APPENDIX 14

ARROW LNG PLANT

Air Quality Impact Assessment

arrow energy
go further

Air Quality Impact Assessment

Arrow LNG Plant

Prepared for

Arrow CSG Pty Ltd (Arrow Energy) and Coffey Environments Australia Pty Ltd

KE1101007

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Final

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Glossary

Term	Definition
Units of measurement	
ng	nanogram
µg	microgram
mg	milligram
g	grams
kg	kilograms
t	tonnes
ng/m^3	nanogram per cubic metre
$µg/m^3$	micrograms per cubic metre
mg/m^3	milligrams per cubic metre (at stack conditions)
mg/Nm^3	milligrams per normal cubic metre (0^oC, 1 Atm)
ppm	parts per million
tpa	tonnes per annum
Mtpa	million tonnes per annum
µm	microns
mm	millimetre
m	metre
km	kilometre
m^2	square metres
m^3	cubic metres
m/s	metres per second
m^3/s	cubic metres per second
Am^3/s	actual cubic metres per second (at stack conditions)
Nm^3/s	normalised cubic metres per second (0^oC, 1 Atm)
g/s	grams per second
km/h	kilometre per hour
Atm	atmosphere (pressure)
Pa	pascal
kPa	kilopascal
kPag	kilopascal gauge
hPa	hectopascal
℃	degrees Celsius
J	joule
kJ	kilojoule: $1.0 \times 10^3 J$
MJ	megajoule: $1.0 \times 10^6 J$
GJ	gigajoule: $1.0 \times 10^9 J$
TJ	terajoule: $1.0 \times 10^{12} J$
PJ	petajoule: $1.0 \times 10^{15} J$
GJ/hr	gigajoule per hour
GJ/s	gigajoule per second
MW	megawatts
mol	mole

Air pollutants and chemical nomenclature

NO	Nitric oxide
NO_X	oxides of nitrogen (total of NO, NO_2 and all compounds that are products of the atmospheric oxidation of NO_X)
NO_2	nitrogen dioxide
SO_2	sulfur dioxide
CO	carbon monoxide
CO_2	carbon dioxide
CH_4	methane
H_2S	hydrogen sulfide
N_2	nitrogen
O_2	oxygen
O_3	ozone
VOC	volatile organic compounds
PM	particulate matter (fine dust)
TSP	total suspended particles
PM_{10}	particulate matter with an aerodynamic diameter less than 10 microns
$PM_{2.5}$	particulate matter with an aerodynamic diameter less than 2.5 microns
ou	odour units - is the number of times that a sample of odour must be diluted to reduce its concentration to its detection threshold
C_3H_8	propane

Other abbreviations

Air EPP	Environmental Protection (Air) Policy
Air Toxics NEPM	National Environment Protection (Air Toxics) Measure
AP 42	USEPA's Compilation of Air Pollutant Emission Factors
Approved Methods	Approved Methods for the Modelling and Assessment of Air Pollutants in NSW (DEC, 2005)
BOM	Bureau of Meteorology
CALMET	Meteorological model used in conjunction with CALPUFF
CALPUFF	An advanced non-steady-state meteorological and air quality modelling system
CBM	coal bed methane
Clean Air Regulation	NSW Protection of the Environment Operations (Clean Air) Regulation 2002
CSG	coal seam gas
DERM	Department of Environment and Resource Management
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
EMP	Environmental Management Plan
EPC	Engineering, Procurement and Construction
GAMS	Gladstone Airshed Modelling System
GBRMP	Great Barrier Reef Marine Park
GBRWHA	Great Barrier Reef World Heritage Area
LNG	liquefied natural gas

Other abbreviations

MCHE	main cryogenic heat exchanger
MOF	Materials Offloading Facility
MR	mixed refrigerant
NPI	National Pollutant Inventory
NEPM	National Environment Protection (Ambient Air Quality) Measure
OEH	NSW Office of Environment and Heritage (formerly Department of Environment and Conservation [DEC])
SCREEN3	Screening Model (includes flaring)
SRDT	Solar Radiation/Delta Temperature
TAPM	The Air Pollution Model
TCEQ	Texas Commission on Environmental Quality Effects Screening Levels
TOR	Terms of Reference
TWAF	Temporary Workers Accommodation Facility
USEPA	United States Environmental Protection
VicSEPP	State Environmental Protection Policy of Victoria

Statistical terms

%ile	percentile
IOA	Index of agreement
MAE	Mean absolute error
FAC2	Factor of 2
PCC	Pearsons correlation coefficient

Scientific terms

Boundary layer	The layer of the atmosphere from the earth's surface to the level where the frictional influence is absent.
Mesoscale	Atmospheric phenomena having horizontal scales ranging from roughly 10 to 100s of km, including thunderstorms, squall lines, fronts, precipitation bands in tropical and extratropical cyclones and topographically generated weather systems such as mountain waves and sea and land breezes.
Ringelmann number	The Ringelmann scale is used to measure the apparent density of smoke. The scale has 5 levels (Ringelmann numbers) of density inferred from a grid of black lines on a white surface which, if viewed from a distance, merge into known shades of grey.
Pasquill-Gifford Scheme	Stability classification widely used in atmospheric dispersion models to define the turbulent state of the atmosphere
Synoptic	General weather patterns that occur at the scale of 100s to 1000s of kilometres such as the migration of high and low pressure systems.

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Executive Summary

Katestone Environmental has been commissioned by Coffey Environments Australia Pty Ltd and Arrow CSG (Australia) Pty Ltd (Arrow Energy) to undertake an Air Quality Impact Assessment in preparation of an Environmental Impact Statement (EIS) for the proposed Arrow LNG Plant. The Arrow LNG Plant (the project) is proposed by Arrow CSG (Australia) Pty Ltd (Arrow Energy). The proponent is a subsidiary of Arrow Energy Holdings Pty Ltd which is wholly owned by a joint venture between subsidiaries of Royal Dutch Shell plc and PetroChina Company Limited.

The Arrow LNG Plant comprises the development of a green-field LNG plant and export terminal at Curtis Island on the northern shore of Port Curtis, near Gladstone in Queensland. The project will facilitate the export of natural gas to international markets from CSG extracted from gas fields in the Bowen and Surat Basins in central and southern Queensland. The project is designed to supply up to approximately 18 million tonnes per annum (MTPA) of LNG product to market through the development of an LNG plant, which will comprise four LNG trains, each with a nominal production capacity of up to 4 MTPA.

