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# Greenhouse gas emissions from the liquified natural gas industry in Australia

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## Engagement

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# Executive summary

In 2019 Australia became the world's largest exporter of liquified natural gas (LNG). Although LNG contributes significantly to Australia's gross domestic product (or GDP) being our second most valuable export (behind iron ore), there is a need to balance the economic value, climate and environmental considerations. Accordingly, similar to many other countries, Australia committed to the Paris Agreement and more recently to net zero emissions by 2050. It has also committed to reduce greenhouse gas emissions by 43% below 2005 levels by 2030[1]. Importantly, even though gas/LNG produces greenhouse gas emissions when burnt to produce energy there is a role for gas/LNG to play in the transition to renewable and low emission technologies to achieve Australia's net zero goal. A first step in understanding this role is a robust understanding of the magnitude of the emissions related to LNG.

This study collated publicly available data from multiple resources in order to provide a picture of the magnitude of greenhouse gas emissions related to the LNG industry in Australia. To help provide context, the Australian greenhouse gas emissions are compared with the emissions of three of the other major exporters of LNG after Australia; Qatar, USA and Russia respectively. Information on the emissions from Qatar, USA and Russia was derived from a number of reputable sources including peer reviewed journal papers and government reports; however, it should be noted that as Qatar and Russia have no compulsory reporting schemes, the authors of above studies relied in some cases on models and as such, the data may not be fully accurate.

An important perspective is Australia's government policy around greenhouse gas reduction and reporting requirements and how these compare with other major LNG exporting countries. Australia has several major policy areas that relate to emissions regulation including the National Greenhouse and Energy Reporting (NGER) Scheme. LNG companies are required to report their emissions under this scheme, which is comparable to the US EPA laws but more comprehensive than current requirements in Russia and Qatar. Australia also has laws for the creation of carbon credits that can be sold to the government or traded. Several LNG companies are using carbon credits to offset their emissions.

To estimate the total scope 1 and 2 emissions from the Australian LNG industry we gathered data from a variety of sources including the NGER scheme and company sustainability reports. Based on this, we estimate that the total scope 1 and 2 emissions for the industry in Australia were approximately 37,519,000 and 4,232,000 tonnes $CO_2e$ respectively in the 2019/2020 financial year. By comparison, the Australia's total greenhouse gas emission for 2019-2020 were 513.5 Mt $CO_2e$[2].

To understand where the largest emissions occur in its life cycle, we reviewed life cycle studies of Australian LNG. LNG from Queensland has been well covered by life cycle studies and the total emissions including upstream, liquefaction and shipping but excluding final use (combustion and regasification) was 11.23 kg $CO_2e$/GJ or 0.611 t $CO_2e$/t LNG.

Life cycle emissions from other projects in Australia are less conclusive. Several studies have calculated emissions from Western Australian projects. However, these suffered from uncertainty related to the injection of $CO_2$ from Chevron's Gorgon project and also did not generally include final emissions due to combustion. Based on current studies we can only conclude a range from 7.06 to 17.49 kg $CO_2e$/GJ (0.38-0.95 t $CO_2e$/t LNG) for the combined upstream, liquefaction and shipping. For the Northern Territory, very few studies have been done and these are inconclusive. Based on the available lifecycle studies, Australian LNG (excepting Gorgon) may be comparable in total life cycle emissions to LNG from Qatar and Russia, albeit there is an amount of uncertainty surrounding emissions from Russia and Qatar; and lower in emissions than LNG from the USA based on delivery to China.

# 1 Introduction

Australia is now the world's largest exporter of liquified natural gas (LNG) having surpassed Qatar in 2019. In 2020-21 Australia exported 78 million tonnes of LNG worth $30 billion. This placed LNG second only to iron ore (at $153 billion) in terms of value of key exports[3]. Clearly, the LNG industry is highly significant in Australia and contributes greatly to our export earnings and economic prosperity. However, LNG produces greenhouse gases when it is burnt to produce energy, which is it's predominate use.

Greenhouse gases may be produced at different stages of the production chain such as at the wells, liquefaction process and shipping. Data on the greenhouse gas emissions from the LNG industry is publicly available but is scattered across a variety of sources and to date there has not been any single publication that seeks to bring together all the available data.

This project aimed to provide a single publicly available resource to inform evidence-based decision making. Specifically, this project examined the total greenhouse gas emissions occurring within Australia due to the LNG industry and the emissions that occurs across the entire life cycle of the LNG, from production to end use outside of Australia.

To put these emissions in context, we also briefly reviewed Australia's related government policies and those of other major LNG exporting countries. We also compared the greenhouse gas emissions of Australian LNG with LNG from three other major international exporters (after Australia) and industry efforts in Australia to reduce emissions.

## 1.1 The Australian LNG industry value chain

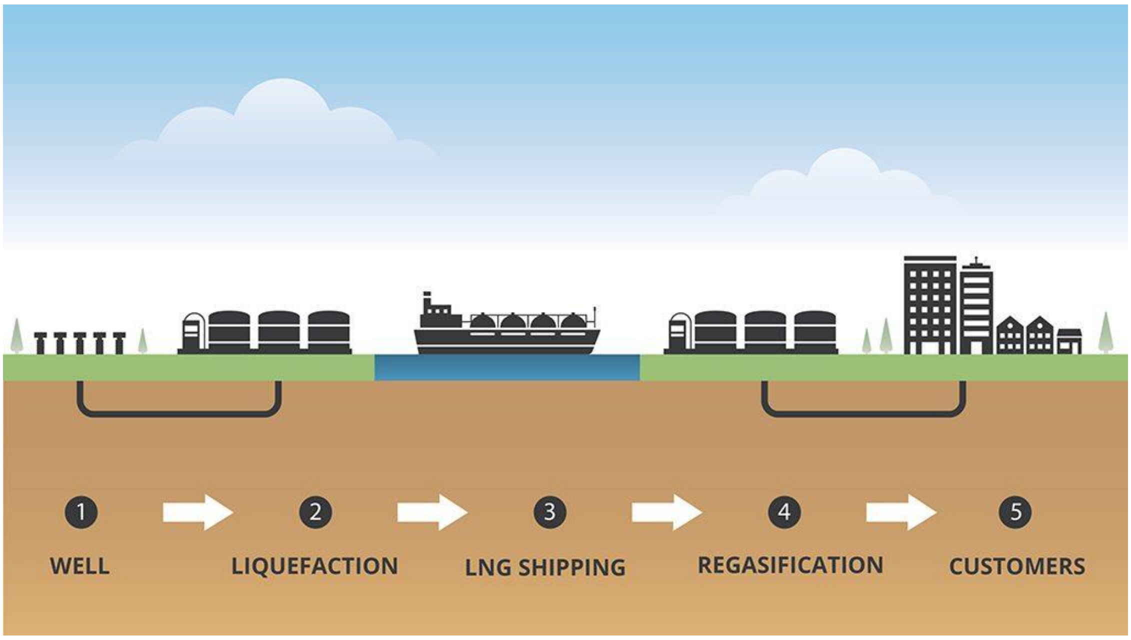


**Figure 1 Stages in the production and use of LNG from https://energyinformationaustralia.com.au/oil-and-gas-explained/how-is-oil-and-gas-produced/liquefied-natural-gas-lng/**

Figure 1 shows the stages in the production and use of LNG. Natural gas is produced at wells and is then transported to a liquefaction facility via pipelines. There is usually some preliminary processing and treatment done on the gas before it reaches the liquefaction facility (not shown). At the liquefaction facility, the natural gas is cooled to -162°C at which point it turns to a liquid at near atmospheric pressure and is stored in large tanks. The LNG is loaded onto specially designed vessels and then shipped to its destination overseas where it is converted back into a gas and sent via pipelines to customers [4-5].

Broadly speaking, there are two production pathways for LNG in Australia: LNG from onshore coal seam gas (CSG) (Figure 2) and LNG from offshore conventional gas. The final liquefaction and shipping stages of these two types are similar; however, the upstream production and processing is quite different. The production of coal seam gas uses thousands of onshore wells that intersect coal seams at relativity shallow depths (less than 1000 m). At the well head water is pumped from the coal formation to allow the gas to flow [6-7]. The water and gas are separated at the well and sent via their own separate gathering lines. The produced water may pass through a series of ponds and treatment plants before being discharged or used in agriculture. Similarly, the gas may pass through a nodal compressor station before reaching a regional treatment and compression hub. CSG production therefore involves a relatively large number of smaller, onshore facilities upstream of the liquefaction plant spread over a large area [8-10]. The facilities may generate their own energy using some of the gas they produce, however many of them now draw electricity from the local grid[11].

Unlike conventional offshore gas, coal seam gas does not produce liquified petroleum gas (LPG) or condensate. Some of the gas that is produced is also sold domestically (eastern states only) and not converted to LNG[12]. The upstream facilities may also be owned and operated by different corporate entities to the downstream facilities who may also trade gas with each other.

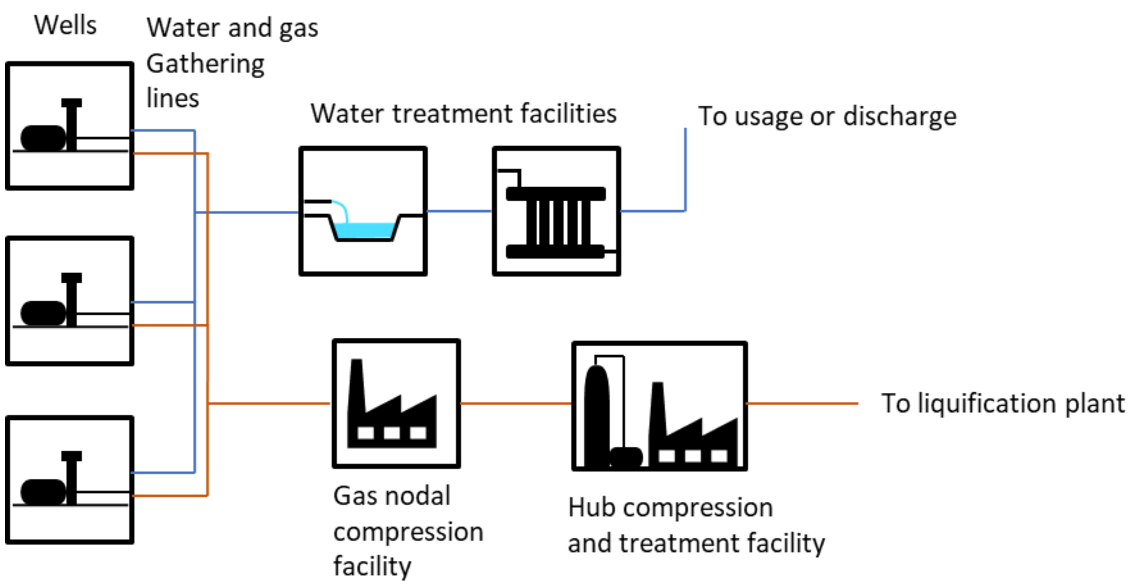


**Figure 2 Stages in LNG production from coal seam gas.**

Figure 3 shows the major components of the upstream production of offshore conventional natural gas. In contrast to CSG, there are significantly fewer but larger facilities located offshore. A single liquefaction plant (located onshore) might be fed by only a few production platforms or subsea structures[10]. The upstream assets tend to be operated by the same corporate entities as the liquefication facilities, and upstream assets only supply gas to a single liquefaction plant. Conventional natural gas will usually produce condensate in addition to the gas, which is a type of light oil, as well as liquified petroleum gas (LPG). Many of the facilities also supply gas to the domestic (WA only) network and so not all the gas they produce is exported as LNG[13-15]. They are usually almost entirely self-sufficient in electricity and generally do not purchase power from the domestic grid[16].

