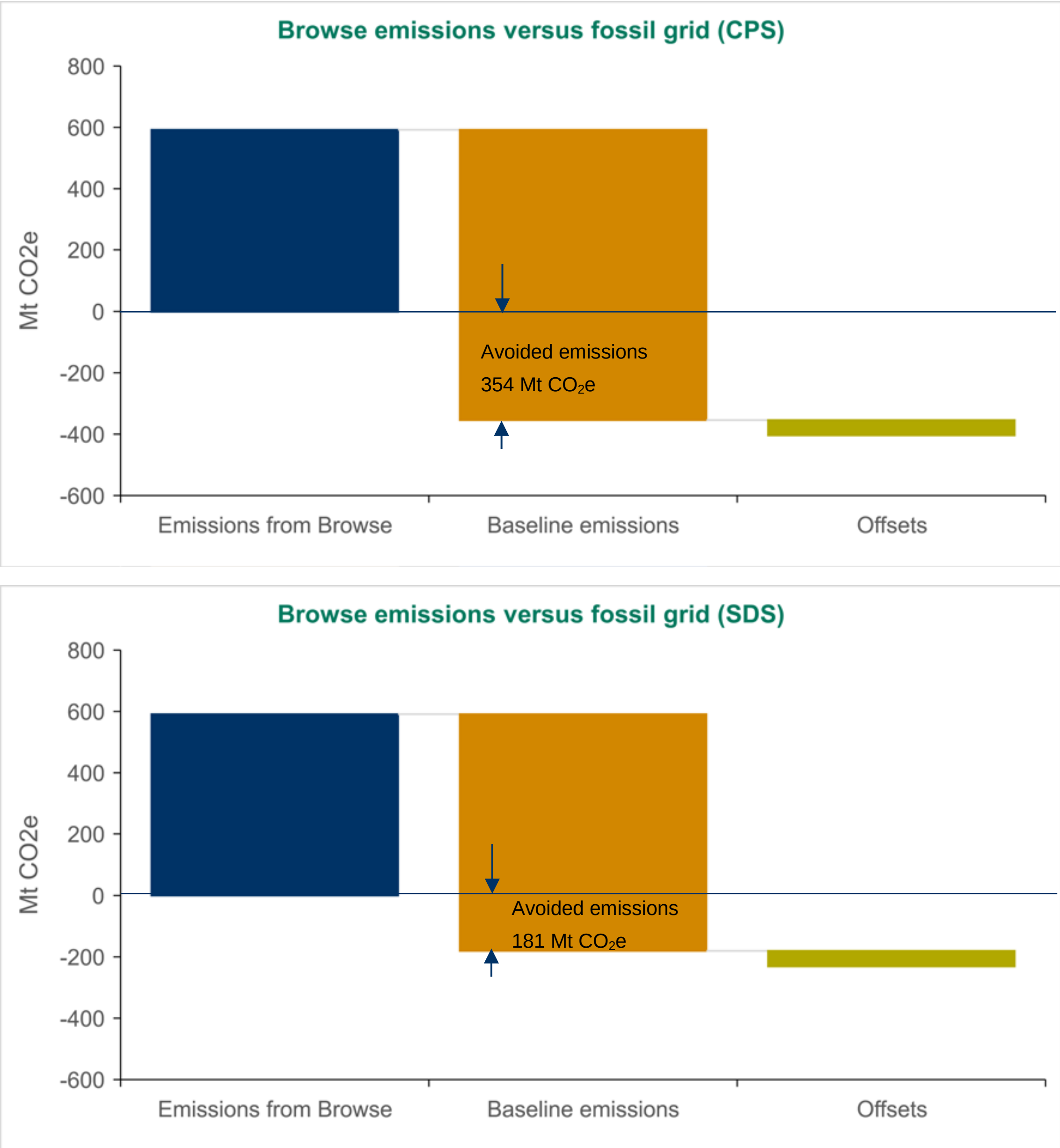
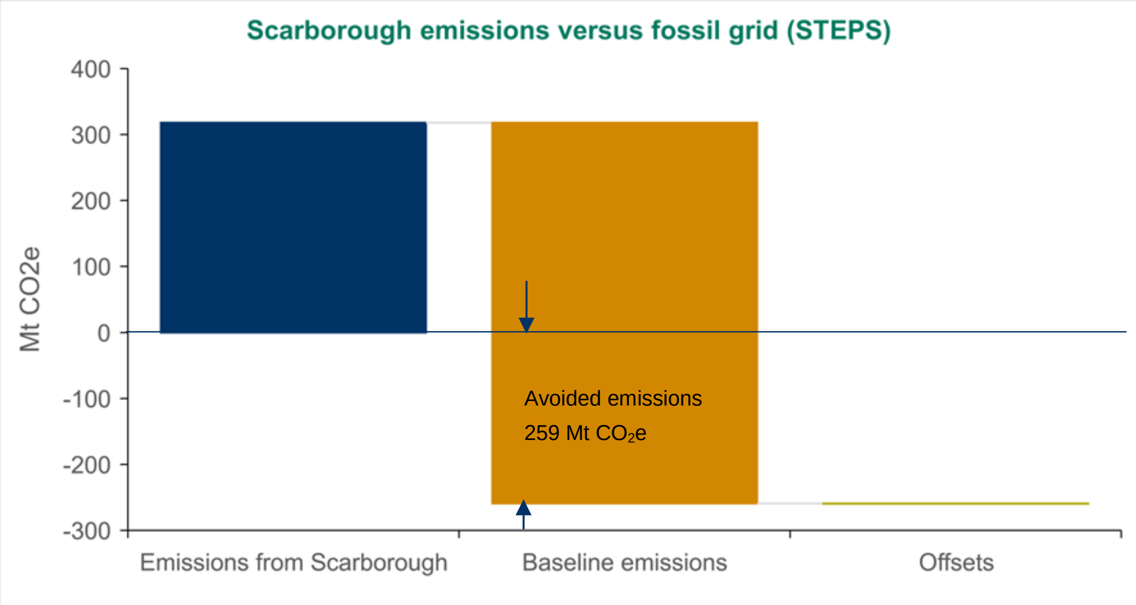
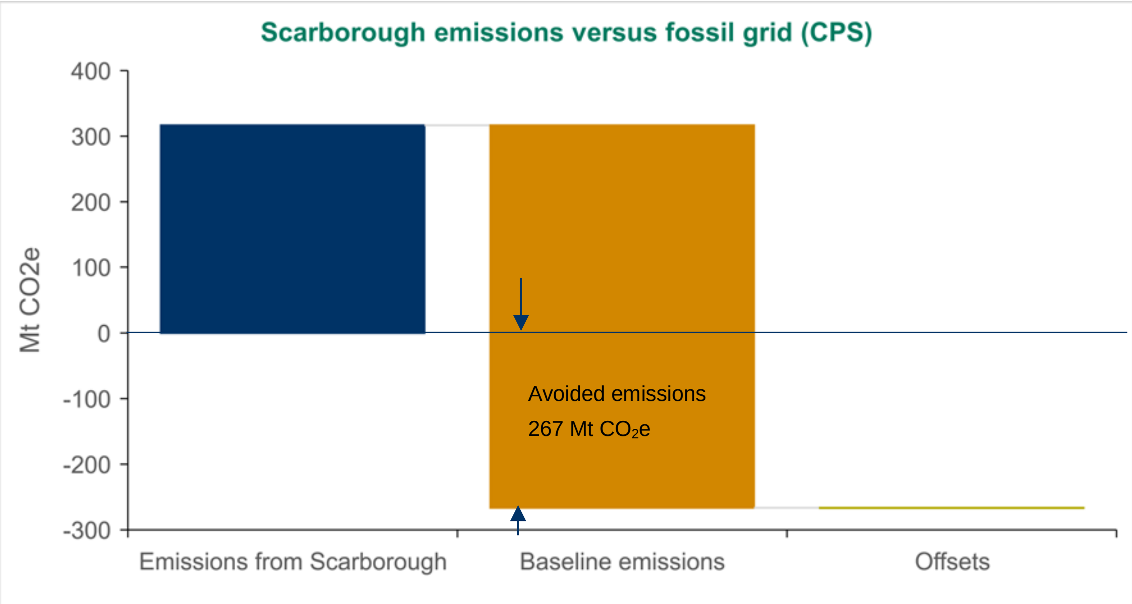