The objective of the assessment is to investigate the potential for air emissions from the Arrow LNG Plant to adversely impact on the air quality in the Gladstone region. The major air pollutant emitted during routine and non-routine operations of the LNG plant is oxides of nitrogen (NO_X)*. Minor emissions of sulfur dioxide* (SO_2)*, carbon monoxide (CO), particulates as* PM_{10} *and* $PM_{2.5}$ *and hydrocarbons are also emitted from the LNG plant during routine and non-routine operations.* NO_X *and some trace compounds emitted from fuel burning activities may be associated with low levels of odour. Each emission source has been assessed for the following air pollutants during routine and non-routine operations at the plant:*

- *Oxides of nitrogen, as nitrogen dioxide* (NO_2)
- *Carbon monoxide*
- *Sulfur dioxide*
- *Particulates as* PM_{10} *and* $PM_{2.5}$
- *Hydrocarbons*
- *Odour*
- *Photochemical smog*

Modelling of oxides of nitrogen and sulfur dioxide emissions from background sources has been carried out using the Gladstone Airshed Modelling System version 3 (GAMSv3), a regional airshed management tool developed for the Department of Infrastructure and Planning by Katestone Environmental. A cumulative assessment of the impacts from nitrogen dioxide and sulfur dioxide has been conducted to include existing and approved (but yet to be built) industries including other proposed LNG facilities on Curtis Island and Fishermans Landing. Background levels of PM_{10}*,* $PM_{2.5}$*, carbon monoxide and ozone* (O_3) *for the assessment of cumulative air quality impacts have been obtained from monitoring data in the Gladstone region, where available.*

The following conclusions may be drawn from the air quality impact assessment.

In relation to dispersion meteorology:

- *The Arrow LNG Plant site is dominated by moderate winds with an average wind speed of 3.9 m/s (at 10 metres above ground). This provides for relatively good dispersion conditions for stack sources*
- *The prevailing wind direction at the site is from the southeast quadrant which will transport the plumes away from the main population centre of Gladstone located to the southeast*
- *Winds from the southwest during the winter months and at night are predicted to transport the plume to the northeast where the plume may come in contact with elevated terrain areas of Curtis Island*
- *Winds likely to carry emissions from the Arrow LNG Plant over the population centre of Gladstone city occur very infrequently*

A cumulative air quality impact assessment was undertaken that included all existing industrial sources in Gladstone and proposed future LNG plants on Curtis Island and at Fishermans Landing, and has shown the following:

- *All air quality objectives are met for routine and non-routine operation of the Arrow LNG Plant (inclusive of background levels) at sensitive receptors for NO_2, CO, PM_{10}, $PM_{2.5}$, odour, O_3, SO_2 and hydrocarbons*

For all pollutants considered, the regional air quality is dominated by existing sources, which include industrial, anthropogenic and natural sources. The assessment indicates that there are no significant constraints to air quality in the Gladstone airshed. Industrial sources such as the existing NRG Gladstone Power Station are the most important contributors to the airshed. The introduction of the Arrow LNG Plant to the cumulative dispersion model does not change the peak concentrations in most locations because:

- *The Arrow LNG Plant's emissions are relatively small compared to the total airshed emissions*
- *The relative locations of the Arrow LNG Plant and existing industries from sensitive receptors are such that the plumes will not overlap*

1. Introduction

Katestone Environmental has been commissioned by Coffey Environments Australia Pty Ltd and Arrow (CSG) Australia Pty Ltd (Arrow Energy) to undertake an Air Quality Impact Assessment in preparation of an Environmental Impact Statement (EIS) for the proposed Arrow LNG Plant, a component of the larger Arrow LNG Project.

The proponent is a subsidiary of Arrow Energy Holdings Pty Ltd which is wholly owned by a joint venture between subsidiaries of Royal Dutch Shell plc and PetroChina Company Limited.

This report describes the methods and findings of an assessment of the potential effect on air quality due to the construction and operation of the Arrow LNG Plant at Curtis Island. The objective of the assessment is to investigate the potential for air emissions from the LNG plant to affect the air quality in the Gladstone region. The air quality impact assessment has focussed on all activities that are likely to emit a significant quantity of air pollutants during routine operations, including the:

- Gas turbines used to drive the gas compressors
- Gas turbines used for power generation
- Marine diesel oil (MDO) engines aboard ships and tugs
- Pilot flare

The assessment has also considered the potential affects to air quality associated with non-routine emission releases such as the combustion and discharging of process gasses through the process system flares, used for plant pressure management during maintenance or upset operating conditions.

The air quality impact assessment has been carried out in accordance with the Environmental Impact Statement (EIS) Terms of Reference (TOR, January 2010). The TOR requires a description of:

- Existing air quality, including:
  - Observations of concentrations of air contaminants recorded at Department of Environment and Resource Management (DERM) monitoring stations in the Gladstone region including NO_2, SO_2, CO, PM_{10}, $PM_{2.5}$, O_3 and some hydrocarbon species.
  - Emissions of air contaminants from background sources within the region reported in the National Pollutant Inventory (NPI).
- Local meteorology that affects the transport and dispersion of air contaminants in the Gladstone area.
- Environmental values and objectives specified in the Environmental Protection (Air) Policy 2008 (Air EPP).
- LNG plant processes associated with the generation of air emissions.
- Routine and non-routine plant operating conditions and their relationship to the generation of air emissions.
- Air pollutant source characteristics, concentrations and emission rates.
- Meteorological and dispersion modelling methodology used to develop the Gladstone Airshed Modelling System version 3 (GAMSv3) and a statistical evaluation of its performance.

- Modelling methodology and assessment of ground-level concentrations of all air pollutants associated with processes at the Arrow LNG Plant including NO_X, SO_2, CO, PM_{10}, $PM_{2.5}$, odour and hydrocarbons, and the incorporation of background concentrations for cumulative impact assessment.
- Discussion and assessment of the potential for the generation of photochemical smog.
- Discussion and assessment of greenhouse gas emissions. (The assessment of greenhouse gas emissions has been undertaken separately. Please refer to the greenhouse gas assessment undertaken by PAEHolmes for further information.)

A detailed review of the TOR is provided in the TOR Cross Reference Table in Appendix A.

2. Project Description

2.1 Proponent

Arrow CSG (Australia) Pty Ltd (Arrow Energy) proposes to develop a liquefied natural gas (LNG) facility on Curtis Island off the central Queensland coast near Gladstone. The project, known as the Arrow LNG Plant, is a component of the larger Arrow LNG Project.

The proponent is a subsidiary of Arrow Energy Holdings Pty Ltd which is wholly owned by a joint venture between Royal Dutch Shell plc and PetroChina Company Limited.

2.2 Arrow LNG Plant

Arrow Energy proposes to construct the Arrow LNG Plant in the Curtis Island Industry Precinct at the south-western end of Curtis Island, approximately 6 km north of Gladstone and 85 km southeast of Rockhampton, off Queensland's central coast. In 2008, approximately 10% of the southern part of the island was added to the Gladstone State Development Area to be administered by the Queensland Department of Local Government and Planning. Of that area, approximately 1,500 ha (25%) has been designated as the Curtis Island Industry Precinct and is set aside for LNG development. The balance of the Gladstone State Development Area on Curtis Island has been allocated to the Curtis Island Environmental Management Precinct, a flora and fauna conservation area.

The Arrow LNG Plant will be supplied with coal seam gas from gas fields in the Surat and Bowen basins via high-pressure gas pipelines to Gladstone, from which a feed gas pipeline will provide gas to the LNG plant on Curtis Island. A tunnel is proposed for the feed gas pipeline crossing of Port Curtis.

The project is described below in terms of key infrastructure components: LNG plant, feed gas pipeline and dredging.

2.2.1 LNG Plant

Overview. The LNG plant will have a base-case capacity of 16 Mtpa, with a total plant capacity of up to 18 Mtpa. The plant will consist of four LNG trains, each with a nominal capacity of 4 Mtpa. The project will be undertaken in two phases of two trains (nominally 8 Mtpa), with a financial investment decision taken for each phase.