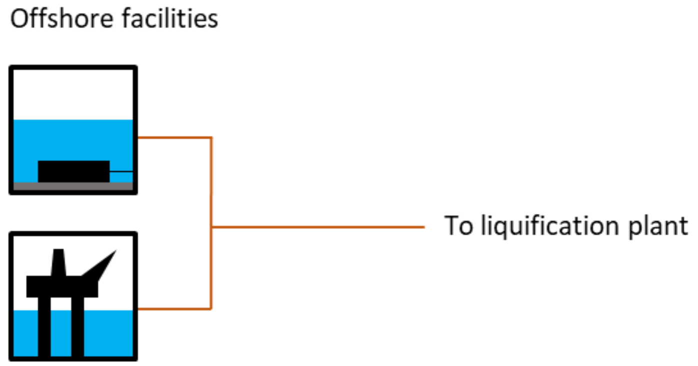


**Figure 3 Stages in LNG production from offshore conventional gas.**

## 1.2 Location of Australian LNG export projects

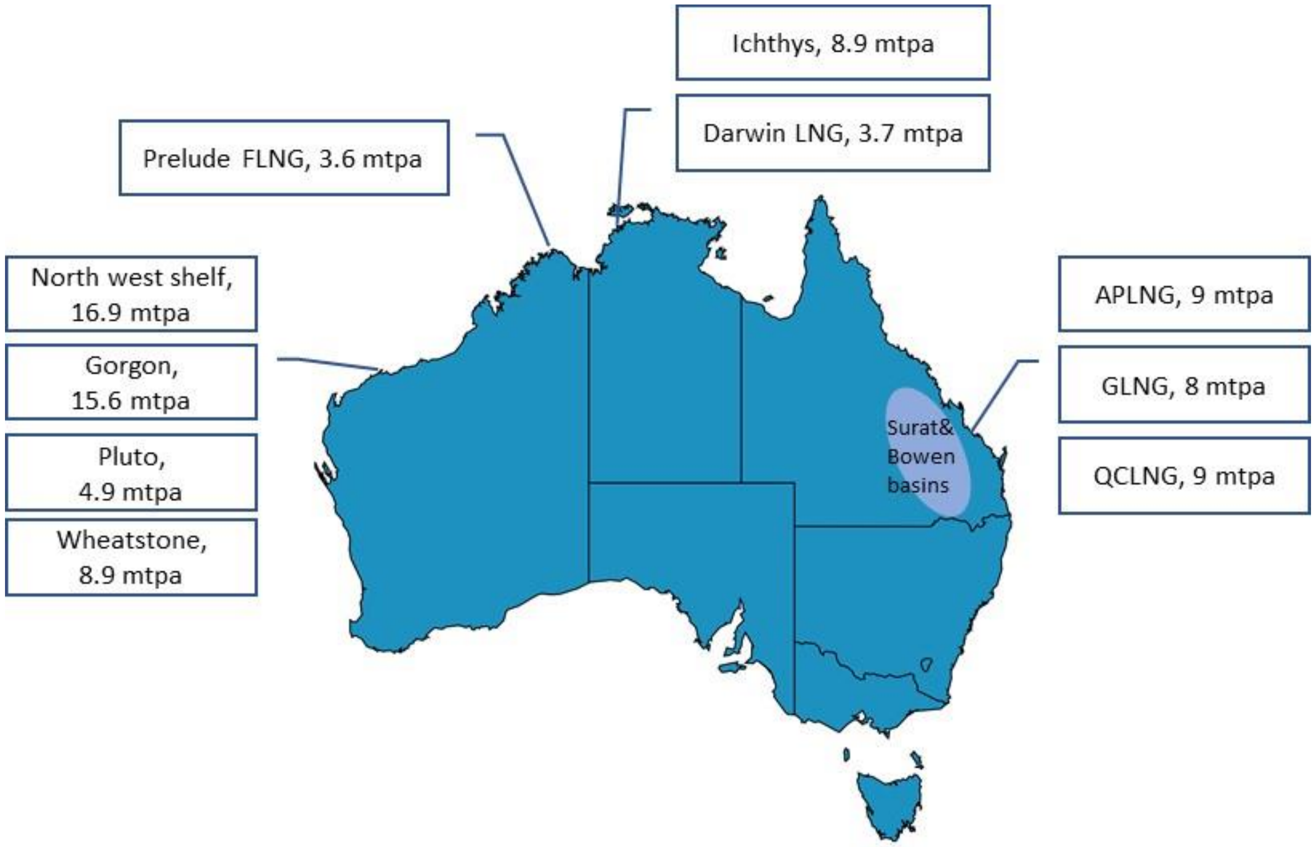


**Figure 4 Location of Australia's LNG liquefaction facilities**

Figure 4 shows the location of the large export orientated LNG projects in Australia along with their LNG production capacity in millions of tonnes per annum (Mtpa)[10]. In Western Australia three LNG plants are located on the Burrup peninsula and are fed by conventional gas fields offshore including Pluto (operated by Woodside), Wheatstone (operated by Chevron) and the North West Shelf project (operated by Woodside). The Gorgon LNG plant operated by Chevron is located on Barrow Island, just off the coast of WA and is also fed by offshore conventional gas fields. Shell has recently developed the Prelude floating LNG plant (FLNG) in Commonwealth waters off the WA coast. The floating plant is located within the Browse Basin from which it sources its gas eliminating the need to pipe it onshore.

Two LNG plants are located onshore in the Northern Territory near Darwin. These include the Darwin LNG plant operated by Santos, and the Ichthys LNG plant operated by Inpex, both of which process and liquify gas from offshore conventional fields.

In Queensland three LNG liquefaction facilities are located on Curtis Island just off the coast of Gladstone including Australia Pacific LNG (APLNG) operated by ConocoPhillips, Gladstone LNG (GLNG) operated by Santos and Queensland Curtis LNG (QCLNG) operated by QGC (which is a subsidiary of Shell). The gas for these LNG plants is sourced from onshore coal seam gas fields in the Surat and Bowen Basins. The upstream wells, compressor stations, central processing plants (and other assets) are operated by multiple companies including Origin (which is the upstream partner of Australia Pacific LNG), Santos, QGC and Arrow Energy[7, 10]. The gas pipeline network within Queensland is highly interconnected and other companies also produce coal seam gas including Senex, Westside, Armour Energy and Denison.

## 1.3 Domestic LNG

The majority of LNG produced in Australia is liquified in large coastal facilities and exported overseas, however some is also produced in smaller scale LNG plants and used domestically. Six such facilities exist within Australia. One is located in Westbury Tasmania and another in Chinchilla Queensland. Both are operated by BOC and both have a production capacity of 50 tonnes of LNG per day. Two plants operate in WA including Evol's plant in Kwinana with a capacity of 250 tonnes per day and EDL's plant in Karratha with a capacity of 180 tonnes per day. APA group operates a liquefaction and storage facility in Dandenong, Victoria with liquefaction capacity of 100 tonnes per day. Finally, AGL operates a liquefaction/storage facility in Newcastle, NSW with a capacity of 180 tonnes per day.

Figure 5 illustrates the domestic LNG value chain in Australia. Currently most of the plants extract gas from a local pipeline which will be from a variety of sources. For example the Westbury plant is fed from the Tasmanian Gas Pipeline which is connected to Longford in Victoria and ultimately the gas comes from offshore assets in the Bass Straight[17]. The Chinchilla plant is supplied with coal seam under an arrangement with QGC and the Evol plant is supplied from the Dampier to Bunbury Natural Gas Pipeline which is supplied from offshore conventional gas [18-19]. Recently plans have been released by BOC and Optimal Group to explore the construction of a waste to biogas plant that will feed the Westbury liquefaction plant and produce bioLNG for the first time in Australia[20]. Biogas, or biomethane is considered a low emissions alternative to fossil derived natural gas and is a potential pathway to decarbonisation for the domestic LNG industry[21].

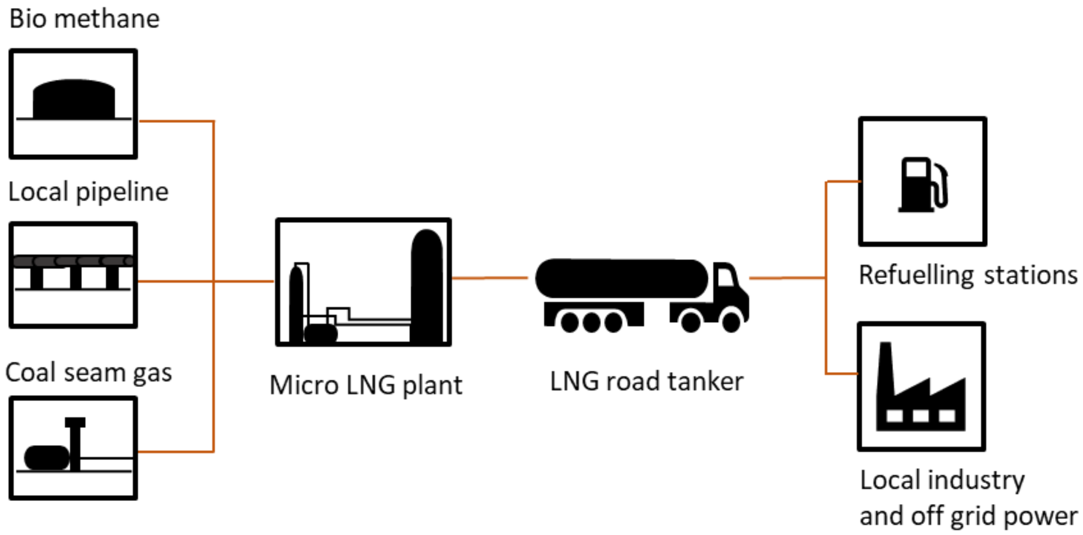


Figure 5 Value chain of domestic LNG in Australia

At the micro-LNG facility, the gas is cooled using a refrigeration process and stored in tanks onsite, similar to the larger scale export orientated LNG plants. The LNG is then transported by specially designed LNG road tankers for a variety of end uses. The most significant use of LNG domestically is for generating electricity at remote mining projects and for marine transport. A number of mine sites located in Western Australia including the Carosue Dam, Daisy Milano, Dalgaranga, Darlot, Deflector and Mt Marion, use LNG to reduce their reliance on diesel and reduce emissions. Marine vessels such as the SeaRoad Mersey 2, which travels between Victoria and Tasmania and the offshore platform supply vessel, the Siem Thiima, which operates out of King Bay in Western Australia, operate on LNG.

Another use of LNG is as a fuel for heavy haulage trucks, which has a number of advantages over diesel such as improved fuel security and lower vehicle greenhouse gas emissions[22-23]. Other uses for the LNG include generating electricity at remote off grid facilities and industrial heat for local industry. Due to the size of the small LNG plants, they fall below the NGER safeguard mechanism and so facility level greenhouse data is not available. The greenhouse gas emissions from these facilities are therefore likely to be small compared to the exporting LNG plants. Woodside, however, also operates an LNG truck loading facility that is supplied from its Pluto LNG plant and supplies domestic users. In this case the greenhouse gas emissions of the domestic LNG are captured under the emissions from the Pluto plant.

## 1.4 Major greenhouse gas emissions

The three most encountered greenhouse gases are carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$). The rising atmospheric concentration of these gases is now widely accepted to be the driver of climate change, which is due to their ability to absorb heat being radiated from the ground [24-25]. The global warming potential (GWP) of a gas is a measure of the amount of energy it will absorb relative to $CO_2$, which is defined as having a GWP of 1. Methane is a much more potent greenhouse gas than $CO_2$ but does not stay in the atmosphere indefinitely. Over a 100-year period, methane has a GWP of 28[25]. 1 tonne of methane is therefore equivalent to 28 tonnes carbon dioxide. $N_2O$ has an even higher GWP of 265–298 over a 100-year period. Greenhouse gas emissions are often measured in $CO_2$ equivalent ($CO_2$e).

There are a wide variety of sources of greenhouse gas emissions that occur throughout the LNG lifecycle. The largest sources of emissions arise from combustion of natural gas (and coal were grid-based electricity is used) to generate heat and electricity that is used in compression stations, offshore platforms, LNG plants, gas processing plants and water treatment plants[26]. Further downstream, the transport of the LNG by tankers will generate further emissions through consumption of fuel. Regassification also requires some gas to be burnt and ultimately the gas will be distributed and burnt in turbines to generate electricity or used for heating [27]. These emissions will be predominantly $CO_2$ and sometimes small amounts of $N_2O$ and hydrocarbons due to incomplete combustion.

Since natural gas is largely composed of methane, which is a potent greenhouse, any leaks in equipment that release methane will add to the greenhouse gas emissions of the facility. These emissions are called fugitive emissions and include any gas lost from production, processing, transport and distribution facilities from leaks in pipes, valves and other equipment[28-30]. Fugitive emissions also include deliberate venting and flaring.

For the purposes of reporting and accounting, greenhouse gas emissions may be separated into scope 1 and scope 2 emissions. Scope 1 emissions are any emissions that occur as a direct result of a process occurring on or within a facility. For example, emissions from the combustion of natural gas onsite to drive a compressor would be included in the scope 1 emissions for the compressor station. Scope 2 emissions are emissions that are created indirectly by the activities occurring at a site and are not actually emitted on that site. For example, if a gas compressor station purchases electricity from a power plant to compress gas, the greenhouse gas emissions created by generating that electricity would be included in the scope 2 emissions for the compressor station (and included in the scope 1 emissions for the power plant).