Figure 6-6 Emissions of Browse-Sourced Power versus Fossil Grid under IEA Scenarios

Figure 6-7 covers the impact of Scarborough-sourced power under the various scenarios. Due to the lower average emissions intensity of Scarborough gas versus Browse, and the lower delivered volumes from the project, emissions total between 316 Mt CO_2e and 318 Mt CO_2e over the 2026 – 2040 period. When displacing fossil-sourced power, avoided emissions are 259 Mt CO_2e under the STEPS, 267 Mt CO_2e under the CPS, and 165 Mt CO_2e under the SDS.

Figure 6-7 also takes into account the use of CO_2e offsets for Scarborough, to compensate for CO_2 vented at the field, as required by Pluto's environmental license condition. Use of offsets effectively reduces emissions versus the baseline by a further 0.2 Mt CO_2e under each scenario.


Scarborough emissions versus fossil grid (STEPS)
400
300
200
100
0
-100
-200
-300
Mt CO2e
Avoided emissions
259 Mt CO_2e
Emissions from Scarborough
Baseline emissions
Offsets


Scarborough emissions versus fossil grid (CPS)
400
300
200
100
0
-100
-200
-300
Mt CO2e
Avoided emissions
267 Mt CO_2e
Emissions from Scarborough
Baseline emissions
Offsets

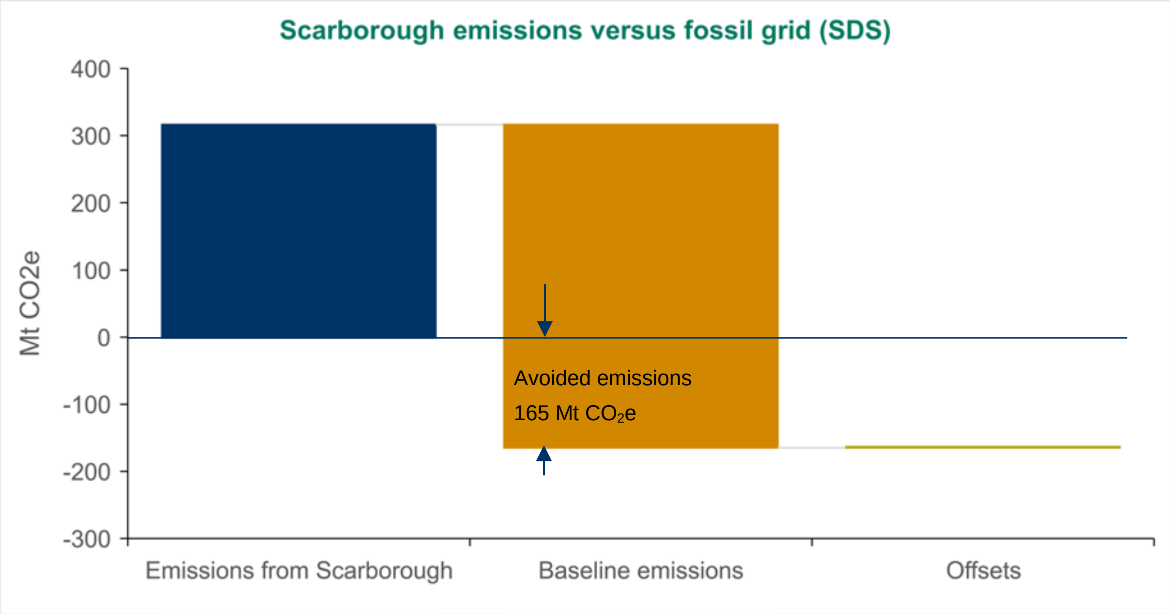


Figure 6-7 Emissions of Scarborough-Sourced Power versus Fossil Grid under IEA Scenarios

6.1.5 *Emissions Intensity Results: Browse Versus Scarborough*

Figure 6-8 show that the climate change impacts for producing 1 GJ of natural gas are higher for Browse (19.65 kg CO_2e) than for Scarborough (10.5 kg CO_2e) mainly due to the associated CO_2 venting at field and higher impacts from offshore gas processing. This compares reasonably with factors for domestic gas production in different states in Australia, which vary from 3.9 to 13.6 kg CO_2e (Department of Energy and Environment (2019)