Operations infrastructure associated with the LNG plant includes the LNG trains (where liquefaction occurs; see 'Liquefaction Process' below), LNG storage tanks, cryogenic pipelines, seawater inlet for desalination and stormwater outlet pipelines, water and wastewater treatment, a 110 m high flare stack, power generators (see 'LNG Plant Power' below), administrative buildings and workshops.

Construction infrastructure associated with the LNG plant includes construction camps (see 'Workforce Accommodation' below), a concrete batching plant and laydown areas.

The plant will also require marine infrastructure for the transport of materials, personnel and product (LNG) during construction and operations (see 'Marine Infrastructure' below).

Construction Schedule. The plant will be constructed in two phases. Phase 1 will involve the construction of LNG trains 1 and 2, two LNG storage tanks (each with a capacity of between 120,000 m^3 and 180,000 m^3), Curtis Island construction camp and, if additional capacity is required, a mainland workforce accommodation camp. Associated marine infrastructure will also be required as part of Phase 1. Phase 2 will involve the construction of LNG trains 3 and 4 and potentially a third LNG storage tank. Construction of Phase 1 is scheduled to commence in 2014 with train 1 producing the first LNG cargo in 2017. Construction of Phase 2 is anticipated to commence approximately five years after the completion of Phase 1 but will be guided by market conditions and a financial investment decision at that time.

Construction Method. The LNG plant will generally be constructed using a modular construction method, with preassembled modules being transported to Curtis Island from an offshore fabrication facility. There will also be a substantial stick-built component of construction for associated infrastructure such as LNG storage tanks, buildings, underground cabling, piping and foundations. Where possible, aggregate for civil works will be sourced from suitable material excavated and crushed on site as part of the bulk earthworks. Aggregate will also be sourced from mainland quarries and transported from the mainland launch site to the plant site by roll-on, roll-off vessels. A concrete batching plant will be established on the plant site. Bulk cement requirements will be sourced outside of the batching plant and will be delivered to the site by roll-on roll-off ferries or barges from the mainland launch site.

2.2.1.1 LNG Plant Power

Power for the LNG plant and associated site utilities may be supplied from the electricity grid (mains power), gas turbine generators, or a combination of both, leading to four configuration options that will be assessed:

- Base case (mechanical drive): The mechanical drive configuration uses gas turbines to drive the LNG train refrigerant compressors, which is the traditional powering option for LNG facilities. This configuration would use coal seam gas and end flash gas (produced in the liquefaction process) to fuel the gas turbines that drive the LNG refrigerant compressors and the gas turbine generators that supply electricity to power the site utilities. Construction power for this option would be provided by diesel generators.
- Option 1 (mechanical/electrical – construction and site utilities only): This configuration uses gas turbines to drive the refrigerant compressors in the LNG trains. During construction, mains power would provide power to the site via a cable (30-MW capacity) from the mainland. The proposed capacity of the cable is equivalent to the output of one gas turbine generator. The mains power cable would be retained to power the site utilities during operations, resulting in one less gas turbine generator being required than the proposed base case.
- Option 2 (mechanical/electrical): This configuration uses gas turbines to drive the refrigerant compressors in the LNG trains and mains power to power site utilities. Under this option, construction power would be supplied by mains power or diesel generators.
- Option 3 (all electrical): Under this configuration mains power would be used to supply electricity for operation of the LNG train refrigerant compressors and the site utilities. A switchyard would be required. High-speed electric motors would be used to drive the LNG train refrigerant compressors. Construction power would be supplied by mains power or diesel generators.

2.2.1.2 Liquefaction Process

The coal seam gas enters the LNG plant where it is metered and split into two pipe headers which feed the two LNG trains. With the expansion to four trains the gas will be split into four LNG trains.
For each LNG train, the coal seam gas is first treated in the acid gas removal unit where the carbon dioxide and any other acid gases are removed. The gas is then routed to the dehydration unit where any water is removed and then passed through a mercury guard bed to remove mercury. The coal seam gas is then ready for further cooling and liquefaction.

A propane, precooled, mixed refrigerant process will be used by each LNG train to liquefy the predominantly methane coal seam gas. The liquefaction process begins with the propane cycle. The propane cycle involves three pressure stages of chilling to pre-cool the coal seam gas to -33℃ and to compress and condense the mixed refrige rant, which is a mixture of nitrogen, methane, ethylene and propane. The condensed mixed refrigerant and precooled coal seam gas are then separately routed to the main cryogenic heat exchanger, where the coal seam gas is further cooled and liquefied by the mixed refrigerant. Expansion of the mixed refrigerant gases within the heat exchanger removes heat from the coal seam gas. This process cools the coal seam gas from -33℃ to approximately -157℃. At this temperature the coal seam gas is liquefied (LNG) and becomes 1/600th of its original volume. The expanded mixed refrigerant is continually cycled to the propane precooler and reused.

LNG is then routed from the end flash gas system to a nitrogen stripper column which is used to separate nitrogen from the methane, reducing the nitrogen content of the LNG to less than 1 mole per cent (mol%). LNG separated in the nitrogen stripper column is pumped for storage on site in full containment storage tanks where it is maintained at a temperature of - 163℃.

A small amount off-gas is generated from the LNG during the process. This regasified coal seam gas is routed to an end flash gas compressor where it is prepared for use as fuel gas.

Finally, the LNG is transferred from the storage tanks onto LNG carriers via cryogenic pipelines and loading arms for transportation to export markets. The LNG will be regasified back into sales specification gas on shore at its destination location.

2.2.1.3 Workforce Accommodation

The LNG plant (Phase 1), tunnel, feed gas pipeline, and dredging components of the project each have their own workforces with peaks occurring at different stages during construction. The following peak workforces are estimated for the project:

- LNG plant Phase 1 peak workforce of 3,500, comprising 3,000 construction workers: 350 engineering, procurement and construction (EPC) management workers and 150 Arrow Energy employees.
- Tunnel peak workforce of up to 100.
- Feed gas pipeline (from the mainland to Curtis Island) peak workforce of up to 75.
- A dredging peak workforce of between 20 and 40.

Two workforce construction camp locations are proposed: the main construction camp at Boatshed Point on Curtis Island, and a possible mainland overflow construction camp, referred to as a temporary workers accommodation facility (TWAF). Two potential locations are currently being considered for the mainland TWAF; in the vicinity of Gladstone city on the former NRG Gladstone Power Station ash pond No.7 (TWAF7) or in the vicinity of

Targinnie on a primarily cleared pastoral grazing lot (TWAF8). Both potential TWAF sites include sufficient space to accommodate camp infrastructure and construction laydown areas. The TWAF and its associated construction laydown areas will be decommissioned on completion of the Phase 1 works.

Of the 3,000 construction workers for the LNG plant, it is estimated that between 5% and 20% will be from the local community (and thus will not require accommodation) and that the remaining fly-in, fly-out workers will be accommodated in construction camps. The 350 EPC management and 150 Arrow Energy employees are expected to relocate to Gladstone with the majority housed in company facilitated accommodation.

The tunnel workforce of 100 people and gas pipeline workforce of 75 people are anticipated to be accommodated in the mainland in company facilitated accommodation. The dredging workforce of 20 to 40 workers will be housed onboard the dredge vessel.