# 2 Australia's greenhouse gas policy and regulatory framework

In Australia, the LNG industry and more broadly all other industries across Australia are subject to a range of government policy and laws that regulate their greenhouse gas emissions. These policies and laws are influenced by international trends which are encapsulated into international agreements and treaties.

Australia is signatory to several international agreements related to climate change and greenhouse gases which indirectly impact on the LNG industry. These include the United Nations Framework Convention on Climate Change (UNFCCC). The UNFCCC is a key foundational treaty between countries that creates a framework under which climate change negotiations are made[31]. Parties to the convention meet regularly at the annual Conference of the Parties (COP) to discuss new agreements.

Australia has also signed the Paris Agreement, which is a treaty on climate change mitigation made under the UNFCCC and adopted at COP 21 (Paris, 2015). The agreement aims to limit the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit temperature increase to 1.5°C[32]. At COP 26 in (Glasgow, November 2021), Australia updated its commitment to now include net zero emissions by 2050. Australia has also recently committed to reduce greenhouse gas emissions by 43% below 2005 levels by 2030[1].

## 2.1 Federal Government Policy

The Australia Government is taking several approaches to reduce greenhouse gas emissions and tackle climate change[33]. Many of these revolve around providing incentives for companies and individuals to reduce their emissions. A key element of this strategy is the *Carbon Credits (Carbon Farming Initiative) Act 2011* which was amended in 2014 to establish the Emissions Reduction Fund and is a key part of the current government policy under the Government's Direct Action Plan. Under this scheme, businesses can identify and register projects that will lead to a reduction in greenhouse gas emissions and then be awarded Australian Carbon Credit Units or ACCUs[34-35]. A wide variety of project types are eligible including changing agricultural practices to increase carbon stores in the soil, increasing industrial energy efficiency by upgrading equipment, reducing transport emissions by improving fuel efficiency or changing fuel types and reducing fugitive emissions for oil and gas projects.

To claim the carbon credits emissions participants must report and undergo auditing to ensure that the emission reduction has been realised[36]. The carbon credits may then be sold to the government or other businesses. The government purchases are funded through the Emissions Reduction Fund or Climate Solutions Fund, to which the government has allocated $3.5 billion[37]. The scheme therefore incentivises companies to reduce emissions by providing additional income; several LNG projects are currently using ACCUs to offset their emissions.

Another incentive driven emissions reduction strategy is the government's Climate Active scheme. This encourages Australian companies to become carbon neutral by awarding carbon neutral certification. Under this scheme companies reduce their emissions as much as possible through changes in the way they operate or upgrades to new technology. They then purchase additional carbon credits to reduce their effective emissions to zero and are awarded Climate Active Certification[38-39].

The Australian Government regulates emissions by requiring organisations emitting above a certain level to report their emissions under the National Greenhouse and Energy Reporting Act 2007 (NGER 2007)[40]. A component of the National Greenhouse and Energy Reporting Scheme is the safeguard mechanism. Under the safeguard mechanism companies that operate facilities that emit over 100,000 tonnes of $CO_2e$ per year must determine an emission baseline for that facility. If the emissions from the facility exceed the baseline in any year the company must surrender Australian Carbon Credit Units to the Clean Energy Regulator equal to the amount exceeded.

All the export orientated LNG liquefaction plants in Australia fall under the safeguard mechanism as do many of the smaller compressor stations and gas processing plants in the Surat and Bowen basins in Queensland. The safeguard mechanism only applies to scope 1 emissions, so if a facility purchases most of its energy as electricity from the grid and has only minimal scope 1 emissions it will not fall under the safeguard mechanism. Scope 1 emission data of facilities that meet the safeguard mechanism threshold are published on the Clean Energy Regulators website.

In addition to the above schemes the Australian government is pursuing several technology-based approaches to reducing emissions that may have an impact on the natural gas/LNG industries and how they function. One of these is carbon capture use and storage (or CCUS), which may be useful in industries where it is difficult to avoid producing greenhouse gas emissions. With this technology $CO_2$ is captured from large emitters, such as LNG plants and then compressed and stored underground in geological formations[41]. The government has invested in research, development and demonstration projects[42]. This technology is also being used to store $CO_2$ from the Gorgon LNG plant on Barrow Island[43].

The Government is also investing $1.2 billion in developing a hydrogen industry in Australia. Hydrogen is a gas and can be made by electrolysing water using renewable energy. If made with renewable energy it produces only very low greenhouse gas emissions and is therefore considered a low emissions fuel. Similarly, hydrogen made from natural gas combined with CCUS may also be considered a low emissions fuel. Under the government's vision, Australia will become a major hydrogen exporter and is working with other countries to plan for this future industry[44]. Over time the current natural gas and LNG industries in Australia may also supply hydrogen and many of the companies involved have active projects exploring hydrogen production[45]. The Australian Government is also currently developing a hydrogen Guarantee of Origin (GO) scheme or certification scheme that will provide information on the carbon footprint of the hydrogen to customers [46].

## 2.2 State Government Policy

In 2019 the Western Australian state government announced an aspirational target of net zero emissions by 2050. The WA state government has also released its Western Australian Climate policy in Nov 2020 which describes a range of actions the government is taking to achieve its goal[47]. The most significant of these for the Western Australian LNG industry is the Greenhouse Gas Emissions Policy for Major Projects. Under this policy significant projects that require approval under the *Environmental Protection Act 1986* may now be required to include a Greenhouse Gas Management plan detailing how the project will contribute to the state's goal of net zero by 2050. The approval process in WA for projects that may have significant environmental impacts involves an assessment by the WA Environmental Protection Authority (WA EPA) under part IV of the *Environmental Protection Act 1986*, which then provides advice to the Minister for final approval. The WA EPA has released the Environmental Factor Guideline – Green House Gases, which sets out its expectations and guidance for the development of new proposals and where greenhouse gas emissions will be considered a key environmental factor in the EPA's impact assessment[48]. The Guideline is however flexible and does not bind the EPA to any decision, projects are still assessed individually on their overall individual merits. The EPA will consider the new guideline when assessing new projects or changes to existing ones and generally when they are expected to exceed 100,000 tpa $CO_2$e of scope 1 emissions. The Guideline identifies several items that may be required by the EPA from the project applicants as part of its assessment. These could include estimates of the emissions, including scope 1, 2 and 3 over the life of the project, a break down by source and also emissions intensity. A Greenhouse Gas management plan may also be required including reduction targets in scope 1 emissions over the life of the project. Specific measures to avoid, reduce or offset emissions may also be requested as part of this plan.

The Northern Territory Government has also committed to a goal of achieving net zero emissions by 2050 and released its Climate Change Response: Towards 2050 in 2020[49]. The NT Government has also released a policy: "Greenhouse Gas Emissions Management for New and Expanding Large Emitters" (the Large Emitters Policy), which is relevant to onshore gas and LNG projects in the NT. The policy sets out the NT Governments minimum expectations regarding emissions management and will apply to new or expanding projects that require environmental approvals such as under the *Environment Protection Act 2019.* The policy applies to industrial projects expected to emit over 100,000 tpa which would include all the major LNG projects currently operating in the NT. The policy is stricter than the WA policy. It specifies that new or expanding projects must submit as part of the environmental approval process a greenhouse gas abatement plan. The plan must include at a minimum a range of details including estimates of scope 1,2 and 3 emissions, a long-term emissions target and interim targets and methods that show how the target is to be achieved. A description of all strategies to avoid, mitigate and offset scope 1 and scope 2 emissions must be included.

The Queensland Government has also committed to net zero emissions by 2050 and has described its strategy in its Queensland Climate Transition Strategy [50]. Queensland has laws in place that relate to emissions reduction. For example, the Queensland *Petroleum and Gas (Production and Safety) Act 2004* and the connected *Petroleum and Gas (Safety) Regulation 2018* which require an ongoing program of leak detection and repair in gas equipment that reduces fugitive emissions. The act also restricts flaring to situations where it is not commercially or technically feasible to sell or use the gas. Venting is only allowed if it is not safe to use or sell the gas and flaring is not technically practicable. Reducing venting and flaring significantly reduces emissions.

# 3 Greenhouse gas reporting requirements for the LNG industry

## 3.1 Australia

Under the NGER scheme companies must register once they meet one of the reporting thresholds and then report each subsequent year. Two types of thresholds exist:

- Facility threshold. If an individual facility emits 25,000 tonnes or more $CO_2$-e per year, including scope 1 and scope 2 emissions or produces or consumes 100 TJ or more of energy per year the controlling corporation is required to register.
- Corporate group thresholds. When a corporation emits 50,000 tonnes or more $CO_2$-e per year or produces or consumes 200 TJ or more of energy per year they are required to register.

Once a corporation has registered, they are required to submit a report each year until the corporation is deregistered. If the corporation exceeded the corporate threshold, they are required to report data at the corporate level as well as data on all their facilities separately. However, if only a facility threshold was met then they are only required to report on that particular facility. The Clean Energy Regulator monitors compliance with reporting requirements, which may include site visits, inspections, and audits.

The corporation must report scope 1 and scope 2 greenhouse gas emissions and energy production and consumption data. In Australia almost all of the gas and LNG producing companies meet the corporate threshold. Many of the individual facilities also meet the facility threshold including all the exporting LNG liquefaction plants. Many of these facilities would also meet the threshold for the safeguard mechanism. Under the safeguard mechanism corporate operators of facilities that exceed 100,000 tonnes of $CO_2$e per year must determine a baseline emission level and are then penalised for exceeding this amount[51]. The baseline levels are determined by a variety of different rules and approaches including calculated baselines, production adjusted baselines and benchmark baselines. Reported baselines, which are based on a high point from historical reported emissions are no longer allowed as of the 1st of July 2021.

Greenhouse gases that must be reported under the scheme include $CO_2$, $CH_4$, $N_2O$, sulphur hexafluoride ($SF_6$) and certain types of hydrofluorocarbons and perfluorocarbons which include refrigerant gases. Only those emissions and energy data for which there is a defined NGER method need to be reported [51]. The methods are detailed in the NGER Measurement Determination, which is updated annually and has a wide variety of methods relevant to the LNG industry[52]. These include methods for estimation of fugitive emissions such as well completions, onshore wellheads, offshore platforms, natural gas gathering and boosting, natural gas processing, natural gas liquefaction and others.

The Determination also has methods for the estimation of scope 1 emissions due to combustion of fuels including natural gas for generating power. Typically, each method includes an equation using data such as total gas produced or number of hours running time, along with an emission factor to calculate the total emissions. Several methods are usually available to estimate the same quantity from which the company may select. Method 1 is generally a default emission factor multiplied by a throughput (e.g., gas throughput), methods 2 and 3 and are based on more detailed calculations on a per equipment or component basis, and method 4 is based on actual measurements. Emission factors are therefore defined values that allow for simple calculation of total emissions based on readily available data.

Scope 2 emissions are calculated by multiplying the amount of electricity purchased by an emission factor that varies from state to state. For the purposes of reporting under the NGER, the emission factor is fixed for each state and represents an average of the emissions per unit of electricity for that state. That emission factor may not correspond to the actual Scope 2 emissions if, for example companies purchased renewables-based electricity through Power Purchase Agreements (PPA).

## 3.2 United States of America

In the USA, greenhouse gas reporting is done under the USA EPA's greenhouse reporting rule 40 CFR Part 98. Under this rule, in general, reporting of greenhouse emissions is mandatory for facilities emitting 25,000 tonnes or more of $CO_2e$ per year. The scheme differs from Australian reporting in the sense that almost all reporting is done at the facility level and not at the corporate level. The scheme rules are highly segmented and granulated by industry compared to the Australian rules with 41 separate industrial categories listed. An individual facility may contain greenhouse gas sources from multiple industrial categories and must always report on all emission sources if it is required to report[53-54].

Greenhouse gases reported under the scheme include $CO_2$, $CH_4$, $N_2O$, $SF_6$, hydrofluorocarbons, perfluorocarbons, and other fluorinated gases. The rule contains different subparts that cover the 41 industrial categories. The subpart most relevant to the natural gas and LNG industries is subpart W—Petroleum and Natural Gas Systems which covers emissions from the entire LNG supply chain including onshore and offshore production, gathering and boosting, processing plants, compression, underground gas storage, LNG storage, transmission pipelines, LNG and export equipment and import equipment including liquefaction but not shipping[55].