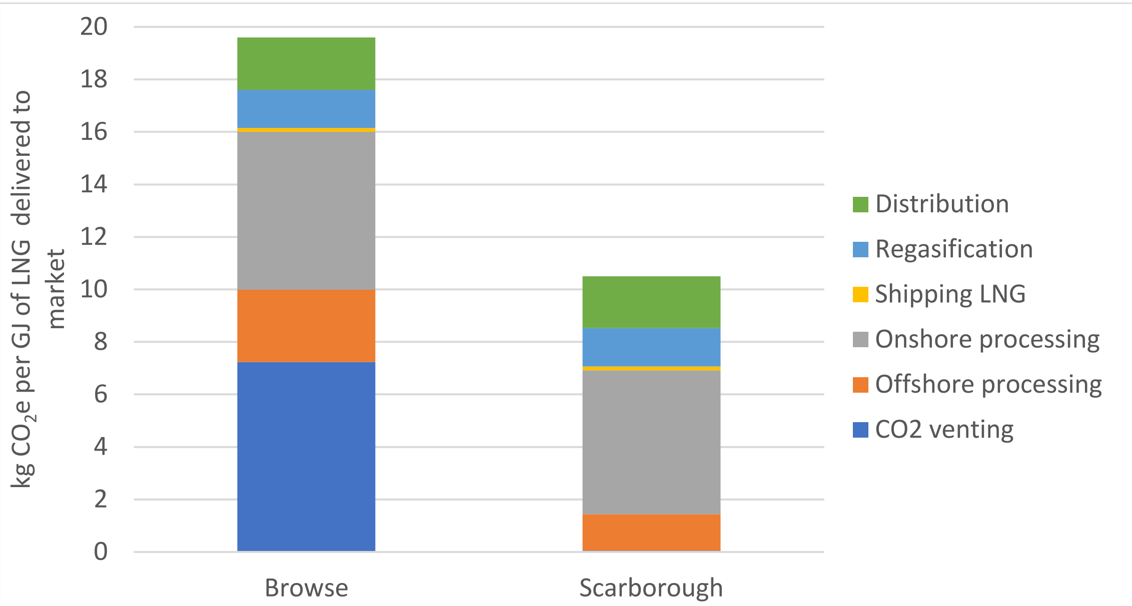


Figure 6-8 Climate Change Results for 1 GJ from Gas Distributed in China

Table 6-2 and **Figure 6-9** shows the impact of the same 1 GJ of gas but also includes its combustion in China. The upstream gas production processes account for 26% and 16% of the electricity climate change results for Browse and Scarborough respectively.

Table 6-2 Climate Change Results for 1 GJ of LNG from Browse and Scarborough Combusted in China

	Combustion	Distribution	Regasification	Shipping LNG	Onshore Processing	Offshore Processing	CO_2 Venting	Total
Browse kg CO_2e	56.10	1.99	1.46	0.15	6.02	2.74	7.24	75.70
Browse % of process	74%	2.6%	1.9%	0.2%	8.0%	3.6%	9.6%	
Scarborough kg CO_2e	56.10	1.98	1.46	0.15	5.47	1.39	0.05	66.60
Scarborough. % of process	84%	3.0%	2.2%	0.2%	8.2%	2.1%	0.1%	

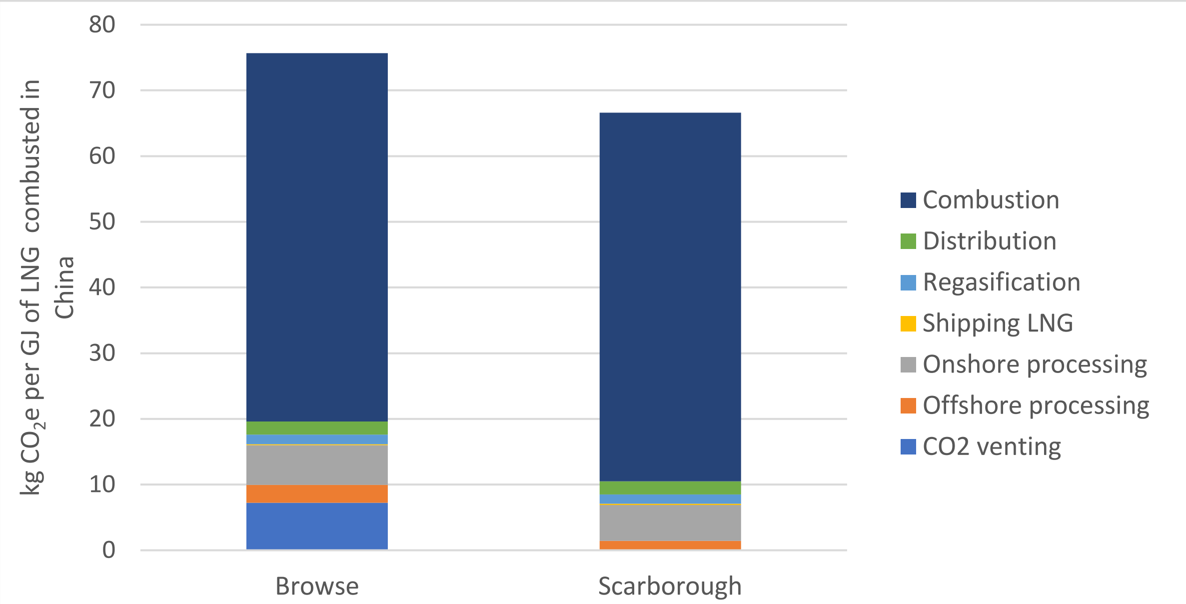


Figure 6-9 Climate Change Results for 1 GJ of LNG from Browse and Scarborough Combusted in China

6.2 Results: Other Impact Categories

Table 6-3 shows the results for electricity produced from fossil fuel portion of the grid and LNG sourced from Browse and Scarborough for all four regions, under the three different policy scenarios, averaged over the timeframe 2026-2040. **Table 6-4** and **Table 6-5** show the same results for a coal-based grid supply and an average grid supply from each region.

For particulate matter most results are an order of magnitude lower for LNG than competing grid mixes. Under the average grid comparisons, the difference is less in Japan and ASEAN regions where the advantage of LNG electricity is a factor four (four times lower) and factor two (half as much) respectively.

For photochemical smog, the results are mostly half that of the best performing grid mixes with only the average grid under SDS scenario in Japan and ASEAN region getting close to being equivalent of LNG.

For acidification LNG results are between half and a quarter of the impacts of average grid supplies in each region. When compared to fossil or coal grids mixes LNG is typically an order of magnitude lower.

Table 6-3 Results for 1 MWh Electricity from Browse and Scarborough LNG Compared to Fossil Grid Scenarios in China, Japan, ASEAN and India

Region	Unit	Climate Change t CO_2e	Particulate Matter g $PM_{2.5}e$	Photochemical Smog kg NMVOC e	Acidification mol H^+ e
China	CPS	1.00	1146	3.15	5.67
China	STEPS	1.03	1189	3.25	5.87
China	SDS	1.03	1149	3.18	5.70
China	LNG Browse	0.56	36	0.56	0.42
China	LNG Scarborough	0.49	36	0.46	0.40
Japan	CPS	0.70	222	1.68	4.03
Japan	STEPS	0.69	213	1.63	3.82
Japan	SDS	0.57	135	1.12	2.23
Japan	LNG Browse	0.50	24	0.51	0.37
Japan	LNG Scarborough	0.44	23	0.41	0.36
ASEAN	CPS	0.79	669	1.68	4.32
ASEAN	STEPS	0.77	631	1.62	4.10
ASEAN	SDS	0.64	394	1.18	2.71
ASEAN	LNG Browse	0.57	100	0.58	0.44
ASEAN	LNG Scarborough	0.49	100	0.47	0.42
India	CPS	0.96	715	2.65	4.90
India	STEPS	0.99	754	2.77	5.15
India	SDS	0.76	473	1.93	3.42
India	LNG Browse	0.57	37	0.67	0.52
India	LNG Scarborough	0.49	36	0.56	0.50