Up to 2,500 people will be housed at Boatshed Point construction camp. Its establishment will be preceded by a pioneer camp at the same locality which will evolve into the completed construction camp.

2.2.1.4 Marine Infrastructure

Marine facilities include the LNG jetty, materials offloading facility (MOF), personnel jetty and mainland launch site.

LNG Jetty. LNG will be transferred from the storage tanks on the site to the LNG jetty via above ground cryogenic pipelines. Loading arms on the LNG jetty will deliver the product to an LNG carrier. The LNG jetty will be located in North China Bay, adjacent to the northwest corner of Hamilton Point.

MOF. Delivery of materials to the site on Curtis Island during the construction and operations phases will be facilitated by a MOF where roll-on, roll-off or lift-on, lift-off vessels will dock to unload preassembled modules, equipment, supplies and construction aggregate. The MOF will be connected to the LNG plant site via a heavy-haul road.

Boatshed Point (MOF 1) is the base-case MOF option and would be located at the southern tip of Boatshed Point. The haul road would be routed along the western coastline of Boatshed Point (abutting the construction camp to the east) and enters the LNG Plant site at the southern boundary. A quarantine area will be located south of the LNG plant and will be accessed via the northern end of the haul road.

Two alternative options are being assessed, should the Boatshed Point option be determined to be not technically feasible:

- South Hamilton Point (MOF 2): This MOF option would be located at the southern tip of Hamilton Point. The haul road from this site would traverse the saddle between the hills of Hamilton Point to the southwest boundary of the LNG plant site. The quarantine area for this option will be located southwest of the LNG plant near the LNG storage tanks.
- North Hamilton Point (MOF 3): This option involves shared use of the MOF being constructed for the Santos Gladstone LNG Project (GLNG Project) on the northwest side of Hamilton Point (south of Arrow Energy's proposed LNG jetty). The GLNG Project is also constructing a passenger terminal at this site, but it will not be available to Arrow Energy contractors and staff. The quarantine area for this option would be located to the north of the MOF. The impacts of construction and operation

of this MOF option and its associated haul road were assessed as part of the GLNG Project and will not be assessed in this EIS.

Personnel Jetty. During the peak of construction, base case of up to 1,100 people may require transport to Curtis Island from the mainland on a daily basis. A personnel jetty will be constructed at the southern tip of Boatshed Point to enable the transfer of workers from the mainland launch site to Curtis Island by high-speed vehicle catamarans (Fastcats) and vehicle or passenger ferries (ROPAX). This facility will be adjacent to the MOF constructed at Boatshed Point. The haul road will be used to transport workers to and from the personnel jetty to the construction camp and LNG plant site. A secondary access for pedestrians will be provided between the personnel jetty and the construction camp.

Mainland Launch Site. Materials and workers will be transported to Curtis Island via the mainland launch site. The mainland launch site will contain both a passenger terminal and a roll-on, roll-off facility. The passenger terminal will include a jetty and transit infrastructure, such as amenities, waiting areas and car parking. The barge or roll-on, roll-off facility will have a jetty, associated laydown areas, workshops and storage sheds.

The two location options for the mainland launch site are:

- Launch site 1: This site is located north of Gladstone city near the mouth of the Calliope River, adjacent to the existing RG Tanna coal export terminal.
- Launch site 4N: This site is located at the northern end of the proposed reclamation area for the Fishermans Landing Northern Expansion Project, which is part of the Port of Gladstone Western Basin Master Plan. The availability of this site will depend on how far progressed the Western Basin Dredging and Disposal Project is at the time of construction.

2.2.2 Feed Gas Pipeline

An approximately 8-km long feed gas pipeline will supply gas to the LNG plant from its connection to the Arrow Surat Pipeline (formerly the Surat Gladstone Pipeline) on the mainland adjacent to Rio Tinto’s Yarwun alumina refinery. The feed gas pipeline will be constructed in three sections:

- A short length of feed gas pipeline will run from the proposed Arrow Surat Pipeline to the tunnel launch shaft, which will be located on a mudflat south of Fishermans Landing, just south of Boat Creek. This section of pipeline will be constructed using conventional open-cut trenching methods within a 40 m wide construction right of way.
- The next section of the feed gas pipeline will traverse Port Curtis harbour in a tunnel to be bored under the harbour from the mainland tunnel launch shaft to a receival shaft on Hamilton Point. The tunnel under Port Curtis will have an excavated diameter of up to approximately 6 m and will be constructed by a tunnel boring machine that will begin work at the mainland launch shaft. Tunnel spoil material will be processed through a de-sanding plant to remove the bentonite and water and will comprise mainly a finely graded fill material, which will be deposited in a spoil placement area established within bund walls constructed adjacent to the launch shaft. Based on the excavated diameter, approximately 223,000 m^3 of spoil will be treated as required for acid sulfate soil and disposed of at this location.

- From the tunnel receival shaft on Hamilton Point, the remaining section of the feed gas pipeline will run underground to the LNG plant, parallel to the above ground cryogenic pipelines. This section will be constructed using conventional open-cut trenching methods within a 30 m wide construction right of way. A permanent easement up to 30 m wide will be negotiated with the relevant land manager or owner.

Should one of the electrical plant power options be chosen, it is intended that a power connection will be provided by a third party to the tunnel launch shaft, whereby Arrow Energy would construct a power cable within the tunnel to the LNG plant.

Other infrastructure, such as communication cables, water and wastewater pipelines, may also be accommodated within the tunnel.

2.2.3 Dredging

Dredging required for LNG shipping access and swing basins has been assessed under the Gladstone Ports Corporation's Port of Gladstone Western Basin Dredging and Disposal Project. Additional dredging within the marine environment of Port Curtis may be required to accommodate the construction and operation of the marine facilities. Up to five sites may require dredging:

- Dredge site 1 (dredge footprint for launch site 1): The dredging of this site would facilitate the construction and operation of launch site 1. This dredge site is located in the Calliope River and extends from the intertidal area abutting launch site 1, past Mud Island to the main shipping channel. The worst-case dredge volume estimated at this site is approximately 900,000 m^3.
- .Dredge site 2 (dredge footprint for launch site 4N): The dredging of this site would facilitate the construction and operation of launch site 4N. This dredge site would abut launch site 4N and extend east from the launch site to the shipping channel. The worst-case dredge volume identified at this site is approximately 2,500 m^3.
- Dredge site 3 (dredge footprint for Boatshed Point MOF 1): The dredging of this site would facilitate the construction and operation of the personnel jetty and MOF at Boatshed Point. This dredge site would encompass the area around the marine facilities, providing adequate depth for docking and navigation. The worst-case dredge volume identified at this site is approximately 50,000 m^3.
- Dredge site 4 (dredge footprint for Hamilton Point South MOF 2): The dredging of this site would facilitate the construction and operation of the MOF at Hamilton Point South. This dredge site would encompass the area around the marine facilities, providing adequate depth for docking and navigation. The worst-case dredge volume identified at this site is approximately 50,000 m^3.
- Dredge site 5 (dredge footprint for LNG jetty): The dredging of this site will facilitate the construction of the LNG jetty at Hamilton Point. This dredge site extends from the berth pocket to be dredged as part of the Western Basin Strategic Dredging and Disposal Project to the shoreline and is required to enable a work barge to assist with construction of the jetty. The worst-case dredge volume identified is approximately 120,000 m^3.