For operators of onshore production wells, which are often distributed over large areas, a facility is defined as all wells they operate within each hydrocarbon basin. The same practise is used to define facilities for gas gathering and boosting systems. For transmission pipelines a facility is defined as all transmission pipelines owned by a single operator within the USA. Subpart W contains calculation methods for a very wide array of specific emission sources that occur within each stage of the LNG supply chain in a similar fashion to the Australian NGER Measurement Determination[56]. The methods generally address specific equipment or activities (e.g. pump venting, dehydrator vents, gas venting and flaring, reciprocating compressor venting and acid gas removal vents). Many of the gas facilities also report under Subpart C, which covers emission from stationary fuel combustion to produce electricity, steam or heat[57].

## 3.3 Qatar

Currently Qatar does not have a compulsory government greenhouse gas reporting scheme, or at least the information is not available publicly. In Qatar the decree Law No. 30 for the Year 2002 "*Law of Environment Protection"* sets out general provisions for environmental protection including response plans for environmental disasters, wastes and hazardous substances, air and water pollution and the environmental impact assessment of major projects[58]. The law, however, contains no provisions for greenhouse gas reporting[59].

Several national greenhouse gas inventory reports have been published for Qatar. Both described the lack of a compulsory and transparent greenhouse gas reporting scheme which necessitated creation of a new database from scratch[60-61]. Despite the lack of compulsory reporting, Qatar Petroleum (now Qatar Energy) and Qatar Gas did report emissions data in their 2019 sustainability reports[62-63].

## 3.4 Russia

Multiple oil and gas companies operate in Russia with the largest being Gazprom that is majority state owned. Novatek is the largest independent gas producer in Russia and is also a significant LNG exporter. Both of these companies report emissions data in their sustainability reports[64-65]. Russia does not have a law in force requiring the reporting of greenhouse gas emissions by corporations. In June 2021, however, the Federal Assembly of Russia passed a law that makes it mandatory for some corporations to begin reporting their greenhouse gas emissions in 2023.

The law requires that from the start of 2023, corporations emitting greater than or equal to 150,000 tonnes of $CO_2$e must report their emissions and, from the start of 2024 corporations emitting greater than or equal to 50,000 tonnes must report their emissions. The collected data, which will include emissions and the types of activities carried out are to be collected in a register of greenhouse gas emissions and made publicly available[66].

# 4 Greenhouse gas emissions of the LNG industry in Australia

For this project, we estimated the total scope 1 and 2 emissions for the Australian export focused LNG industry. The greenhouse gas emissions data that were used for the analysis are drawn from several publicly available sources. These include the scope 1 and scope 2 corporate emissions data reported under the NGER scheme and available on the Clean Energy Regulator's website. The Clean Energy Regulator also publishes scope 1 emissions for facilities that are covered by the safeguard mechanism. This data is reported on a financial year basis, with 2019-2020 year being the most recent available at the time of writing[51].

Data is also available via the Australian Greenhouse Emissions Information System (AGEIS) which is an online interactive data base maintained by the Department of Industry, Science, Energy and Resources and takes its data from the Australian National Greenhouse Accounts[67]. Data from the AGEIS system are, however, difficult to use for the purpose of estimating emissions from the LNG industry since some emissions classes are aggregated with oil production and others are confidential. Other data sources for emissions include corporate sustainability reports.

In the Australian oil and gas industry, almost all the large projects are joint ventures between different corporations. This means that the construction costs, profits and other financial and legal assets and liabilities are divided between the partners according to their equity stake in the project. One company will usually be the designated operator of the project and will have responsibility for decisions on operating, environmental and health and safety policies. Most of the project staff, particularly management will also be employees of the operating company. Greenhouse gas emissions may therefore be reported on either an equity or operational control basis. Operational control basis emissions are calculated by summing all the emissions across the facilities which the company operates. Since the NGER data is reported on an operational control basis, all the data in this section is also presented on an operational control basis.

Many of the large facilities in Australia produce products other than LNG including LPG, condensate and also supply gas to the domestic market. In an effort to apportion emissions specifically to LNG, we investigated methods of categorising the different products and then calculating proportions using publicly available data. In some cases, this included production volumes in barrels of oil equivalent but also included sales data. In some cases no data was available, hence due to the variety of different methods of reporting across the industry, a consistent approach was not possible. In order the simplify the analysis, we have therefore decided to attribute 100% of the emissions from most facilities solely to LNG, especially where it is clear the facility exists mainly for that purpose. The exception to this is the upstream CSG operations in Queensland which are geographically separated from the LNG plants on Curtis Island, and where gas is diverted to the domestic market before it reaches the plants.

## 4.1 Western Australia

### 4.1.1 Methods

2019-2020 Scope 1 Emissions data for Chevron's Gorgon and Wheatstone projects, Shells FLNG project and Woodside's Pluto and North West Shelf projects were obtained from the NGER website as facility level data[51].

### 4.1.2 Discussion

The results of our analysis of the greenhouse gas emissions from the LNG industry in Western Australia for 2019-2020 are summarised in Table 1. We were not able to include scope 2 emissions for any of these projects because of the use of facility level data from the NGER. Corporate level scope 2 data is available but since these companies have multiple projects in Australia it was difficult to allocate them to individual facilities.

Since these facilities are generally remote and self-sufficient in electricity, scope 2 emissions are likely to be negligible compared with scope 1. This is supported by corporate level data from the NGER which shows that Chevron's and Woodside's total scope 2 emissions were 3,782 tonnes and 10,955 tonnes for 2019-2020 respectively, which is small compared to their scope 1 emissions in Table 1. In total, we estimate that the scope 1 emissions due to the LNG industry in WA were approximately 20,566,000 tonnes for 2019-2020.

**Table 1 Summary of emissions and production data for LNG projects in Western Australia 2019/2020**

| **Operating Company** | **Facility** | Scope 1 emissions (tonnes $CO_2e$) | Scope 2 emissions (tonnes $CO_2e$) | Comments |
|---|---|---|---|---|
| **Chevron** | Gorgon Operations | 6,263,348 | no data | Net emissions after accounting for $CO_2$ sequestered |
| **Chevron** | Wheatstone Operations | 3,848,864 | no data | |
| **Shell** | FLNG | 1,712,983 | No data | |
| **Woodside** | Pluto LNG | 1,862,948 | No data | |
| **Woodside** | North West Shelf Project | 6,878,006 | No data | |
| | | **20,566,149** | **No data** | Total WA emissions due to LNG |

## 4.2 Northern Territory

### 4.2.1 Methods

For the Santos Darwin LNG and Inpex Ichthys LNG projects 2019-2020 scope 1 emissions data was obtained from facility level data from the NGER. For Darwin LNG, Santos's total corporate scope 2 emissions data was not usable since Santos has many operations within Australia. However, for

Ichthys LNG, we used Inpex's corporate scope 2 emissions data from the NGER since they only operate the Ichthys project in Australia.

### 4.2.2 Discussion

Based on our analysis, we estimate the total scope 1 greenhouse gas emissions due to LNG in the NT to be around 8,971,845 tonnes (Table 2). Scope 2 emissions were only available for the Ichthys project. However, we expect the scope 2 emissions from Darwin LNG to be small compared with the scope 1 emissions.

**Table 2 Summary of emissions data for LNG projects in the Northern Territory 2019/2020**

| Operating Company | Facility | Scope 1 emissions (tonnes $CO_2$e) | Scope 2 emissions (tonnes $CO_2$e) | Comments |
|---|---|---|---|---|
| **Santos** | Darwin LNG | 1,348,163 | No data | |
| **INPEX** | Ichthys LNG | 7,623,682 | 1,038 | Scope 2 emissions from corporate level data |
| | | **8,971,845** | **1,038** | Total NT emissions due to LNG |

## 4.3 Queensland

### 4.3.1 Methods

The gas and LNG industries in Queensland differ from those in WA and the NT and involve numerous smaller facilities onshore as well as the liquefaction plants. For Queensland, we have separated the emissions into a downstream component, which includes only the liquefaction facilities on Curtis Island and, an upstream component which includes all other activities upstream of the liquefaction plants. Based on data from AMEO, currently QGC and Origin Energy produce an excess of gas needed to supply their corresponding downstream LNG plants (APLNG and QC LNG). GLNG/Santos utilises their own gas and third party supply from other producers including Senex, Westside and Origin[68-70]. Arrow Energy, which is another producer of coal seam gas does not currently supply gas to the LNG plants.

For the upstream component, data on Origin Energy's emissions due to gas production were obtained from their FY2020 Sustainability data under "integrated gas", which is their gas production business[71]. NGER scope 1 and 2 emissions for QGC's Condamine power station were subtracted from the corporate scope 1 and 2 emission for QGC's "QGC upstream investments" to estimate the emissions from QGC's upstream gas production. Corporate level scope 1 and 2 emissions data for Westside was obtained from the NGER.

For Santos, we were only able to identify NGER scope 1 facility data for the Fairview and Ballera sites. Since Santos operates across multiple sites and states, their corporate data was not usable. Instead, we have estimated a combined total scope 1 and 2 emissions for Santos using a production weighted average of Origin's and QGC combined scope 1 and 2 emissions. The production weightings were obtained from data supplied by AMEO. We have calculated a combined scope 1 and 2 figure since there may be a difference in the ratio of grid to onsite power used by Santos vs the other producers.

The proportion of gas produced in Queensland by QGC, Origin, Santos, Senex and Westside which was exported as LNG was calculated from their total production and total flows to Curtis Island which was supplied by AEMO. Over 2019-2020, Queensland produced an excess of gas and was a net exporter to other states, and so we have not considered emissions due to production within other states[12].

Scope 1 emissions data for the LNG plants on Curtis Island was obtained from facility data from the NGER. For the APLNG facility we used scope 2 emissions data from ConocoPhillips corporate data since they only operate the APLNG facility in Australia. For QCLNG we used the corporate scope 2 emissions data from QGC Midstream Investments Pty Ltd since the scope 1 facility emissions data matched exactly.

#### 4.3.2 Discussion

Table 3 summarises our estimates for the upstream emissions due to LNG in Queensland. We estimate that the scope 1 and scope 2 emissions are approximately 2,532,000 and 4,230,000 tonnes, respectively, with Santos's scope 2 emissions included in scope 1. Table 3 also shows that most emissions due to upstream gas production in Queensland are now indirect scope 2 emissions. In contrast, Table 4 shows that the vast majority of emissions due to LNG liquefaction are scope 1. In total across both the upstream and downstream Queensland operations we estimate the scope 1 and 2 emissions due to LNG for 2019/2020 to be 7,980,000 and 4,230,000 tonnes $CO_2$e respectively.

**Table 3 Summary of emissions data for upstream production of natural gas in QLD related to LNG 2019/2020**

| Operating Company | Scope 1 emissions (tonnes $CO_2$e) | Scope 2 emissions (tonnes $CO_2$e) | Other | Comments |
|---|---|---|---|---|
| **Origin** | 740,000 | 2,121,000 | | Scope 1 and 2 emissions due to “integrated gas” from Origin sustainability report data. |
| **QGC** | 854,390 | 2,579,045 | | Scope 1 and 2 data from NGER corporate data from “QGC upstream investments” minus scope 1&2 data from Condamine Power Station |
| **Santos** | 1,139,862* | | | *Scope 2 included in Scope 1- estimated from production weighted average of Origin and QGC scope 1 + scope 2 |
| **Westside** | 79,176 | 687 | | Scope 1 and 2 data from NGER corporate data |
| | | | 0.90 | Proportion of gas produced in Queensland exported as LNG |
| | **2,532,085** | **4,230,658** | | Total upstream emissions due to LNG in QLD |

**Table 4 Summary of emissions data for LNG plants on Curtis Island for 2019/202.**

| Facility | Scope 1 emissions (tonnes $CO_2$e) | Scope 2 emissions (tonnes $CO_2$e) | Comments |
|---|---|---|---|
| **APLNG Facility** | 2,061,529 | 335 | Scope 1 from NGER facilities data, scope 2 from ConocoPhillips Australia Operations PTY LTD corporate data |
| **Queensland Curtis LNG Plant** | 1,793,519 | 0 | Scope 1 from NGER facilities data, scope 2 from QGC Midstream Investments PTY LTD corporate data |
| **GLNG Plant** | 1,593,684 | no data | Scope 1 from NGER facilities data, scope 2 from Santos corporate data not useable |
| | **5,448,732** | **335** | Total emissions due to LNG plants in QLD |

## 4.4 Australia

Table 5 summarises the emissions due to LNG across the different states and shows the totals for Australia. In total, we estimate the Scope 1 emissions to be 37,519,000 tonnes and the scope 2 emissions to be 4,232,000 tonnes. These numbers compare well with data in Australia's emissions projections 2021 recently released by the Australian Government[72]. The emissions projections give a breakdown of emissions due to LNG production across Australia in 2019 consisting of onsite electricity generation (5 Mt $CO_2e$), onsite stationary energy (18 Mt $CO_2e$) and fugitive emissions (15 t $CO_2e$). These include only scope 1 emissions since both the electricity and stationary energy categories refer to generation onsite. The total of 38 Mt $CO_2e$ compares very well with our estimate of scope 1 emissions of 37,519,000 tonnes $CO_2e$, considering that the Australian Government figures appear to have been rounded to the nearest 1 Mt. The projections predict that the emissions from the LNG sector will stay constant up to 2025 at 38 Mt, with the level of fugitive emissions falling (12 Mt) and electricity and stationary energy increasing (6 and 20 Mt respectively). By comparison, the Australia's total greenhouse gas emission for 2019-2020 were 513.5 Mt $CO_2e$[2].