Table 6-4 Results for 1 MWh Electricity from Browse and Scarborough LNG Compared to Coal Grid Scenarios in China, Japan, ASEAN and India

Region	Unit	Climate Change t CO_2e	Particulate Matter g $PM_{2.5}e$	Photochemical Smog kg NMVOC e	Acidification mol H^+ e
China	CPS	1.09	1331	3.59	6.52
China	STEPS	1.11	1352	3.64	6.63
China	SDS	1.13	1383	3.73	6.78
China	LNG Browse	0.56	36	0.56	0.42
China	LNG Scarborough	0.49	36	0.46	0.40
Japan	CPS	0.93	353	2.58	6.89
Japan	STEPS	0.92	351	2.57	6.86
Japan	SDS	1.01	382	2.79	7.47
Japan	LNG Browse	0.50	24	0.51	0.37
Japan	LNG Scarborough	0.44	23	0.41	0.36
ASEAN	CPS	1.00	1082	2.40	6.67
ASEAN	STEPS	1.01	1085	2.41	6.69
ASEAN	SDS	1.03	1107	2.46	6.83
ASEAN	LNG Browse	0.57	100	0.58	0.44
ASEAN	LNG Scarborough	0.49	100	0.47	0.42
India	CPS	1.03	796	2.87	5.35
India	STEPS	1.03	798	2.88	5.37
India	SDS	1.02	788	2.84	5.30
India	LNG Browse	0.57	37	0.67	0.52
India	LNG Scarborough	0.49	36	0.56	0.50

Table 6-5 Results for 1 MWh Electricity from Browse and Scarborough LNG Compared to Average Grid Scenarios in China, Japan, ASEAN and India

Region	Unit	Climate Change t CO_2e	Particulate Matter g $PM_{2.5}e$	Photochemical Smog kg NMVOC e	Acidification mol H^+ e
China	CPS	0.60	687	1.92	3.44
China	STEPS	0.59	678	1.89	3.39
China	SDS	0.42	473	1.36	2.41
China	LNG Browse	0.56	36	0.56	0.42
China	LNG Scarborough	0.49	36	0.46	0.40
Japan	CPS	0.48	169	1.09	2.56
Japan	STEPS	0.44	156	0.97	2.21
Japan	SDS	0.30	102	0.55	1.07
Japan	LNG Browse	0.50	24	0.51	0.37
Japan	LNG Scarborough	0.44	23	0.41	0.36
ASEAN	CPS	0.66	540	1.35	3.82
ASEAN	STEPS	0.61	477	1.22	3.47
ASEAN	SDS	0.36	206	0.60	1.97
ASEAN	LNG Browse	0.57	100	0.58	0.44
ASEAN	LNG Scarborough	0.49	100	0.47	0.42
India	CPS	0.68	520	1.94	3.56
India	STEPS	0.63	491	1.82	3.35
India	SDS	0.35	243	1.00	1.74
India	LNG Browse	0.57	37	0.67	0.52
India	LNG Scarborough	0.49	36	0.56	0.50

7. INTERPRETATION

7.1 Sensitivity Analysis Climate Change

The study covered a very broad range of options assessing the effects of the use of LNG from Browse and Scarborough. This includes:

- Assessment of four regions where LNG may be sold;
- Assessment of three policy scenarios for grid mixes in the future; and
- Assessment of average, fossil and coal grid mixes as displaced electricity mixes.

An additional sensitivity is included below to test the impact of higher than anticipated methane fugitive emissions across the supply chain.

7.1.1 Fugitive Methane Emissions across the LNG Processing Supply Chain

The fugitive emission of methane (CH_4) is a potential concern given the global warming potential of methane is 25 times that of CO_2. Methane is emitted from a variety of points along the LNG supply chain and whilst the data for Woodside operations are robust, only generic data from ecoinvent have been available for other parts of the supply chain. Not all emissions are fugitive, as some are residual methane after combustion, and some are methane contained in venting emissions. **Table 7-1** shows the current emissions of methane across the supply chain for LNG from both Browse and Scarborough. Browse has total methane emissions equivalent to 0.125% of gas delivered while Scarborough is 0.107%. For this sensitivity we compared the current result with the median and highest results from the ecoinvent data.

Table 7-1 Methane Emissions from the LNG Supply Chain for Scarborough and Browse, as percentage of GJ of Gas Delivered

	Browse	Scarborough
Offshore AGRU	0.010%	Not Applicable
Offshore fugitive	0.000010%	0.00014%
Offshore flare	0.000007%	0.00022%
Onshore fugitive	0.011%	0.005%
Onshore flare	0.002%	0.003%
Shipping	0.0001%	0.0001%
Transmission	0.032%	0.032%
Other individual upstream processes <0.0001%	0.070%	0.067%
Total	0.125%	0.107%

An analysis of 29 different region high pressure gas supply inventories from ecoinvent LCA database has methane values ranging from as low as 0.096% of gas supplied, up as high as 1.85% with a median value of 0.78% (shown in Appendix A). The difference between the ecoinvent results compared to the Browse and Scarborough results can be explained in part because ecoinvent is based historical data and Browse and Scarborough are based predominantly on current and/or new technology and equipment. Nevertheless, it is valuable to examine the sensitivity of the results to potentially higher methane fugitive emissions.

Table 7-2 show the results of a sensitivity when varying the total methane fugitive emissions between the current value (0.125% for Browse and 0.107% for Scarborough), to both 0.78% and 1.85% respectively for Browse and Scarborough in all regions. These two values have been used for demonstration purposes and does not infer that these are likely scenarios

At 0.78% fugitive emissions the electricity production climate change result increases by 4% for Browse and 5% for Scarborough which flows on to reduce the overall emission offset by 7%. At 1.85% fugitive emissions the electricity production climate change result increases by 12% for Browse and 14% for Scarborough which flows on to reduce the overall emission offset by 19%.

Table 7-2 GWP (tCO_2e/MWh of electricity) Results Variation with Different Methane Emission Levels (China Scenario) and Total Project Emission Offsets

	Current	0.78% Fugitive	1.85% Fugitive
Browse tCO_2e per MWh	0.561	0.585	0.624
% change to result for 1 GJ of gas		4%	11%
Scarborough tCO_2e per MWh	0.487	0.512	0.551
% change		5%	13%
Avoided emissions for STEPS scenario based on fossil grid.	601	558	489
% change in avoided emissions for STEPS scenario based on fossil grid.		-7%	-19%

7.2 Contribution Analysis: Particulate Matter

Table 7-3 shows the process contribution to particulate matter results for Chinese average grid, electricity from Browse and Scarborough LNG in China. The electricity from coal production is main contributor with onsite power generation at the mine being the most significant source. For LNG the emissions are small, with the largest component being from use of grid electricity for regasification in the destination country.