The spoil generated by dredging activities will be placed and treated for acid sulfate soils (as required) in the Port of Gladstone Western Basin Dredging and Disposal Project reclamation area.

3. Air Quality Impact Assessment Methodology

The air quality impact assessment of the proposed Arrow LNG Plant has been conducted in accordance with the requirements of the project's TOR issued by the Coordinator-General in January 2010. The assessment utilises information on the existing environment, source characteristics and air pollutant emission rates in a dispersion modelling study to assess potential changes in air quality against air quality objectives contained in the Air EPP.

This section outlines the approach taken for the dispersion modelling study and impact assessment study.

3.1 Air Emissions

The assessment has been carried out to investigate the potential for air emissions from the Arrow LNG Plant to adversely impact on the air quality in the Gladstone region. The major air pollutant emitted during routine and non-routine operations of the LNG plant is NO_X. Minor emissions of SO_2, CO, PM_{10} and $PM_{2.5}$ and hydrocarbons are also emitted from the LNG plant during routine and non-routine operations. NO_X and SO_2 emissions are also emitted by LNG ships burning marine diesel oil. NO_X and some trace compounds emitted from fuel burning activities may also be associated with low levels of odour. Each emission source has been assessed for the following air pollutants during routine and non-routine operations at the plant:

- Oxides of nitrogen, as nitrogen dioxide
- Carbon monoxide
- Sulfur dioxide
- Particulates as PM_{10} and $PM_{2.5}$
- Hydrocarbons
- Odour
- Photochemical smog

These pollutants have been assessed because they have been found to adversely affect human health and amenity at elevated levels, and are legislated as environmental indicators under the Queensland Environmental Protection Act.

Emissions of air pollutants associated with the gas turbines and process system flares have been estimated using data from:

- Data supplied by Arrow Energy
- National Pollutant Inventory Emission Estimation Techniques (EET)
    - Combustion Engines v3.0
    - Maritime Operations v2.0
- United States Environmental Protection Agency (USEPA)
    - Current Methodologies in Preparing Mobile Source Port-Related Emission Inventories, Final Report (ICF, 2009)
- USEPA AP 42 Emission Factors
    - AP 42 Emission Factors Chapter 13.5, Industrial Flares (USEPA, 1991)

3.2 Scenarios

The air quality impact assessment considers separately the emissions to air from both routine and non-routine operations at the Arrow LNG Plant. For the routine operating scenario, the worst case power generation option in terms of air emissions is the base case, all mechanical drive configuration. The all mechanical drive option has been assessed in this air quality study. For the non-routine operating scenario, air emissions associated with the process relief flare system will be the same under all power generation configurations. Table 1 details the sources included in each scenario.

Table 1 Source summary for operational scenarios

Operations	Sources
Routine	Eight gas turbine compressor drivers @ 50% and 100% load Seven power generation gas turbines @ 50% and 100% load One LNG carrier and four tug boats Flare pilot
Non-routine	Cold dry gas flare
Table note: Routine operations refer to general day to day operation of the plant to produce LNG and has been assessed for the base case all mechanical drive configuration.	

A sensitivity analysis of the Arrow LNG Plant operating at 50% and 100% production capacity was carried out to determine the worst case scenario based on predicted ground-level concentrations of the primary air pollutant NO_2. The findings of the sensitivity analyses are presented in Appendix B.

3.3 Existing Environment

A description of the existing environment has been presented including geophysical features and local meteorology that will influence the transport and dispersion of air pollutants from the Arrow LNG Plant. The terrain, land use and coastal setting including interactions at the land-sea interface are described in terms of meteorological parameters such as wind speed, wind direction, atmospheric stability and boundary layer growth (mixing height).

The existing environment in the region has been described in terms of:

- Regional terrain and land use
- Meteorology
- Location of sensitive receptors
- Existing Air Quality
    - Emissions associated with existing local industries
    - Existing ambient air quality (in terms of background NO_2, SO_2, CO, PM_{10}, $PM_{2.5}$, air toxics (hydrocarbons) and O_3 concentrations)
    - GAMSv3 for existing and approved industries

3.4 Air Quality Impact Assessment

The air quality objectives presented in the Environmental Protection (Air) Policy 2008 (Air EPP) were adopted for the assessment. For some air pollutants, the Air EPP does not specify air quality objectives. Where this is the case project objectives have been determined from the following documents:

- NSW Department of Environment and Climate Change (NSW DECC) *Approved Methods for the Modelling and Assessment of Air Pollutants in NSW (2005)*

- Texas Commission on Environmental Quality Toxicological section list of Effects Screening Levels

The air quality assessment includes:

- A comparison of predicted ground-level concentrations of criteria air pollutants (including NO_2, SO_2, CO, PM_{10} and $PM_{2.5}$) associated with emissions from the Arrow LNG Plant in isolation and with background at sensitive receptor areas with the Air EPP objectives
- A comparison of predicted ground-level concentrations of key air pollutants (including hydrocarbons) associated with emissions from the Arrow LNG Plant in isolation and with background concentrations based on conservative assumptions for other LNG facilities at sensitive receptor areas with the relevant air quality criteria
- Assessment of odour by comparison of the 99.5th percentile 1-hour average ground-level concentration of individual odorous compounds, in odour units, at sensitive receptor areas with the DERM odour guideline
- Quantitative assessment of photochemical smog (ozone) based on the potential for ozone generation through the secondary photochemical transformation of primary pre-cursor air pollutants such as oxides of nitrogen and volatile organic compounds

3.5 GAMSv3 for Existing and Approved Industries

The impact assessment has been conducted using the Gladstone Airshed Modelling System version 3 (GAMSv3), a regional airshed dispersion modelling tool developed by Katestone Environmental for the Department of Infrastructure and Planning (DIP) for use in planning studies. The GAMSv3 includes emissions of NO_X and SO_2 associated with existing and approved industry in the Gladstone region. A detailed description of the GAMSv3 and a statistical performance evaluation is presented in Appendix B.

Since the development of the GAMSv3 in 2008, four LNG production projects have been proposed for the Gladstone region with three to be situated at Curtis Island and one at Fishermans Landing. Each of the projects: APLNG, QCLNG, GLNG and LNG Ltd, has attained environmental approval from both the State and Commonwealth Governments. Emissions from these facilities have been added to the baseline information in the GAMSv3 and have been assessed in addition to existing industry and the Arrow LNG Plant. Information is currently available for each of the LNG proposals through publication of the Environmental Impact Statement for each project.

The potential cumulative effect of all of the projects operating concurrently according to their published design specifications and NO_X emission rates has been assessed using the GAMSv3 dispersion model. NO_X is the most important air pollutant for the LNG projects through gas-fuel burning, particularly in gas turbines, as other compounds such as CO and hydrocarbons[1] are commonly found to have a lower risk of impact. Emissions of SO_2 are not a major concern from each of the LNG plants due to the removal of reduced sulfur compounds from the gas combusted, however, transient emissions of SO_2 associated with fuel burning aboard LNG Carriers and tug boats has been assessed.