**Table 5 Total emissions across Australia due to LNG for 2019/2020**

| | Scope 1 emissions (tonnes $CO_2e$) | Scope 2 emissions (tonnes $CO_2e$) |
|---|---|---|
| **WA** | 20,566,149 | No data |
| **NT** | 8,971,845 | 1038 |
| **QLD upstream** | 2,532,085 | 4,231,000 |
| **QLD LNG plants** | 5,448,732 | 335 |
| **Total** | **37,518,811** | **4,232,031** |

# 5 Emission intensities and life cycle analyses of Australian LNG

Clearly, examining the total emissions associated with Australia's LNG industry, as presented in section 4 is important in assessing the environmental impact of the industry. Nevertheless, it is difficult to use these totals to compare Australian LNG as an energy source with other energy sources, or even with LNG from other countries. This is because the numbers in section 4 are dependent on the amount of LNG produced.

To compare with other LNG projects or energy sources we need to express the emissions in terms of another functional unit, such as emissions per mass of LNG (t $CO_2$e/t LNG), or emissions per energy content (kg $CO_2$e/GJ)[73]. This is termed an "emission intensity" and both units are used for LNG. However, the emissions per energy content is more representative of the LNG's intended use and is more convenient when comparing with other energy sources[26-27, 74]. The energy content here refers to the amount of heat released through combustion. However, if it is used to generate electricity, the efficiency of the power plant will need to be considered to calculate the emissions per unit of electricity.

The focus of the data in section 4, on the Australian emissions associated with LNG production, means that the data does not include emissions associated with other parts of the lifecycle of LNG including shipping and final use. Lifecycle studies aim to analyse the environmental impact of a product across each stage of its life. In the case of LNG, this would include the greenhouse gas emissions occurring due to construction of facilities such as wells, gas processing plants, pipelines and liquefaction plants. The emissions during the operational phase are also included such as fugitive emissions, flaring, onsite energy use (both scope 1 and 2), fuel use during shipping, regasification in destination country and emissions due to combustion of the LNG as its final use. Individual lifecycle studies vary in their approach to estimating the emissions listed above and can be complex[26]. In this report, life cycle studies are reviewed, and emissions are categorised into "upstream" (which includes all emissions upstream of the liquefaction plant), emissions due to the liquefaction plant and emissions due to shipping. Emissions due to end use which includes regasification and combustion are the largest source of emissions but are treated separately at the end of this section. This is because these emissions generally do not vary according to the source of the LNG and so are not useful in comparing different LNG sources. They are therefore not included in many lifecycle studies.

Generally, emissions from LNG liquification plants globally fall in a fairly narrow range from 4.1 to 7.6 kg $CO_2$e/GJ LNG (0.22-0.41 t $CO_2$e/t LNG)[74]. This is partly a function of age and technology but also ambient temperature. The Snohvit LNG plant in Norway has the lowest emission intensity for liquification because the low ambient temperature makes cryogenic liquification more efficient. Emission intensities due to upstream are much more variable which is due to differences in production technologies such as hydraulic fracking or horizontal drilling, different gas transmission distances and especially different amounts of $CO_2$ in the feed gas. Gan, et al.(2020)[74] found that upstream emissions varied from 7.15 kg $CO_2$e/GJ for the Qatargas North Field to 26.29 kg CO2e/GJ for LNG from north central shale gas, USA. Shipping is dependent on distance but can vary quite significantly from one study to another due to differing assumptions and models for the shipping emissions. Gan, et al.(2020)[74], who used a model, found emissions due to shipping for Australian LNG shipped to China to be 2.93 between 3.64 kg $CO_2$e/GJ (0.16-0.198 t $CO_2$e/t LNG). However, some studies which had access to propriety project data found significantly lower numbers for the same scenario[75-76].

Apart from lifecycle studies, there are other sources of greenhouse gas emission intensities for LNG including environmental reports published by private companies. These are generally not comparable to lifecycle emissions intensity values since they are calculated using annual operational emissions (scope 1) and the annual LNG production, rather than full lifecycle emissions including construction and decommissioning. They are, however, reported more regularly that lifecycle studies and so can provide more up to date data and are often used in comparing LNG projects. The trend over time of these operational emission intensities for a particular facility is also illustrative of different stages of the project, including the transition to a steady state and industry efforts to reduce emissions.

## 5.1 Queensland

Several studies have investigated the emissions from different stages of the life cycle of LNG from Queensland. Most of these studies gave emission intensity values in terms of units of energy or mass of LNG, or sometimes both and where possible conversions have been made (Table 6). Amongst the first was Barnett (2010)[77]who focused mainly on the emissions from the liquefaction stage of the process but also estimated the emissions from shipping to an average destination in Asia, and regasification. His study was conducted before the plants in Queensland were built and so many of his assumptions were based on estimates.

Another life cycle study was performed by Clark, et al.(2011)[27] on the basis of a 10 Mtpa CSG to LNG project, exporting from Queensland to China for electricity generation and considered all stages of the life cycle. The study was again performed before many of the projects were complete and much of the input data was sourced from the company's environmental impact assessments. Hardisty, et al.(2012)[78] arrived at the same figures for liquefaction and shipping but had lower results for upstream emission intensities. More recently Schandl, et al.(2019)[26] performed a study using commercial-in-confidence data from a company operating a CSG-LNG project in Queensland. Schandl, et al.(2019)[26] found the emission intensities across the upstream, liquefaction and shipping to be lower than the other studies. Table 7 provides further breakdown of the different categories used by Schandl, et al.(2019)[26] that we have aggregated under "upstream". Since this study focused on an operating CSG project in Queensland the categories used are particularly illustrative of the supply chain for CSG production, however since other studies do not provide the same level of detail or categorisation it is only possible to compare aggregated upstream values across studies (Table 6). Table 7 shows that the largest source of upstream emissions for CSG comes from pipeline transport which includes energy use for compression, diesel for construction and emissions from flaring and blowdown. Emissions from gas processing and well heads also contribute significantly whereas produced water treatment and gas dehydration contribute only a minor amount.

Finally, a study has been performed by Gan, et al.(2020)[74], who performed life cycle analysis of LNG from 37 different fields in different countries based on shipment to China. The study included emissions from extraction, processing, transmission, liquefaction, shipping and storage and regasification but did not include final combustion. Emissions were only presented in terms of energy content of LNG; however, we calculated the equivalent mass base emission intensities using a calorific energy content of 54.4 GJ/tonne of LNG[79]. We combined their categories of extraction, processing and transmission into upstream in Table 6, although some processing may take place at the liquefaction plant for some projects. Most of the emission intensities for this study were comparable to the other studies except for shipping, which was significantly higher. The shipping for this study also included emissions due to storage at the exporting and receiving terminal which may explain the difference. Figure 6 shows the results from the life cycle studies. Amongst all the studies, Schandl, et al.(2019)[26] has the lowest total non-end use emission intensity which may reflect their access to commercial-in-confidence data from an operational project.

In addition to life cycle studies, the Australian Department of Industry, Science, Energy and Resources has also published default emissions intensity values within its Safeguard Mechanism document[80]. The purpose of these default emissions intensity values are to allow the industry to calculate an emissions baseline for a particular facility as part of the safeguard mechanism. This is done by multiplying the default emissions intensity by the total production of the facility. The Government has so far published an emission intensity for LNG from processed natural gas. This emission intensity relates specifically to the LNG plants on Curtis Island including APLNG, GLNG and QCLNG which liquify gas that has already been processed upstream. The emission intensity was derived from industry average data over the last 5 years and included scope 1 emissions from the liquification facilities. The calculated emissions intensity is equivalent to 4.01 kg $CO_2$e/GJ (or 0.218 tonnes $CO_2$e/tonne LNG). This is lower than the emission intensities for the liquification plant derived from life cycle studies which are typically 5-6 kg $CO_2$e/GJ. The difference is partly explained by the Safeguard Mechanism emission intensity including only operational emissions rather than full lifecycle emissions (which would also include construction). However, it may also be due to the use of more up to date industry data which better represents true level of emissions.

**Table 6 Emissions intensities in kg $CO_2$e/GJ LNG (t $CO_2$e/t LNG) from life cycle studies of LNG from Queensland (all 100 year GWP).**

| Study | Comments | Upstream | Liquefaction plant | Shipping | Total |
|---|---|---|---|---|---|
| **Barnett 2010** | QCLNG<br>GLNG | | 5.87 (0.32)<br>4.19 (0.23) | 0.95 (0.05)<br>0.95 (0.05) | |
| **Clark et al 2011** | CSG to LNG and export to China | 9.8 (0.584) | 6.2 (0.37) | 1.6 (0.094) | 17.6 (1.05) |
| **Hardisty et al 2012** | CSG to LNG and export to China | 7.8 (0.454) | 6.2 (0.37) | 1.6 (0.095) | 15.6 (0.919) |
| **Schandl et al 2019** | CSG to LNG export to Asia | 5.57 (0.303) | 4.72 (0.257) | 0.94 (0.051) | 11.23 (0.611) |
| **Gan et al 2020** | APLNG<br>QCLNG | 8.68 (0.472)<br>9.43 (0.513) | 5.63 (0.306)<br>5.71 (0.311) | 3.64 (0.198)<br>3.68 (0.200) | 17.95 (0.976)<br>18.82 (1.024) |

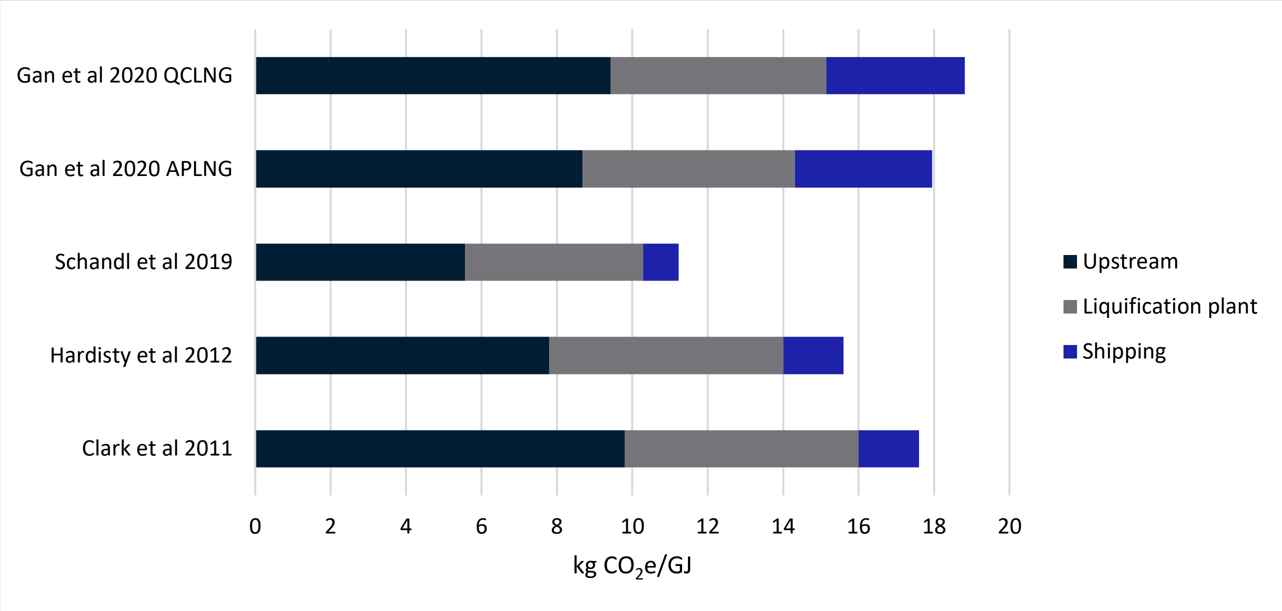


**Figure** 6 **Emissions intensities (kg $CO_2$e/GJ) for different stages of the life cycle of LNG from Queensland.**

**Table 7 Emissions intensities in kg $CO_2$e/GJ LNG (t $CO_2$e/t LNG) from Schandl et al 2019.**

| Study | Upstream | | | | | Liquefaction plant | Shipping | Total |
|---|---|---|---|---|---|---|---|---|
| | Well head | Gas processing facility | Water treatment | Gas dehydration | Pipeline transport | | | |
| **Schandl et al 2019** | 1.56 (0.085) | 1.61 (0.088) | 0.015 (0.0008) | 0.006 (0.0003) | 2.37 (0.129) | 4.72 (0.257) | 0.93 (0.051) | 11.23 (0.611) |