Table 7-3 Particulate Matter Process Contributions for Average Chinese Grid Electricity and Electricity from LNG in China (kg $PM_{2.5}$ e /MWh)

	Average Grid China	Electricity from Browse LNG	Electricity from Scarborough LNG
Electricity production, hard coal	0.134	<0.001	<0.001
Electricity, co-generation, wood chips	0.007	<0.001	<0.001
Electricity production, hard coal, at coal mine	0.512	0.013	0.013
Electricity production, LNG	<0.001	0.003	0.003
Excavation, skid-steer loader (pipeline infrastructure)	<0.001	0.001	0.001
Natural gas processing plant	<0.001	0.001	0.001
All remaining processes	0.034	0.018	0.018
Total	0.687	0.036	0.036

7.3 Contribution Analysis: Photochemical Smog

Table 7-4 shows the process contribution to photochemical smog for Chinese average grid, electricity from Browse and Scarborough LNG in China. The majority of the emissions are from coal fired power, with the main contributor being nitrogen oxide emissions. The most significant contributions for electricity from LNG are from the use of onshore LNG compressors. The remaining processes contribute a lot of very small amounts from across the supply chain.

Table 7-4 Photochemical Smog Process Contributions for Average Chinese Grid Electricity and Electricity from LNG in China (kg NMVOCe /MWh)

	Average Grid	Electricity from Browse LNG	Electricity from Scarborough LNG
Electricity production, LNG	<0.01	0.20	0.20
Excavation, skid-steer loader (pipeline infrastructure)	<0.01	<0.01	0.02
Natural gas, burned in gas compressors, onshore	<0.01	0.14	0.04
Natural gas, burned in gas compressors, offshore	<0.01	0.04	0.04
Natural gas, GT, electricity generation, onshore	<0.01	<0.01	0.03
Electricity production, hard coal	1.50	<0.01	<0.01
Electricity production, at coal mine from coal	0.08	<0.01	<0.01
Hard coal mine operation	0.05	<0.01	<0.01
All remaining processes	0.29	0.17	0.13
Total	1.92	0.56	0.46

7.4 Contribution Analysis: Acidification

Table 7-5 shows the process contribution acidification results for Chinese average grid, electricity from Browse and Scarborough LNG in China. Coal-fired power generation is the largest contributor to acidification from the Chinese average grid. This is caused mostly by sulphur oxides and nitrogen oxide emissions. The largest acidification contribution from electricity from LNG is from nitrogen oxide emissions from natural gas combustion in the electricity power plant.

Table 7-5 Acidification Process Contributions for Average Chinese Grid Electricity and Electricity from LNG in China (mol H^+e /MWh)

	Average Grid China	Electricity from Browse LNG	Electricity from Scarborough LNG
Electricity production, LNG	<0.01	0.14	0.14
Gas compressors at onshore	<0.01	0.04	0.02
Gas compressors at offshore	<0.01	0.03	0.03
GT, electricity generation, Pluto	<0.01	<0.01	0.02
Natural gas processing plant	<0.01	<0.01	<0.01
Electricity production, hard coal	2.72	<0.01	<0.01
Electricity, co-generation, wood chips	0.05	<0.01	<0.01
Electricity production, hard coal, at coal mine	0.29	<0.01	<0.01
All remaining processes	0.38	0.21	0.19
Total	3.43	0.42	0.40

7.5 Data Quality Assessment

Table 7-6 shows the data quality assessment for the LCA. As Woodside own and operate LNG infrastructure the access to data is excellent, with the main uncertainties being the need to extrapolate to the future. For power generation technologies, ecoinvent has high quality data as this area has been studied extensively in LCA over many years due to its high impact in most LCAs. The ecoinvent 3.5 release updated much of the data on electricity production and expanded coverage globally. The data on grid mixes and energy efficiency is good at the macro level for countries, with the main difficulties being the inherent uncertainties of modelling into the future and the limitation of collecting data from many nation states.

Table 7-6 Data Quality Assessment for LCA

Process	Reliability	Time Period	Geography	Technology	Representativeness	Comment
Offshore extraction and processing	Good	Good	V.Good	V.Good	V.Good	The data are sourced directly from the teams designing gas extraction and processing. Data are extrapolated from current practice across the next 15 years of extraction.
Onshore gas processing	Good	Good	V.Good	V.Good	V.Good	The data are sourced directly from the existing gas processing facilities. Data are extrapolated from current to future processing
Shipping LNG	V.Good	Good	V.Good	V.Good	Good	The data are sourced directly from the existing shipping operations.
Regasification	Good	Fair	Good	Good	Fair	Data are source from ecoinvent for Japan for evaporation of LNG into the distribution system. Data were extrapolated to other geographies with adaption of the grid mix.
Distribution	Good	Fair	Good	Good	Fair	Data are sourced from ecoinvent for distribution in Japan. Data were extrapolated to other geographies with adaption of the grid mix.
Power generation natural gas, coal and oil	Good	Good	Good	Good	Good	All power generation data with the exception of efficiencies are taken directly from ecoinvent 3.5 which has updated power generation technologies for many countries. Where are large range of power generation regions were included the median region based on climate change impacts was chosen as representative median of the country. Generation efficiency interpreted from IEA published fuel use and power generation projections for each of the regions examined and averaged between 2026 and 2040

Process	Reliability	Time Period	Geography	Technology	Representativeness	Comment
Power generation renewables	Good	Fair	Good	Fair	Fair	All power generation data with the exception of efficiencies are taken directly from ecoinvent 3.5 which has updated power generation technologies for many countries. Where are large range of power generation regions were included the median region based on climate change impacts was chosen as representative of the country. Technology does not change through timeframe.
Power generation nuclear	Good	Good	Good	Fair	Fair	All power generation data with the exception of efficiencies are taken directly from ecoinvent 3.5 which has updated power generation technologies for many countries. Where are large range of power generation regions were included the median region based on climate change impacts was chosen as representative of the country. Technology does not change through timeframe.
Grid mixes	Fair	Good	V.Good	Good	V Good	Based on IEA published grid scenario for the future for each of the regions examined and averaged between 2026 and 2040

8. DISCUSSION AND CONCLUSIONS

8.1 Discussion

This study indicates that gas, sourced via LNG from the Browse and Scarborough developments can help facilitate the energy transition to lower-carbon electricity generation in Asia Pacific markets, even under transformative decarbonisation scenarios. The key is the flexibility of gas as a fuel, and the proximity of Browse and Scarborough to markets which are simultaneously high-growth, and at a relatively early stage of the transition to lower-carbon energy.