[1] Hydrocarbons have not explicitly been included in the GAMSv3 modelling for all the other LNG facilities. Notwithstanding this, a cumulative assessment has been undertaken, refer to Section 5.5.

For this assessment, GAMSv3 industrial sources include:

- NRG Gladstone Power Station (coal-fired power generation)
- Queensland Alumina Ltd (alumina refining)
- Boyne Smelters Ltd (aluminium smelting)
- Rio Tinto Yarwun refinery Stage 1 (alumina refining)
- Rio Tinto Yarwun refinery Stage 2 (alumina refining) (approved and nearing commissioning)
- Cement Australia (cement manufacturing)
- Orica Australia Pty Ltd (basic inorganic chemical manufacturing)
- Australia Pacific LNG [Origin/ConocoPhillips] (LNG production and export facility) (approved but not built)
- Queensland Curtis LNG [QGC/BG Group] (LNG production and export facility) (approved but not built)
- Gladstone LNG [Santos/Petronas] (LNG production and export facility) (approved but not built)
- LNG Limited Fishermans Landing (LNG production and export facility) (approved but not built)

The following three industries were formally a part of GAMSv3 (2008) submitted to the DIP, but have been excluded from the Arrow LNG Plant air quality assessment at the request of Arrow Energy, as the projects have been approved by the State and Commonwealth Governments but are yet to take any final investment decision regarding their development:

- Queensland Energy Resources
- Queensland Pacific Nickel
- Aldoga Aluminium Smelter

3.6 Method for the Conversion of Oxides of Nitrogen to Nitrogen Dioxide

NO_X is the term used to describe the total of nitric oxide (NO), NO_2 and all other related oxidised nitrogen based compounds (including the greenhouse gas nitrous oxide) that are produced during combustion processes. The prediction of ground-level concentrations of NO_2 has been conducted by modelling the total emission rate in grams per second for NO_X from each source, with the results scaled by an empirical NO/NO_2 conversion ratio.

Measurements around power stations in Central Queensland show that under worst case conditions a conversion ratio of 25 - 40% of nitric oxide to nitrogen dioxide occurs within the first ten kilometres of plume travel. During days with elevated background levels of hydrocarbons (generally originating from bush-fires, hazard reduction burning or other similar activities), the resulting conversion is usually below 50% in the first thirty kilometres of plume travel (Bofinger *et al*., 1986).

For this assessment, the sensitive receptor areas are within 25 km of the Arrow LNG Plant and a conservative ratio of 30% has been applied for the conversion of NO_X to NO_2.

3.7 Method for the Assessment of Ozone

Ozone is not directly released from the Arrow LNG Plant as a primary pollutant; rather it is generated through the oxidation of NO_X in the presence of volatile organic compounds (VOCs) and sunlight in the atmosphere. The exhaust from the Arrow LNG Plant fuel burning sources contains approximately 90-95% of NO_X in the form of NO. Once this NO has been transformed into NO_2, O_3 may be produced via a multi-stage process. The rate at which ozone is generated is a function of:

- The in-plume concentration of NO_X
- The concentration and reactivity of VOCs in the ambient air
- The rate of plume dispersion
- The prevailing atmospheric conditions, including temperature and solar radiation fluxes

The transformation of NO_X and possible formation of O_3 involves a number of chemical reactions. Generally, during the first phase of chemical transformations, the mixing of the exhaust plume with ambient air results in a local reduction of ambient O_3, reaction of the emitted NO with O_3 to form NO_2. The second phase (ozone generation) will commence only if the ambient air is sufficiently aged (i.e., reactions have reached an equilibrium where no more NO_2 is produced). This phase continues with O_3 being both generated and diluted in the plume. The generation continues until the final phase, the NO_X-limited state, is reached in the plume. The duration of each phase will depend on the nature of the ambient air, the emission rates and characteristics of the industrial source and the dispersion rates.

Ozone levels near the surface have a pronounced diurnal variation, with levels of 10-25 parts per billion (ppb) (20-50 µg/m^3) overnight rising relatively quickly in the early to mid-morning and reaching a maximum of 25-35 ppb in the early afternoon. The origins of O_3 in a non-urban area are the downward diffusion of stratospheric O_3 and the interaction between naturally occurring hydrocarbons and NO_X. For urban areas, the maximum values can often be enhanced to 35-50 ppb by the presence of anthropogenic emissions of VOC, NO_X and water vapour.

Within Queensland, there are relatively few studies of O_3 generation within industrial plumes. Monitoring networks around the Tarong, Callide and NRG Gladstone Power Stations have tended to focus on those areas within ten to fifteen kilometres of the main sources, areas that are unlikely to experience extra O_3 generation. There have not been any readily identifiable episodes of O_3 generation during those times when the industrial plumes have been present at the monitoring locations.

The first investigation of the chemical transformations in industrial plumes was undertaken in 1986 around NRG Gladstone Power Station, a major emitter of nitrogen oxides (over 2000 g/s at full load, or approximately one hundred times the emission rate for the Arrow LNG Plant). An aerial survey measured NO_X and O_3 concentrations at distances out to two hundred kilometres for a set of late winter conditions. These studies demonstrate the relatively slow rate of transformation of emitted nitric oxide into NO_2.

Due to the proportionally low emissions for NO_X from the Arrow LNG Plant in comparison to the background emissions from NRG Gladstone Power Station and other industrial sources in the region, modelling of O_3 generation has not been conducted for this assessment. In order to assess the potential of the Arrow LNG Plant to cause air quality impacts in relation to ozone, an extremely conservative method has been applied.

The assessment has assumed that 100% of the predicted incremental ground-level concentrations of NO_2 associated with emissions from the Arrow LNG Plant, at a distance of ten kilometres from the site, will be transformed in to O_3. The cumulative assessment has been calculated by adding the maximum 1-hour average O_3 concentration recorded at the Targinie monitoring station and compared to the air quality objective.

4. Legislative Context

4.1 National Environment Protection Measure

The National Environment Protection Council (NEPC) defines national ambient air quality standards and goals in consultation, and with agreement from, all state governments. The air quality standards and goals were first published in 1998 in the National Environment Protection (Ambient Air Quality) Measure (Air NEPM) and covered six pollutants – NO_2, SO_2, CO, lead, O_3 and PM_{10}. Since this time, goals have been introduced for additional pollutants such as $PM_{2.5}$ and various air toxics. Compliance with the Air NEPM standards is assessed via ambient air quality monitoring undertaken at locations promulgated in the Air NEPM and that are representative of large urban populations.

The objectives of NEPMs are to ensure:

- *That people enjoy the benefit of equivalent protection from air, water and soil pollution and from noise, wherever they live; and,*
- *That decisions by businesses are not distorted and markets not fragmented by variations between jurisdictions in relation to the adoption or implementation of major environment protection measures.*

The goal of the Air NEPM is for the ambient air quality standards to be achieved at these monitoring stations within ten years of commencement, in 2008.

4.2 Queensland Government Legislation for the Protection of the Air Environment

The *Environmental Protection Act 1994* (EP Act) provides for the management of the air environment in Queensland. The legislation applies to government, industry and individuals and provides a mechanism for the delegation of responsibility to other government departments and local government and provides all government departments with a mechanism to incorporate environmental factors into decision-making.