## 5.2 Western Australia

Several studies have also investigated the life cycle emissions from West Australian LNG projects. Most of them have so far included all stages of the life cycle except end use. Barnett(2010)[77] calculated life cycle emissions due to liquefaction for all the current LNG plants in WA. However, at the time of his study most projects were only projected and so his input data was based on many assumptions. The North West Shelf project was, however, operating and Barnett(2010)[77] calculated the emissions as shown in Table 8. The Chevron Gorgon project was also included in the study based on the projected design and an assumption that 80% of the $CO_2$ from the feed gas would be permanently stored in geological formations rather than vented. The gas from the Gorgon field has a high content of $CO_2$ (~15vol%)[74] and storage of the $CO_2$ was part of the original project plan to avoid the greenhouse gas emissions from releasing the $CO_2$. The start of the $CO_2$ storage was significantly delayed however and only started in 2019[43]. This delay has resulted in uncertainty across life cycle studies.

Gan, et al.(2020)[74] also calculated life cycle emissions for LNG from the Gorgon field but, assumed that all $CO_2$ was vented (due to the delays), which resulted in much higher calculated upstream emissions (Table 8). Since the $CO_2$ injection has now begun, this data for Gorgon will now significantly overstate the emissions. The same study also calculated emission intensities for LNG from the Jansz-lo field (another gas field that feeds the Gorgon project) and the upstream emissions are significantly lower. Biswas, et al.(2013)[81] also performed a life cycle study based on a hypothetical Western Australian LNG project. The study used a process flow diagram based on the North West Shelf and Darwin LNG projects and included data from Chevron's environmental impact statements. The feed gas was assumed to have a typical Australian value of 2.6 mol % $CO_2$, which was assumed to be vented[82].

Recently, Woodside has also commissioned a life cycle study for its planned Scarborough project which was performed by McConnell and Grant(2020)[76]. This study found substantially lower emissions than other studies, especially for upstream and shipping. Scarborough has a very low $CO_2$ content of 0.1 mol % which may explain the lower upstream emissions. The emissions estimate due to shipping were also much lower. In this study the emissions data for shipping including fuel use and emissions was supplied directly from the third party currently providing shipping for Woodside existing operations and is therefore highly relevant.

Figure 7 shows the emission intensities in graphical form. The total emission intensities excluding final combustion varies considerably between studies so taking an average was not feasible. However, the range of total emission intensities for Biswas, et al.(2011)[82], Gan, et al.(2020)[74] and McConnell and Grant(2020)[76] was 7.06 – 29.67 kg $CO_2$e/GJ. The upper value for this range is due to Gorgon, based on the assumption that all the $CO_2$ is vented which is no longer correct. By excluding Gorgon, this range narrows to 7.06 -17.49 kg $CO_2$e/GJ.

Along with life cycle studies, emission intensities are also published in a number of company reports covering LNG projects in Western Australia. These are often available for a number of years allowing the trend to be visible for a particular facility and are graphed in Figure 8. Woodside released emissions intensity data in its Pluto LNG Facility Greenhouse Gas Abatement Program report and is shown in Figure 8[83]. Here the facility included everything in the Pluto LNG Park on the Burrup peninsula and downstream of the Gas Receipt Point. It therefore includes the liquification facility but not upstream offshore platforms or wells. It also included only operational scope 1 emissions. Figure 8 shows there is a gradual downward trend in the emission intensity since the plant was commissioned in the 12/13 financial year with the most recent number being 0.36 t $CO_2$e/t LNG for 19/20. In the same report, the emission intensities of Pluto including offsets are also shown, which is being undertaken to reduce the projects emissions. They are significantly lower than the raw numbers by around 0.07 t $CO_2$e/t LNG. Woodside also released data for its Karratha gas plant (part of the North West Shelf Project) in the NWS expansion environmental review document[84]. The emission intensity included scope 1 emissions from the Karratha gas plant and did not include upstream operations. The emissions intensity for the Karratha gas plant (Figure 8) is very stable and in all but on year was equal to 0.41 36 t $CO_2$e/t LNG. The stability is likely due to the length of time it has been operating with LNG trains 1-3 being commissioned between 1989-1992 and 4 and 5 in 2004 and 2008 respectively. Chevron has also released emission intensity data for the Gorgon project[85]. In this case the emission intensity was calculated including all scope 1 emissions for the facility divided by saleable LNG for each financial year and excluded upstream emissions. Figure 8 shows that there has been a dramatic fall the in emissions intensity for Gorgon since it was commissioned, from 19.6 t $CO_2$e/t LNG (off scale) in 15/16 to 0.46 t $CO_2$e/t LNG in 20/21. Much of this variation is due to start-up of the liquification plant, where emissions are initially high with very little production. The fall between 18/19 to 19/20 was due to the start of $CO_2$ injection on Barrow Island.

**Table 8 Emissions intensities in kg $CO_2$e/GJ LNG (t $CO_2$e/t LNG) from life cycle studies of LNG from Western Australia (all 100 year GWP).**

| Study | Comments | Upstream | Liquefaction plant | Shipping | Total |
|---|---|---|---|---|---|
| **Barnett 2010** | North West Shelf | | 3.76 (0.20) | 0.95 (0.05) | |
| | Gorgon | | 3.97 (0.22) | 0.95 (0.05) | |
| **Biswas et al 2013** | West Australia LNG export to China | 6.08 (0.33) | 7.08 (0.38) | 2.44 (0.13) | 15.6 (0.84) |
| **Gan et al 2020** | Gorgon field, to China | 19.11 (1.04) | 7.60 (0.41) | 2.96 (0.16) | 29.67 (1.61) |
| | Jansz-lo field, to China | 7.15 (0.39) | 7.41 (0.40) | 2.93 (0.16) | 17.49 (0.95) |
| **McConnell and Grant 2020** | For planned Scarborough LNG to China | 1.44 (0.08) | 5.47 (0.29) | 0.15 (0.01) | 7.06 (0.38) |

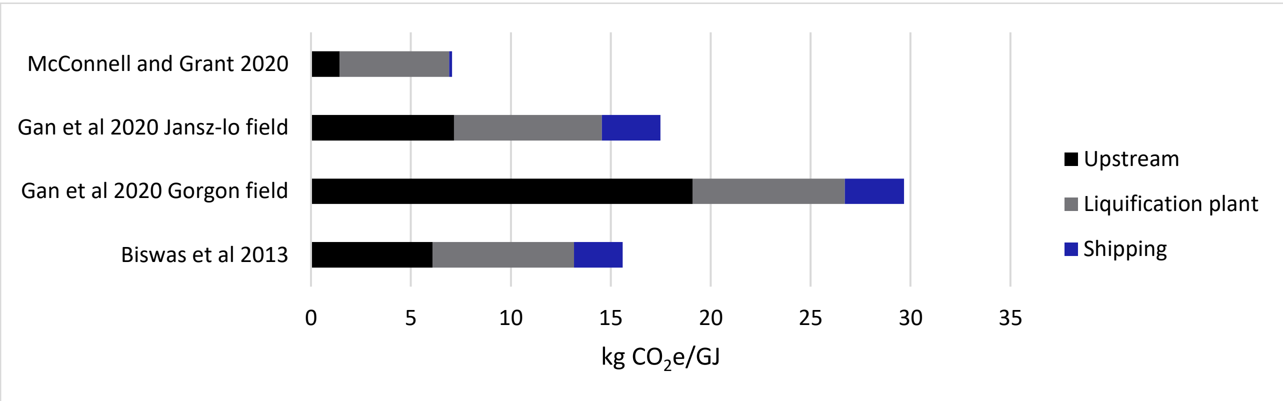


**Figure 7 Emissions intensities (kg $CO_2$e/GJ) for different stages of the life cycle of LNG from Western Australia**

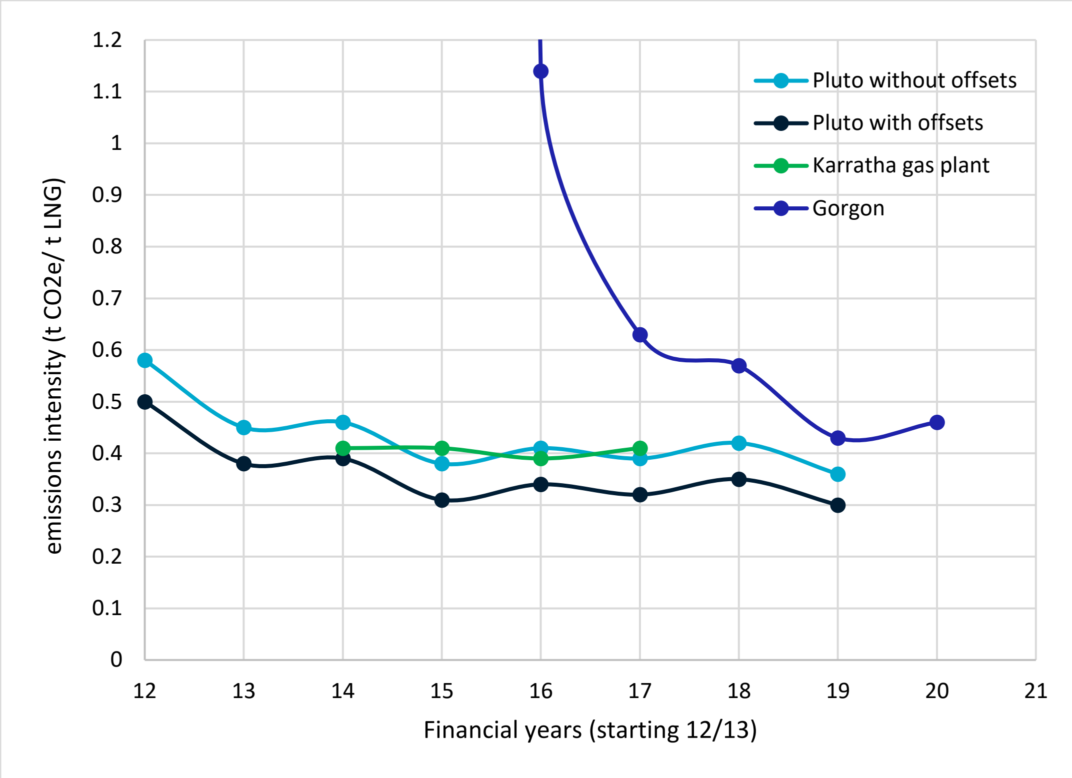


**Figure 8 Trend over time of emissions intensities from LNG plants in Western Australia from company reports.**

Since the emission intensities in Figure 8 from the company reports all relate to emissions from the liquefaction plants, we can attempt to compare them with the life cycle emission intensities for the liquefaction in Table 8. Bearing in mind the differences between life cycle studies (which often include emissions due to construction and material inputs) and the company reports (which are operational emission intensities) we find that there is generally good agreement. Excepting Barnett(2010)[77] which was an early study, all the lifecycle studies found liquefaction emission intensities to be between 0.29-0.41 t $CO_2$e/t LNG which is similar to the company reports, considering that Gorgon is still trending downwards.

## 5.3 Northern Territory

Few studies have performed life cycle studies of the greenhouse gas emissions due to LNG from the Northern Territory. Barnett(2010)[77] calculated emission intensities due to the liquefaction stage for both the Darwin LNG project, and Ichthys LNG but did not include upstream emissions. At the time Darwin LNG was already operating and Ichthys was being planned. For Ichthys, Barnett assumed a feed gas $CO_2$ content for Ichthys of 17 mol %, which significantly increased the emissions from liquefaction. However, to date feed gas has come from the Brewster reservoir which has a $CO_2$ content of about 8%.