Gas, combusted as either a power generation fuel or for heating, industry or cooking, is a cleaner fuel than coal. The analysis indicates that electricity generated from Browse or Scarborough-sourced LNG has significant benefits in reducing photochemical (ground-level) ozone formation, acidification, and particulate matter generation in all modelled regions, for both the IEA's STEPS and CPS scenarios. The benefit of LNG sourced electricity are sustained in the SDS, which demands a wholesale shift away from coal towards lower-carbon fuels (renewables and nuclear) and also gas. Critically, the impact of gas remains a beneficial one across all scenarios, in comparison to the fossil mix in the grid.

With regard to climate change, the picture is more nuanced, but still positive. From a power sector emissions intensity perspective, Asia Pacific markets are generally characterised as 'high carbon', featuring a large share of coal in the overall mix. Adding gas from Browse or Scarborough to the power mix is expected to lead to a decline in CO_2e emissions intensity in comparison to the fossil mix in the grid in each market under consideration, to at least 2040.

8.2 Limitations of the Study

The forecast of future production always comes with a degree of uncertainty. In particular the emission profiles predicted for Browse and Scarborough are based on current design and estimates of operational parameters.

The policy scenarios developed by the IEA are not forecasts, but rather highly specific views of what the future could look like under certain conditions. Nevertheless, they represent a reasonable boundary for the lower and upper range of technology development and implementation.

When analysing the net benefits or impacts gas might have in the electricity generation in each target market, the likely long-run marginal fuel (what type of electricity generation will be constructed, if additional or replacement generating capacity is required) should be considered. This will depend on several factors, but is likely to be fossil-based, rather than renewables or nuclear. Therefore comparing Browse and Scarborough gas to the fossil mix in the grid gives a fair assessment of its relative benefits.

In this study, grid mixes are predicted for the future, but current technology is used for each individual generation type. It can be expected that future generation could improve efficiencies, especially for renewable electricity generation.

The IEA scenarios take no account of carbon capture and storage, which could become a requirement for fossil fuelled electricity generation within the study period.

8.3 Conclusion

For climate change, LNG impacts vary through time, but are net negative (i.e. the CO_2e emissions burden is lower) on the basis of electricity derived from Browse and Scarborough LNG competing with average fossil fuelled electricity generation, in the markets under consideration, under all scenarios.

Increasing LNG electricity generation in Asia Pacific will improve air quality outcomes compared to all grid mixes projected by the IEA. For the fossil grid mix, the photochemical impact is almost twice as high as LNG, and the acidification impact four times higher. Only when the SDS is fully implemented in Japan do the photochemical and acidification impacts trend close to those from LNG electricity.

For particulate matter impacts Browse and Scarborough LNG electricity is eight times lower than the fossil based electricity mix under the SDS scenario. For all other scenarios and regions, the impacts of average fossil grids are more than 10 times that of LNG electricity in that region.

Understanding how electricity sourced from Browse and Scarborough LNG performs against electricity from other fossil fuels is critical, as this reflects most closely how gas will compete in the target markets. Gas-on-renewables competition is considered to be limited, due to policy support and falling costs for renewables under the STEPS and especially the SDS scenarios, and the limited presence of renewables under the CPS. Furthermore, physical constraints on the development of renewables are likely in three of the four target markets[8], meaning imported fossil energy will remain essential to satisfy growing demand.

Even under very ambitious scenarios such as the SDS, gas can play a role in delivering the lower-carbon energy transition. In fact, the success of achieving a lower-carbon outcome as described by the SDS is predicated on the increased use of gas in the target markets, especially in the years to 2030.

[8] Electricity generation technology cost projections 2017 – 2050, CSIRO 2017

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APPENDIX A ASSUMPTIONS AND LIMITATIONS.

Assumptions and Limitations

Assumptions

HC and VOC emissions – assumed to be 98% methane, 2% non-methane VOC
Emissions intensity for projects has been determined based on the time that they are operating at full output. This data has been applied to the full time scale – including a short period before Browse has even been constructed.

Limitations

- This report was performed by ERM Australia Pty Ltd (ERM) for Woodside Energy Ltd (the Client). The Scope of Work was governed by a contract between ERM and the Client (4610001822).
- No limitation, qualification or caveat set out below is intended to derogate from the rights and obligations of ERM and the Client under the Contract.
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  b. must not be relied upon or used by any other party outside of the intended use (8a) ;

  c. does not purport to provide, nor should be construed as, legal advice.

- Methane emissions from high pressure gas supply to different regions in ecoinvent LCA database. **Figure A-9-1** shows the results for methane emission for different regions included in ecoinvent LCA database (version 3.5, Allocation at Point of Substitution version) using the market processes. The regions are identified by ISO two letter country codes with two value for Canada (CA-QC for Quebec) and CA-AB Alberta) and row is the default value for rest of world and GLO stands for global average. Note that none of these are specifically for LNG supply chain but each country includes a mix of gas supply.