The object of the EP Act is summarised as follows:

> *The object of the Environmental Protection Act 1994 is to protect Queensland's environment while allowing for development that improves the total quality of life, both now and in the future, in a way that maintains the ecological processes on which life depends. (Section 3, EP Act)*

The EP Act gives the Minister the power to create Environmental Protection Policies that aim to protect the environmental values identified for Queensland. The initial Environmental Protection (Air) Policy was gazetted in 1997. Subsequently, this policy was reviewed and the Environmental Protection (Air) Policy 2008 (Air EPP) commenced on 1 January 2009.

> The objective of the Air EPP is *to identify the environmental values of the air environment to be enhanced or protected and to achieve the object of the Environmental Protection Act 1994, i.e., ecologically sustainable development. (Air EPP Explanatory Notes)*

The application and purpose of the Air EPP is summarised as follows:

The purpose of this policy is to achieve the object of the Act in relation to the air environment (Air EPP Part 2, Section 5).

The purpose of this policy is achieved by -

a) identifying environmental values to be enhanced or protected; and
b) stating indicators and air quality objectives for enhancing or protecting the environmental values; and
c) providing a framework for making consistent, equitable and informed decisions about the air environment (Air EPP Part 2, Section 6).

The environmental values to be enhanced or protected under the Air EPP are –

a) the qualities of the air environment that are conducive to protecting the health and biodiversity of ecosystems; and
b) the qualities of the air environment that are conducive to human health and wellbeing; and
c) the qualities of the air environment that are conducive to protecting the aesthetics of the environment, including the appearance of buildings structures and other property; and
d) the qualities of the air environment that are conducive to protecting agricultural use of the environment. (Air EPP, section 7)

The administering authority must consider the requirements of the Air EPP when it decides on an application for an environmental authority, amendment of a licence or approval of a draft Environmental Management Plan. Schedule 1 of the Air EPP specifies air quality objectives for various averaging periods.

The Queensland Environmental Protection (Air) Policy 2008 (Air EPP) has adopted the Air NEPM (1998) goals as ambient air quality objectives, and will therefore be referenced throughout the report.

Ambient air quality objectives for air pollutants emitted by the project that are included in the Air EPP are presented in Table 2.

Table 2 Ambient air quality objectives for air pollutants included in the Air EPP

Indicator	Environmental value	Averaging period	Air quality objective[1] (µg/m³)	Number of days of exceedance allowed per year
Criteria air pollutants				
Nitrogen dioxide (NO_2)	Health and wellbeing	1-hour	250	1
		1-year	62	N/A
	Health and biodiversity of ecosystems	1-year	33	N/A
Sulfur dioxide (SO_2)	Health and wellbeing	1-hour	570	1
		24-hour	230	1
		1-year	57	N/A
	Protecting agriculture	1-year	32	N/A
	Health and biodiversity of ecosystems (for forests and natural vegetation)	1-year	22	N/A
Carbon monoxide (CO)	Health and wellbeing	8-hour	11,000	1
Particles as PM_{10}	Health and wellbeing	24-hour	50	5
Particles as $PM_{2.5}$	Health and wellbeing	24-hour	25	N/A
		1-year	8	N/A
Ozone (O_3)	Health and wellbeing	1-hour	210	1
		4-hour	160	1
Hydrocarbons				
Benzene	Health and wellbeing	Annual	10	N/A
1,3-Butadiene	Health and wellbeing	Annual	2.4	N/A
Formaldehyde	Health and wellbeing	24-hour	54	N/A
	Protecting aesthetic environment (odour)	30-minute	110	N/A
Toluene	Protecting aesthetic environment (odour)	30-minute	1,100	N/A
	Health and wellbeing	24-hour	4,100	N/A
	Health and wellbeing	Annual	410	N/A
Xylene	Health and wellbeing	24-hour	1,200	N/A
	Health and wellbeing	Annual	950	N/A

Table note:
[1] Air quality objective at $0^{o}C$, 101.3 kPa
N/A: Not applicable
Source: Air EPP (2008)

4.3 Other Air Quality Objectives

There is a suite of hydrocarbons emitted from the Arrow LNG Plant through the combustion of carbon-based fuels that are not included in the Air EPP. Notwithstanding their omission from the Air EPP, these compounds are considered air contaminants and have been assessed against other suitable national and international air quality standards and assessment criteria.

Where an air quality objective for a particular pollutant is not published in the Air EPP, it is accepted practice to carry out a review of air quality standards from other jurisdictions to develop an appropriate assessment criterion. For the Arrow LNG Plant air quality impact assessment, the following guidelines and standards have been adopted:

- Department of Environment and Conservation (NSW DEC) *Approved Methods for the Modelling and Assessment of Air Pollutants in NSW 2005* (NSW DEC, 2005) (now known as the NSW Office of Environment and Heritage)
- Texas Commission on Environmental Quality (TCEQ) *Effects Screening Levels 2010* (TCEQ, 2010)

The air quality objectives adopted for air contaminants not included in the Air EPP are presented in Table 3.

Table 3 Air quality objectives for air pollutants not included in the Air EPP

Indicator	Environmental value	Averaging period	Air quality objective[1] (µg/m³)	Source
Hydrocarbons				
Acetylene	Health	1-hour	26,600	TCEQ[1]
Acetaldehyde	Health	1-hour	42	DEC[2]
Acrolein	Health	1-hour	0.42	DEC[2]
Dioxins and furans	Health	1-hour	2.0 E-06	DEC[2]
Ethane	Health	1-hour	12,000	TCEQ[1]
Ethylbenzene	Health	1-hour	8,000	DEC[2]
Propane	Health	1-hour	18,000	TCEQ[1]
Propylene	Health	1-hour	8,750	TCEQ[1]

Table note:
[1] The TCEQ air quality objective is compared against the predicted highest (100^{th} percentile) ground-level concentrations.
[2] The DEC air quality objective is compared against the predicted ninth highest (99.9^{th} percentile) ground-level concentrations.
Objectives are expressed at 25°C, 1 Atm.

4.4 Odour Performance Criteria

The DERM's odour guidelines are published in a document entitled: *Guideline - Odour Impact Assessment from Developments, July 2004* (Queensland EPA, 2004). The odour guideline defines generic criteria for assessing odour annoyance in terms of odour units (ou). An odour unit is the number of times that a sample of odour must be diluted to reduce its concentration to its detection threshold. The odour guidelines are as follows:

- *0.5 ou for a 1-hour average, 99.5th percentile concentration for tall stacks.*
- *2.5 ou for a 1-hour average, 99.5th percentile concentration for ground-level sources and down-washed plumes from short stacks.*

In accordance with DERM's odour guidelines, a down-washed plume from a short stack is defined as one having a release point less than two and a half times the height of nearby buildings within a distance of ten times the lesser of the height or width of the building. The odour guideline applies to odour sensitive places such as residences, schools, hospitals, caravan parks, national parks, shops and business premises.

4.5 Emission Performance Standards

In NSW, the *Protection of the Environment Operations (Clean Air) Regulation (2002)* provides standards of emission concentrations for new and existing scheduled premises. The standards for gas turbines, presented in Table 4, have been considered in the Arrow LNG Plant design philosophy for the selection of process equipment and in the calculation of emission rates for plant sources.