**Table 9 Emissions intensities in kg $CO_2e$/GJ LNG (t CO2e/t LNG) from life cycle studies of LNG from the Northern Territory (all 100-year GWP).**

| Study | Comments | Upstream | Liquefaction plant | Shipping | End use | Total |
|---|---|---|---|---|---|---|
| **Barnett 2010** | Darwin LNG | | 5.17 (0.28) | 0.95 (0.05) | | |
| | INPEX Ichthys LNG | | 8.05 (0.44) | 0.95 (0.05) | | |

## 5.4 Emission intensities across Australian LNG

In sections 5.1-5.3, we have reviewed the available data on emission intensities for Australian LNG. In general, the number of Lifecyle studies is low and there is considerable variation between the study's results. In some cases, the variation is explainable due to differences in the projects that were examined, however in many cases it is less clear and is likely due to different methodologies and data sources. Apart from Barnett(2010)[77] (which was an early study that relied on predicted data) five studies have examined Queensland. Amongst these Schandl, et al.(2019)[26] has the lowest total non-end use emissions (11.23 kg $CO_2e$/GJ) and is likely the most reliable due to use of industry data from an operating CSG project, and it is also fairly recent. Gan, et al.(2020)[74] reported higher emissions of 17.95 and 18.82 kg $CO_2e$/GJ for ALPNG and QLNG respectively but relied on a range of publicly available and other propriety data. Regardless, due to the breadth of Gan, et al.(2020)[74] and its recent publication it is still useful for comparison purposes. The other two studies gave results on par with Gan, et al.(2020)[74] but are significantly older. In addition, the Department of Industry, Science, Energy and Resources has also published an emission intensity for the liquefaction plants on Curtis Island of 4.01 kg $CO_2e$/GJ. This is less than the liquefaction emission intensity from Schandl, et al.(2019)[75] (4.72 kg $CO_2e$/GJ) although since it only includes operational emissions it is difficult to compare.

Amongst life cycle studies focusing on Western Australian projects there is significant variation due to differing assumptions and the range of different types of feed gas in WA projects. Barnett(2010)[77] was an early study that did not include emissions from upstream and so is of little use for comparison purposes. Gan, et al.(2020)[74] calculated Lifecycle emission for several fields that feed the Gorgon project including the Jansz-lo and Gorgon fields. However their results for the Gorgon field are now outdated since Chevron has started $CO_2$ injection on Barrow Island. McConnell and Grant(2020)[76] has also recently completed a life cycle assessment of the planned Scarborough project which gave the lowest total non-end use emission of any study in this review (7.06 kg $CO_2e$/GJ). Since the project has not been built yet it may be speculative but it is based on real industry data from related projects, including shipping emissions data which was particularly low in this study. The upstream emissions are expected to be low due to the very low $CO_2$ content of the Scarborough. Industry reports are also a source of operational emission intensities for the liquefaction plants in WA. These show that the emission intensities of some of the plants are still falling after ramping up production. They are also in general agreement with the Lifecyle studies, considering that lifecycle studies incorporate a broader scope of emissions.

Currently very few lifecycle studies have addressed projects in the Northern Territory, the only one being Barnett(2010)[77] which focused only on the liquification plants. This represents a significant gap in our knowledge.

As mentioned at the start of section 5, final use contributes the largest amount of greenhouse gas emissions of any stage in the lifecycle of LNG. This is mainly made up of emissions from combustion, although regasification also contributes a small amount, typically less than 2 kg $CO_2$/GJ[26, 74, 86-87]. Lifecycle studies do not always contain an estimate for the combustion stage since it is argued that it does not vary much by sources and is therefore not useful for comparison purposes. Nevertheless, different emission intensities for final combustion are available since the exact composition can vary slightly. The US Energy Information Administration has published a value of 50.15 Kg $CO_2$/GJ from a study of a large number of samples of pipeline gas used in the USA[88-89]. It is also usually assumed that natural gas from imported LNG has the same final combustion emissions as natural gas from a domestic pipeline source. The 2006 IPCC Guidelines for National Greenhouse Gas Inventories gives a default emission factor for natural gas in stationary combustion of 56.1 kg $CO_2$/GJ, which may reflect different grades of natural gas internationally[90]. It should be noted that the above emission intensity's do not include the contribution from other greenhouse gases such as $CH_4$ and $N_2O$ although they were almost negligible. In Australia the NGER measurement determination gives a emission factor for both LNG and pipeline natural gas of 51.53 kg $CO_2$e/GJ including $CH_4$ and $N_2O$ and this is the most relevant value for Australian LNG[52]. Unlike many Lifecyle studies, Schandl, et al.(2019)[26] did include an emission intensity for final combustion in Asia of Queensland coal seam LNG of 64.4 kg $CO_2$e/GJ. They noted that this was much higher than the NGER emission factor because of their comprehensive life-cycle approach. Along with their figure for regasification (1.98 kg $CO_2$/GJ) and upstream, liquification, and shipping (11.23 kg $CO_2$/GJ from table 6), this gave total lifecycle emissions of 77.6 kg $CO_2$/GJ. Final combustion was therefore 83% of the total estimated emissions.

# 6 Australia's LNG industry in an international context

To compare the Australian LNG greenhouse gas emissions with the emissions from international LNG sources, data on the lifecycle emission intensities for international sources was obtained from several studies and are summarised in Table 10 based on similar scenarios (shipment to China). These do not include emissions due to final combustion because these emissions (on a mass or heat energy basis) do not vary significantly by source and are not included in most studies. Combustion emissions per unit of electricity produced in China would be affected by power plant technology, however this is also generally not considered in these studies. Also included is data for several Western Australian projects and the results from Schandl, et al.(2019)[26] for Queensland. Where necessary, we have converted units to kg $CO_2$e/GJ using a conversion factor of 54.4 GJ/tonne of LNG and/or the power plant efficiency stated in the studies. Figure 9 shows the same data as Table 10 with the LNG sources ranked by total emission intensity including upstream, shipping, liquefaction and regasification.

Generally, LNG from the USA sources appear to have the highest greenhouse gas emissions. This is due to large shipping distances and higher upstream emissions, especially where the source of the gas is unconventional shale gas. For USA/Appalachian shale, upstream emissions are 3.22x higher than the equivalent category for Queensland LNG. USA unconventional gas tends to have higher fugitive emissions and lower estimated ultimate recovery rates, which increase the impact of one-off emissions[74].

Australian LNG from Jansz-lo appears to be comparable to LNG from Russia's South Tambey and Qatar Gas's North Field. These figures should be used with some caution, however. Both results come from a single study using publicly available data, and input data on the emissions for projects in Qatar and Russia are sparse due to a lack on compulsory reporting in these countries. The International Energy Agency's methane tracker database indicates that fugitive emissions in Russia may be higher than previously thought based on satellite detections of large emitters, although these were not specifically attributed to LNG projects[91]. The lowest emissions in Figure 9 are for Western Australian LNG from the Scarborough field based on a study by McConnell and Grant(2020)[76], although this project is yet to be commissioned.

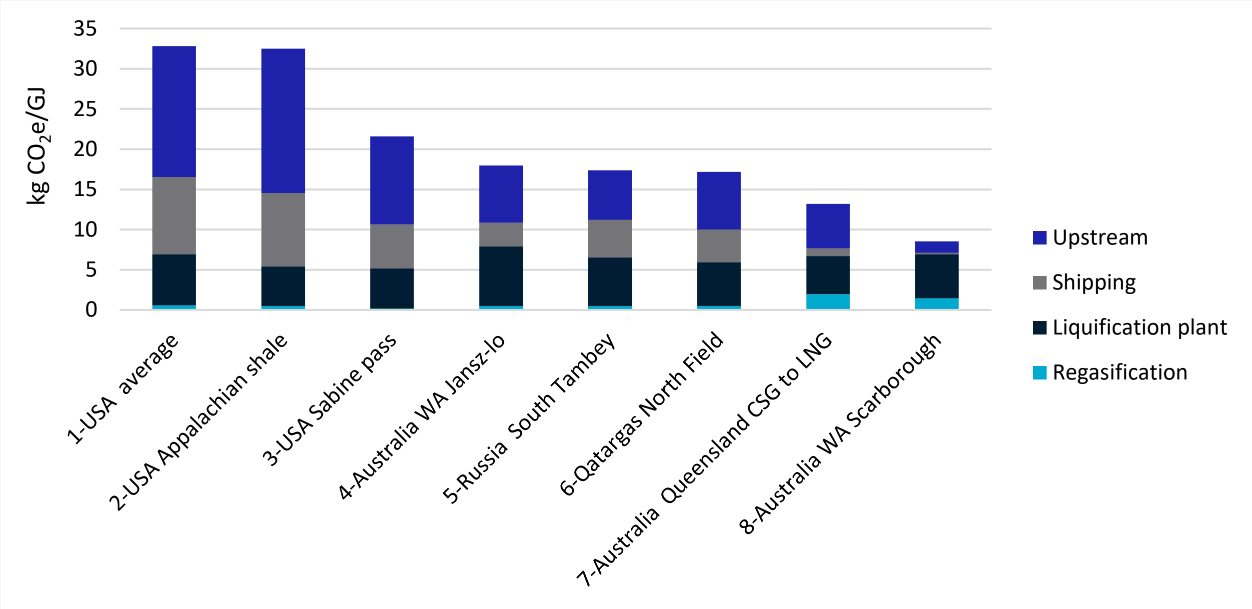


**Figure 9 International and Australian LNG lifecycle emission intensities in kg $CO_2$e/GJ LNG ranked by total.**

**Table 10 Emissions intensities in kg $CO_2e$/GJ LNG (t $CO_2e$/t LNG) from life cycle studies of LNG from different international sources and Australia**

| # | Country/field | Study | Upstream | Liquefaction plant | Shipping | Regasification | Total |
|---|---|---|---|---|---|---|---|
| **1** | USA/Average from 22 US conventional and non-conventional fields shipped to China | Gan et al 2020 | 16.31 (0.89) | 6.37 (0.35) | 9.58 (0.52) | 0.57 (0.03) | 32.84 (1.79) |
| **2** | USA/Appalachian shale gas shipped from New Orleans to China | Roman-White eta al-2019 | 17.95 (0.98) | 4.93 (0.27) | 9.15 (0.5) | 0.48 (0.03) | 32.5 (1.77) |
| **3** | USA/Sabine Pass liquification and supply chain delivered to China | Roman-White et al 2021 | 10.94 (0.6) | 4.99 (0.27) | 5.49 (0.3) | 0.18 (0.01) | 21.6 (1.18) |
| **4** | Australia/Jansz-lo field LNG shipped to China | Gan et al 2020 | 7.15 (0.39) | 7.41 (0.4) | 2.93 (0.16) | 0.49 (0.03) | 17.98 (0.98) |
| **5** | Russia/ South Tambey LNG shipped to China | Gan et al 2020 | 6.18 (0.34) | 6.06 (0.33) | 4.64 (0.25) | 0.49 (0.03) | 17.36 (0.94) |
| **6** | Qatar/ Qatargas North Field LNG shipped to China | Gan et al 2020 | 7.15 (0.39) | 5.48 (0.3) | 4.06 (0.22) | 0.48 (0.03) | 17.17 (0.93) |
| **7** | Australian Queensland CSG to LNG export to Asia | Schandl et al 2019 | 5.57 (0.3) | 4.72 (0.26) | 0.94 (0.05) | 1.98 (0.11) | 13.21 (0.72) |
| **8** | Australia/ Proposed Scarborough field LNG shipped to China | McConnell and Grant 2020 | 1.44 (0.08) | 5.47 (0.3) | 0.15 (0.01) | 1.46 (0.08) | 8.52 (0.46) |

# 7 Industry initiatives to reduce emissions and certification of low emissions LNG

A number of initiatives are underway in Australia to reduce emissions from LNG. One that is occurring across the industry is an effort to reduce flaring. Flaring occurs when excess gas is burnt at a processing facility rather than being turned into a useful product. For example, used domestically or used to produce LNG. Flaring produces greenhouse gases without usefully producing energy and is therefore considered undesirable. In Australia flaring makes up about 15% of the oil and gas industries greenhouse gas emissions[92]. The World Bank has introduced the "Zero Routine Flaring by 2030" (ZRF) initiative which asks for voluntary commitments from companies and governments to eliminate routine flaring[93].