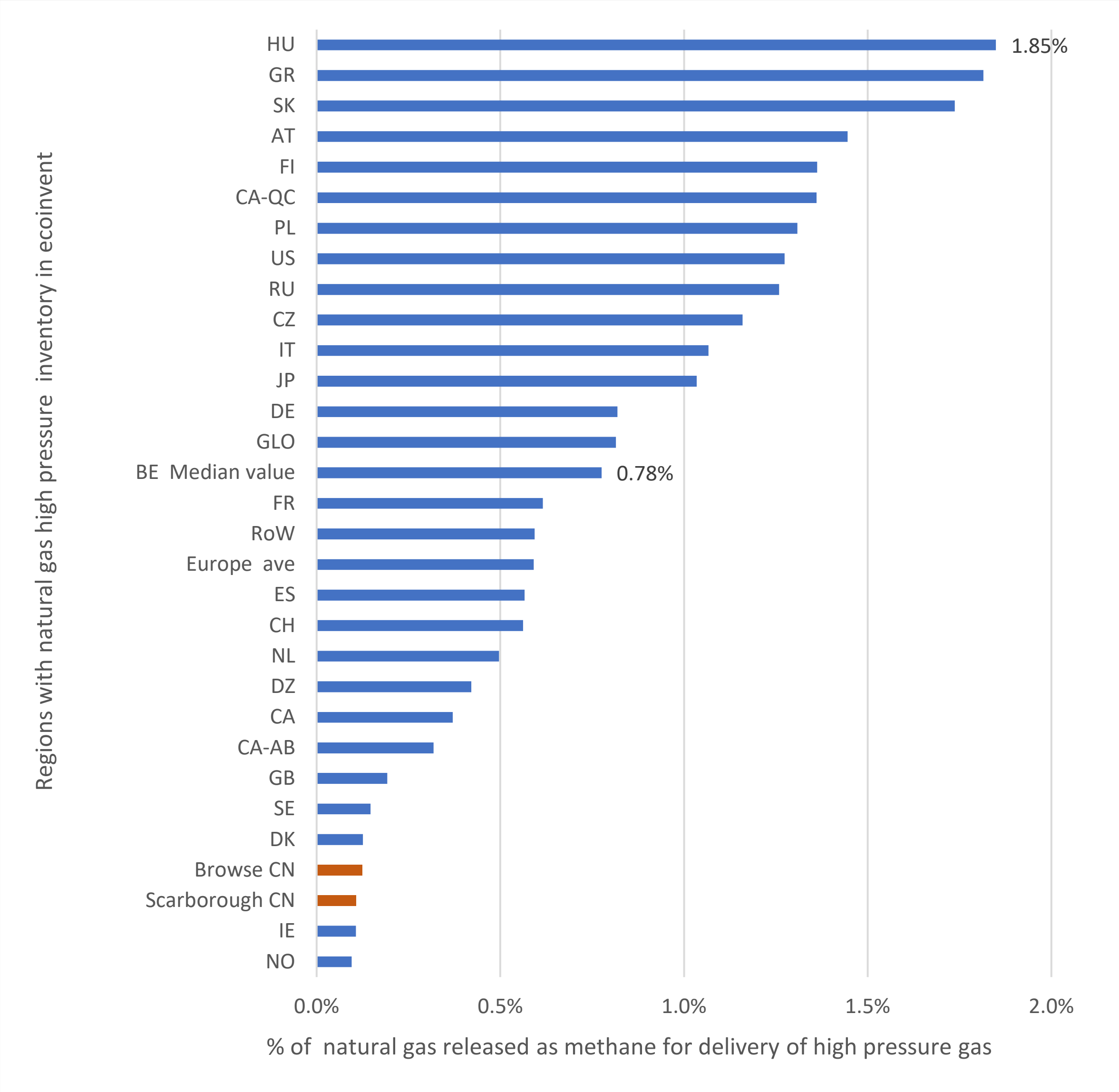

Figure A-9-1 Methane Emission Results as % of Natural Gas for Different Regions Included in Ecoinvent LCA Database

APPENDIX B LIFE CYCLE INVENTORY FOR LNG PRODUCTION.

B – Foreground LCA data from Woodside

Please note: granular production and emissions data for Browse, Scarborough and shipping has been removed from Appendix B of this public report since it is commercially sensitive.

Regasification

Data from ecoinvent is used for both the electricity use and infrastructure for regasification of gas into the regions distribution network, however the electricity is localised to each regional market. Table B-9-1 shows the process flows for regasification of gas.

Table B-9-1 Process Flows for Regasification of 1m^3 Gas in Destination Market

Process	Unit	Flow
Process output		
Gas evaporated into gas network at overseas market	m^3	1
Process inputs		
Electricity, medium voltage (local grid)	kWh	0.051
Natural gas processing plant,	Plants	7.89E-13
LNG	MJ	38.6[1]

[1] Note this energy content is the value used in the ecoinvent and is therefore used to scale the regasification inputs in this inventory.

Gas Transmission

The data have been sourced from ecoinvent global databases 3.5 (Weidema, Bauer et al. 2018) and data from Japan have been used for all regions as specific data for other regions assessed is not available.

The data from ecoinvent is used for both the electricity use and infrastructure but the electricity is localised to each regional market. **Table B-9-2** shows the process flows for gas transmission.

Table B-9-2 Process Flows for Natural Gas Transmission in Destination Market

Process	Unit	Flow
Process output		
Natural gas, at powerplant	GJ	1
Distribution fugitives	kg	0.0057
Inputs		
LNG, regasified into local transmission network	GJ	1.0131
Heat, from natural gas	GJ	0.0014
Electricity, medium voltage (local grid)	kWh	0.063
Pipeline, natural gas, high pressure distribution network	km	2.253E-05

1 Note that the gas loss of 0.013 GJ is not all lost to fugitives in the original ecoinvent inventory.

APPENDIX C LIST OF ECOINVENT ELECTRICITY INVENTORIES USED IN REGIONAL GRIDS

Appendix C List of Ecoinvent Electricity Inventories Used in Regional Grids

Electricity Processes Included in Chinese Grid

The coal, oil and gas grids were selected based on the median climate change impact grid. Photovoltaic electricity was taken from Japan as Chinese data were too complex. Geothermal was taken from Japanese process as one was not available for China

- Electricity, high voltage [CN-GZ}| electricity production, hard coal | APOS, U
- Electricity, high voltage [CN}| electricity production, hydro, reservoir, non-alpine region | APOS, U
- Electricity, high voltage [CN}| electricity production, hydro, run-of-river | APOS, U
- Electricity, high voltage [CN}| electricity production, natural gas, existing | APOS, U
- Electricity, high voltage [CN}| electricity production, nuclear, pressure water reactor | APOS, U
- Electricity, high voltage [CN-GZ}| electricity production, oil | APOS, U
- Electricity, high voltage [CN}| electricity production, wind, <1MW turbine, onshore | APOS, U
- Electricity, high voltage [CN}| electricity production, wind, >3MW turbine, onshore | APOS, U
- Electricity, high voltage [CN}| electricity production, wind, 1-3MW turbine, offshore | APOS, U
- Electricity, high voltage [CN}| electricity production, wind, 1-3MW turbine, onshore | APOS, U
- Electricity, high voltage [CN}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | APOS, U
- Electricity, high voltage [JP}| electricity production, deep geothermal | APOS, U
- Electricity, low voltage [JP}| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | APOS, U
- Electricity, low voltage [JP}| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | APOS, U
- Electricity, high voltage [CN-CQ}| electricity production, wind, 1-3MW turbine, onshore | APOS, U
- Electricity, high voltage [CN}| electricity production, LNG | APOS, U

Electricity Processes Included in Indian Grid

The coal, oil and gas grids were selected based on the median climate change impact grid. Photovoltaic electricity was taken from Japan as Chinese data were too complex. Solar thermal was taken from rest of world inventory as a local one was not available.