Routine flaring commonly occurs with oil production in several countries but is not performed in Australia where flaring is usually done for safety reasons and to a lesser extent to reduce vented fugitive methane emissions. Despite this, the Western Australian Government and companies including Chevron, Woodside and Shell have now committed to the ZRF[94] and also made efforts to reduce other types of flaring. Woodside has reduced emissions due to flaring by 46% since 2017[95] and Shell's QGC has reduced flaring by 65% in 2020 compared with 2019[96]. Origin has also successfully reduced flaring by 57%[97].

Reducing emissions due to leaks is also done by companies under regulated leak detection and repair programs (LDAR) according to the *Queensland Petroleum and Gas (Production and Safety) Act 2004*. All companies operating within Queensland including Santos, Origin, Arrow and QGC carry out LDAR programs[98]. This involves regular inspection of well heads, process piping, valves and other equipment using a variety of technologies to find and repair leaks. Research has found that these programs can reduce emissions due to leaks from 15% to over 70%[99].

Arrow Energy has also embarked on a program to replace gas driven pneumatic control devices with air driven ones. Gas driven pneumatic control devices vent small quantities of gas containing methane by design. If they are incorrectly installed or malfunctioning, they may also release additional methane. By replacing 139 gas driven devices with ones actuated by compressed air, Arrow has largely eliminated the issue and reduced emissions by up to 1000 tonnes $CO_2e$ per year[98].

Another source of emissions in LNG production is fuel used to generate power to run facilities. Efficiency improvement projects are underway to reduce emissions associated with these sources. For example, Woodside has undertaken electrical load management system improvements on its Pluto LNG train 1, which has allowed it to run the train on three rather than the original 4 turbines reducing emissions by 3.7%. Other improvements at Pluto have included modifications to heat exchangers and upgrades to air filters to improve efficiency and reduce emissions[100]. Woodside has also installed a 1MWh lithium-ion battery on its Goodwyn A platform which enables the platform to run with only three out of the four turbines running, reducing annual $CO_2$ emissions by around 7,500 tonnes per year[101]. Arrow Energy has also recently made modifications to its fuel gas handling equipment at its central compressor facilities in Queensland. These modifications allow the fuel gas to be specifically compressed to the pressure required for the compression engines and this has reduced fuel gas use by 8-10% per unit of gas produced[98].

Emission offsets are another way in which Australian companies are seeking to reduce the emissions from LNG. Offset programs seek to reduce the emissions in other parts of the economy or sequester $CO_2$ in various ways, and then offset these reductions against the emissions from the LNG operations. In this way, it is possible for an LNG project to become a net zero emitter if the emissions are fully offset. Woodside plans to limit emissions from the Pluto LNG project using emission offsets. To offset the emissions, Woodside must first acquire and then retire (i.e., use) eligible offset units. Eligible offset units include Australian Carbon Credit Units or ACCUs as described in section 2.1 and, also other units administered by non-government organisations that meet certain integrity standards. To generate ACCUs, Woodside has several carbon farming projects across Australia and, has spent over A$100 million planting over 25 million native Australian blue mallee trees in WA and NSW. In addition, Woodside has purchased offset units generated by renewable energy projects from overseas[100].

Another offset program is West Arnhem Land Fire Abatement (WALFA) project[102]. Under this scheme, Indigenous rangers have returned to the practice of traditional fire management in West Arnhem land, Northern Territory. Fires in the native savanna landscape are one of the major contributors to the greenhouse gas emissions of the Northern Territory and by carrying out strategic burning during the cooler months, hotter more intense fires are avoided which reduces emissions. The program generates ACCUs, some of which have been sold to the Darwin LNG Joint Venture in recent years. Ichthys LNG, operated by Inpex has invested in several offset projects as part of its goal of reducing its net emissions to zero by 2050. These include funding a savanna fire management program in the Northern Territory which reduces emissions fires similar to the WALFA[103].

One of the most significant actions to reduce emissions that the industry is taking, is carbon capture and storage, or CCS where the $CO_2$ from a project is captured and then injected into a geological formation rather than being vented. The Gorgon project on Barrow Island, operated by Chevron is currently using this method to reduce the $CO_2$ emissions that would have otherwise occurred due to venting of the $CO_2$ component of the natural gas. As discussed above, the injection was significantly delayed but started in August 2019 and has injected 5 million tonnes of $CO_2$ up to July 2021[43, 104]. When the injection reaches full capacity, it is expected to store up to 4 million tonnes per year[43]. Other industry players are also investing in CCS. Santos has recently made a final investment decision on the Moomba CCS project which will store 1.7 million tonnes per year $CO_2$ from the Moomba plant and is also working on plans for a CCS project using the Bayu-Undan facilities once gas production finishes[105-106]. Inpex has also committed to invest in carbon capture and storage as well as other technologies to reduce emissions from the Ichthys project and achieve their target of net zero emissions by 2050[107].Alongside efforts by producers to reduce their net emissions, there is now a growing demand from buyers of LNG to have those cargos specifically certified as being low emissions[108]. Several different classes of low emissions LNG have begun to emerge but as yet there are no commonly accepted definitions. Generally, "carbon neutral LNG" has been used to refer to LNG in which the seller has offset the emissions related to upstream, liquefaction, shipping and end use (including combustions) of the LNG. This has also been referred to as low carbon LNG or Green LNG. In some cases, emissions are only partially offset depending on the request of the buyer[109].

Approximately 15 carbon neutral LNG cargos have been delivered to date, or are scheduled to be delivered, several of which originated in Australia[108]. In Oct 2020, Total delivered to a customer in China, a shipment of carbon neutral LNG which was sourced from the Ichthys project in Australia. The emissions were offset across the full lifecycle of the LNG including upstream, liquefaction, shipping and end use using offsets from a forest protection project in Zimbabwe and a wind energy project in China. INPEX has also delivered shipments of carbon neutral LNG to it Japanese domestic customers from the Ichthys project[110]. Shell was the first to deliver carbon neutral LNG and has facilitated at least 13 carbon neutral LNG cargos to date by working with producers and buyers and providers of carbon offsets.  Shell has now also signed an five-year agreement with PetroChina to supply carbon neutral LNG[111].

Significant gaps remain in the certification of carbon neutral LNG. There are no universally agreed international industry standard for how to measure and account for the emissions from LNG projects. A variety of methods are available, but these vary between jurisdictions and often use emissions factors that are specific to particular basins. Developments are occurring in this area however. Recently Pavilion Energy, QatarEnergy and Chevron jointly released a quantification and reporting methodology to produce a statement of greenhouse gas emissions (SGE) for delivered LNG cargoes[110].  The types of offset projects that may be allowed and how to measure, account and verify their offsets is still being developed. A third-party auditor for the offset schemes to ensure they meet basic standards is also required. INPEX has recently received third party validation for its carbon neutral gas[112]. low emissions LNG is a growing trend and likely to accelerate in coming years[113].

# 8 Conclusion

In this report we examined the greenhouse gas emissions from Australian LNG. This was motivated by a recognition that the LNG industry in Australia is a significant emitter of greenhouse gases but will also continue to play a role in the world's shift to a low emissions future. Several key questions presented themselves:

- what are the total emissions due to Australia's LNG industry?
- how are these emissions distributed across the value chain?
- what are the total life cycle emissions of Australian LNG compared with LNG from other sources?
- what industry trends are currently occurring that may change the emissions from the industry over time?

The emissions from the LNG industry needs to be understood in the context of the current government policy and regulatory environment. Australia has a comprehensive greenhouse gas reporting scheme in place (NGERS) which differs but is comparable to the US EPA's reporting requirements. Australia also has legal frameworks in place for the creation and trading of carbon credits which can be sold to the government to generate an income stream, incentivising emissions reductions.

Another tool by which the Australian government limits emissions is the safeguard mechanism which penalizes operators of facilities that exceed their pre-set emission limit. At the international level Australia has also committed to significantly reduce its emissions to net zero by 2050. Many LNG producing companies in Australia have now also committed to transition to net zero by 2050 and are investing in a range of projects such as hydrogen, carbon capture and storage and emission offsets. The industry is therefore in a state of transition while continuing to supply LNG during this phase.

We assessed data from a variety of sources to estimate the total scope 1 and 2 emissions due to the LNG industry in Australia. We initially attempted to apportion the emissions across the different products produced by LNG projects including condensate, domestic gas and LNG. However, we faced significant challenges in obtaining useable data and in some cases, it was not possible to obtain a value for a particular emission source. For example, apportioning emissions to LNG rather than condensate or LPG was only possible if data could be located on production for a particular facility. Ultimately, we chose to consider the total emissions for LNG facilities to be solely due to LNG since that is their main purpose. For upstream facilities in Queensland however, we did separate emission due to domestic gas from LNG.

Greenhouse gas emissions data is publicly available from the NGER. However, due to varying corporate structures and company profiles we could not always use a consistent approach. Rather the data was assessed on a case-by-case basis and in some cases NGER facility data or data from corporate sustainability reports was used. Most companies provide emissions data according to activity type (flaring, fuel use, etc). However, providing data by facility (or aggregated facilities if distributed and similar in function) would have simplified the challenge. Methane fugitive emissions are likely to be a source of some uncertainty in the reported data as it is only in the last few years that accurate methods for quantification are becoming available. In total for Australia, we estimate these emissions to be approximately 37,519,000 and 4,232,000 tonnes $CO_2e$ respectively. These figures compare well with data released by Australian Government Department of Industry, Science, Energy and Resources, which put the scope 1 emissions from the Australian LNG industry at 38 million tonnes $CO_2e$.

To gain an understanding of life cycle emissions due to LNG we reviewed life cycle studies that have investigated Australian LNG projects. For Queensland, the work by Schandl, et al.(2019)[26] is the most recent and reliable and gave a total life cycle emission intensity of 11.23 Kg $CO_2e$/GJ excluding final use. For WA several studies have been done. Some of these considered the Gorgon project, however due to differing assumptions over the projects $CO_2$ injection the life cycle emissions for Gorgon vary. Currently based on lifecycle studies that appear to be still relevant the total emission intensities excluding final use range from 7.06 to 17.49 kg $CO_2e$/GJ for projects in Western Australia. Further life cycle analysis would be of benefit for Western Australian LNG especially Gorgon. LNG projects in Darwin are even less well covered. Barnett(2010)[77] did calculate emission intensities for Darwin LNG and Ichthys LNG but did not include upstream emissions. A life cycle study would also be valuable for Ichthys. Other than lifecycle studies, operational emission intensities are available for several Australian LNG liquefaction plants in company reports. These indicate that operational emission intensities tend to be high early in the plant's life but then decrease due to production ramp and stabilisation. The operational emissions for the liquefaction plants are also in general agreement with liquefaction lifecycle emissions, keeping in mind the fundamental differences of these approaches.

There is clearly considerable variation in the emissions intensity for different LNG sources. From Table 10 emission intensities vary significantly between 32.84 kg $CO_2e$/GJ for the USA conventional average, down to lows of 13.21 and 8.52 kg $CO_2e$/GJ for Queensland CSG and the proposed Scarborough project respectively. Amongst Australian LNG the variation is also significant, from 17.98 (Jansz-Io) to 8.52 (proposed Scarborough) kg $CO_2e$/GJ. It is likely that the variation would be even higher if lifecycle studies for Gorgon and Ichthys were available due to their high $CO_2$ feed gas content. Clearly therefore, not all LNG is created equal in terms of its emissions intensity. While this represents a significant challenge, it also represents an opportunity if the industry can achieve and demonstrate the lowest comparative emissions intensity at each stage of the lifecycle. Based on the available data, Australian LNG is approximately comparable to LNG from Qatar and Russia and has lower emissions than LNG from the USA when delivered to markets in Asia, although there remains a high degree of uncertainty over fugitive emissions in Russia.

Several new trends are emerging in the industry that may affect the emissions over time. Many companies have now set targets to become carbon neutral by 2050 in line with Australia commitment at COP 26. A range of emission reduction strategies are being pursued including emissions offsets, efficiently improvements, $CO_2$ sequestration and hydrogen. There is also mounting pressure to reduce emissions from the demand side of the LNG industry, including buyers in Asia, and there have been several LNG cargos that were certified as carbon neutral. Ongoing research including additional Lifecyle studies and improved greenhouse gas estimation methods will ensure that emissions reporting and reductions will improve over time. This study found that Australia is leading amongst other key LNG exporters in terms of rigorous reporting, finding new methods of reducing emissions from existing assets and embracing new technologies on the pathway to net zero emissions.

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