- Electricity, high voltage [IN}| electricity production, hard coal | APOS, U
- Electricity, high voltage [IN-Hydro}| electricity, high voltage, production mix | APOS, U
- Electricity, high voltage [IN-KL}| electricity production, natural gas India conventional power plant | APOS, U
- Electricity, high voltage [IN-TN}| electricity production, oil | APOS, U
- Electricity, high voltage [IN- Nuclear}| electricity, high voltage, production mix | APOS, U
- Electricity, high voltage [IN-Wind}| electricity, high voltage, production mix | APOS, U
- Electricity, high voltage [CN}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | APOS, U
- Electricity, high voltage [ID}| electricity production, deep geothermal | APOS, U
- Electricity, high voltage [JP}, solar, average
- Electricity, high voltage [RoW}| electricity production, solar thermal parabolic trough, 50 MW | APOS, U
- Electricity, high voltage [CN-CQ}| electricity production, wind, 1-3MW turbine, onshore | APOS, U
- Electricity, high voltage [IN-KL}| electricity production, LNG India conventional power plant | APOS, U

Electricity Processes Included in Japanese Grid

Japan did not have sub grids so national generation inventories were used.

- Electricity, high voltage [JP}| electricity production, hard coal | APOS, U
- Electricity, high voltage [JP}| electricity production, oil | APOS, U
- Electricity, high voltage [JP}| electricity production, natural gas, combined cycle power plant | APOS, U
- Electricity, high voltage [JP}| electricity production, nuclear, boiling water reactor | APOS, U
- Electricity, high voltage [JP}| electricity production, nuclear, pressure water reactor, heavy water moderated | APOS, U
- Electricity, high voltage [JP}| electricity production, hydro, run-of-river | APOS, U
- Electricity, high voltage [JP}| electricity production, hydro, pumped storage | APOS, U
- Electricity, high voltage [JP}| electricity production, hydro, reservoir, alpine region | APOS, U
- Electricity, high voltage [RoW}| ethanol production from sweet sorghum | APOS, U
- Electricity, high voltage [RoW}| ethanol production from wood | APOS, U
- Electricity, high voltage [JP}| electricity production, wind, <1MW turbine, onshore | APOS, U
- Electricity, high voltage [JP}| electricity production, wind, >3MW turbine, onshore | APOS, U
- Electricity, high voltage [JP}| electricity production, wind, 1-3MW turbine, offshore | APOS, U
- Electricity, high voltage [JP}| electricity production, wind, 1-3MW turbine, onshore | APOS, U
- Electricity, high voltage [JP}| electricity production, deep geothermal | APOS, U
- Electricity, low voltage [JP}| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | APOS, U
- Electricity, low voltage [JP}| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | APOS, U
- Electricity, high voltage [RoW}| electricity production, solar thermal parabolic trough, 50 MW | APOS, U
- Electricity, high voltage [JP}, wind, average
- Electricity, high voltage [JP}| electricity production, LNG, combined cycle power plant | APOS, U

Electricity Processes Included in ASEAN Grid

Mostly Indonesian processes were used with the exception of hard coal which was taken from Malaysia as a hard coal inventory was not available in ecoinvent.

- Electricity, high voltage [ID}| electricity production, deep geothermal | APOS, U
- Electricity, high voltage [ID}| electricity production, hydro, reservoir, tropical region | APOS, U
- Electricity, high voltage [MY}| electricity production, hard coal | APOS, U
- Electricity, high voltage [ID}| electricity production, natural gas combined cycle power plant | APOS, U
- Electricity, high voltage [ID}| electricity production, oil | APOS, U
- Electricity, high voltage [ID}| heat and power co-generation, biogas, gas engine | APOS, U
- Electricity, high voltage [JP}| electricity production, nuclear, boiling water reactor | APOS, U
- Electricity, high voltage [ID}| electricity production, wind, <1MW turbine, onshore | APOS, U
- Electricity, high voltage [JP}, wind, average
- Electricity, high voltage [RoW}| electricity production, solar thermal parabolic trough, 50 MW | APOS, U
- Electricity, high voltage [ID}| electricity production, LNG, combined cycle power plant | APOS, U

Electricity Processes Included in Global Grid

Thermal generation processes were selected based on median climate change impact from full range of each technology type. Average of all hydro power inventories in the ecoinvent global grid mix was used but represent too many processes to display.

- Electricity, high voltage [RoW}| electricity production, geothermal | APOS, S
- Global hydro average
- Electricity, high voltage [GLO}| electricity production, natural gas, combined cycle power plant | APOS, U
- Electricity, high voltage [CN-GS}| electricity production, hard coal | APOS, U
- Electricity, high voltage [CA-QC}| electricity production, oil | APOS, U - GLO
- Electricity, high voltage [ID}| heat and power co-generation, biogas, gas engine | APOS, U
- Electricity, high voltage [ZA}| electricity production, nuclear, pressure water reactor | APOS, S
- Electricity, high voltage [WECC, US only}| electricity production, wind, >3MW turbine, onshore | APOS, S
- Electricity, low voltage [CN-SH}| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | APOS, S
- Electricity, high voltage [RoW}| electricity production, solar thermal parabolic trough, 50 MW | APOS, U
- Electricity, high voltage [GLO}| electricity production, LNG, combined cycle power plant | APOS, U
- Electricity, high voltage, label-certified [CH}| electricity production, hydro, run-of-river, label-certified | APOS, U
- Electricity, high voltage, label-certified [CH}| electricity production, hydro, reservoir, alpine region, label-certified | APOS, U
- Global hydro average –

APPENDIX D PEER REVIEW DECLARATION

Critical Review Statement

Critical Review of the Study "Comparative Life Cycle Assessment: Browse and Scarborough. Version 22 April 2020. Project No 0541307" by Paul McConnell, Tim Grant.

Commissioned by: Woodside

Critical Review Panel: Maartje Sevenster, Jenny Hayward, Nawshad Haque (CSIRO)

Draft Date: 15 March 2020

Reference: ISO 14044:2006 Environmental Management–Life Cycle Assessment–Requirements and Guidelines

The review panel assessed that:

- the methods used to carry out the comparative LCA are consistent with ISO 14044:2006
- the methods used to carry out the LCA are scientifically and technically valid,
- the data used are appropriate and reasonable in relation to the goal of the study,
- the interpretations reflect the limitations identified and the goal of the study,
- the reporting is transparent and consistent, and meets the criteria specified by ISO 14044:2006 for studies that support comparative assertions intended to be disclosed to the public,
- the energy scenarios used for LCA-based comparisons are appropriate and relevant.

Analysis and validation of the inputs and outputs for the LNG production processes was outside the scope of this review.

Process. The review panel provided comments on the final draft of the technical report. These were discussed with the authors and informed the final report. The reviewers also evaluated the underlying life cycle inventory modelling. The process was constructive and comprehensive.

Conclusion. The study has been carried out in compliance with ISO 14044:2006. The critical review panel deems the overall quality of the study and methods to be high, and the used data appropriate and reasonable. The LCA reporting is sufficiently transparent and consistent, and meets the criteria specified by ISO 14044:2006.

Reviewer	Signature	Reviewer	Signature
Dr M. Sevenster	M Sevenster	Dr N. Haque	NHaque
Dr J. Hayward	J Hayward		

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