Table 4 Point source emission concentration standards

Air impurity	Applicability	NSW Standard of concentration (mg/Nm^3)
Oxides of nitrogen (as NO_2)	Gas turbines	70[1]
PM_{10}	All combustion equipment	50
Carbon monoxide	All combustion equipment	125
	Firewater pumps	5,880
Volatile organic compounds	All combustion equipment	40
	Firewater pumps	1,140

Table note:
Reference conditions: Turbine - Dry, 273 K, 101.3 kPa, 15% oxygen content; Other combustion equipment operating on gas or liquid fuels – Dry, 273 K, 101.3 kPa, 3% oxygen content
[1] 70 mg/Nm3 of NO_X is equivalent to 35 ppm.
Source: NSW DEC 2002

5. Existing Environment

5.1 Regional Terrain and Land Use

The coastal city of Gladstone is located approximately 525 km north of Brisbane in Central Queensland. It is situated in a sub-tropical region comprising of a flat coastal plain bordered by a range of mountains to the west, typically 5-10 kilometres from the coast, with the most prominent peak, Mount Larcom, rising to 600 metres in elevation. The coastline in the region generally faces northeast to the Pacific Ocean. Two large barrier islands including Curtis Island to the north and Facing Island to the east shelter the Gladstone coast to form a deepwater harbour known as Port Curtis. A map showing the Arrow LNG Plant site and assessment area is presented in Figure 1.

The development of the harbour as a major shipping port has contributed to industrial growth in the region. Consequently, the Gladstone region is now a major industrial centre with highly developed chemical, mineral processing and refining, power generation and bulk raw material handling industries. The infrastructure of the region includes the deepwater port and associated shipping facilities, rail and road connections, an airport and the Gladstone State Development Area (GSDA).

The terrain in the region is relatively flat coastal plain, flood plain and mangrove with mildly undulating hills with the exception of Mount Larcom, as illustrated in the terrain map presented in Figure 2. Curtis Island is a low lying coastal island with a ridge running through its centre from northwest to southeast at the northeastern boundary of the proposed LNG facilities, which rises up to approximately 50 metres above sea level. The relatively flat terrain and coastline location of the proposed site will influence the wind patterns. Dominant meteorological conditions will include sea and land breezes while boundary layer growth above the site will be modulated by its proximity to the harbour and ocean.

The nearest existing industries to the Arrow LNG Plant are Cement Australia and the Queensland Energy Resources Limited Stuart Oil Shale Project on the mainland, which lie on either side of Landing Road at Fishermans Landing and are adjacent to the Arrow LNG Plant mainland launch site 4N. Further significant industries within the region include Rio Tinto Alcan Yarwun alumina refinery, Orica, NRG Gladstone Power Station, Queensland Alumina Ltd and Rio Tinto Alcan Boyne Smelters. The location of the major industry in Gladstone, including the other proposed LNG plants, is also shown in Figure 1.

5.2 Meteorology

5.2.1 Wind Speed and Direction

The Arrow LNG Plant is situated on the south-western side of Curtis Island, a low lying barrier island located to the north of Gladstone city. The city's coastal, sub-tropical location is reflected in the meteorology with strong land-sea interactions superimposed upon the dominant synoptic and mesoscale weather patterns associated with the southeast trade winds and the advection of warm moist air masses from the Pacific Ocean over land. The winds on the eastern coast of the island can be expected to be significantly stronger than the more sheltered western coast. The island is bisected in a north-south direction by a small ridge that can generate light drainage winds at night under stable conditions.

The annual distribution of winds at the Arrow LNG Plant site is presented as a wind rose diagram in Figure 3. The wind rose indicates that the annual variability in the wind direction is dominated by winds from the south-eastern sector. These winds account for 66% of the annual wind field, with maximum sustained winds of approximately 9.5 m/s. The second most dominant sector is from the north to northeast. Winds at the site are less frequent from the southwest and northwest sectors. The average modelled wind speed for the site is 3.9 m/s (at a height of 10 metres above the ground).

The seasonal distribution of winds is presented as a wind rose diagram in Figure 4. During the spring and summer, the wind direction is dominated by the south-easterly and north-easterly flows, while during the autumn and particularly the winter, the frequency of north-easterly flows are substituted by south-westerly winds.

The diurnal distribution of winds is presented as a wind rose diagram in Figure 5. The diurnal wind pattern indicates that the south-easterly flows begin to intensify by 9 am and gradually rotates counter clockwise to a north-easterly flow by the mid afternoon. Night time flows predominantly consist of a light westerly land breeze as the pressure gradient reverses due to the regional proximity to the coast and the influence of the surrounding terrain.

5.2.2 Atmospheric Stability and Mixing Height

Stability in this context is used to describe the properties of the atmosphere that govern the vertical motion of an air parcel. The vertical motion is promoted in an unstable atmosphere (turbulence increases), and resisted when the atmosphere is stable (turbulence is suppressed). Atmospheric stability is typically classified under the Pasquill-Gifford scheme, with six main categories designated as A (highly unstable or convective), B (moderately unstable), C (slightly unstable), D (neutral), E (slightly stable) and F (stable). The Pasquill-Gifford stability classification is widely used in atmospheric models to define the turbulent state of the atmosphere.

Unstable conditions (Class A-C) are characterised by strong solar heating of the ground that induces convective mixing in the atmosphere close to the ground, and usually results in a plume released from an elevated stack reaching the ground closer to the source than for neutral conditions or stable conditions. This convective mixing is the main driver of dispersion during unstable conditions.

Dispersion processes for neutral conditions (Class D) are dominated by mechanical turbulence generated as the wind passes over irregularities in the local surface, such as terrain features and building structures. During night time, the atmospheric conditions are neutral or stable (Class D, E and F).

During stable conditions the plume released from the stack will be subject to minimal atmospheric turbulence. A plume released below an inversion layer during stable conditions that does not have sufficient vertical momentum or thermal buoyancy to penetrate the inversion will be trapped beneath it and result in elevated ground-level concentrations. Conversely, a plume that is hotter than its surroundings and emitted above, or is able to penetrate the night time inversion through momentum, will remain relatively undiluted, and will not reach the ground unless it encounters elevated terrain.

Atmospheric stability class has been calculated using the USEPA approved Solar Radiation/Delta-T (SRDT) method (EPA, 2000). This method utilises the CALMET modelled wind speeds and TAPM modelled solar radiation (W/m^2) to determine daytime stability, while nocturnal stability is determined by wind speeds and the vertical temperature gradient between the surface and the next vertical sigma level at the site location, based on modelled data. This approach has been found to provide a more robust and verifiable classification scheme than the one produced internally in CALMET.

The percentage distribution of stability classes for Curtis Island is presented in Table 5. There is a high percentage of D class stability (59%), indicative of coastal sites. This is due to the high heat capacity of water dampening the development of a strong convective boundary layer. The water has a similar effect at night, where the warmth of the water prevents the development of any strong temperature inversions.

Table 5 Percentage frequency distribution for atmospheric stability under the Pasquill-Gifford stability classification scheme for the Arrow LNG Plant site

Pasquill-Gifford Stability Class	Frequency (%)
A - Extremely unstable	2
B - Unstable	12
C - Slightly unstable	15
D - Neutral	59
E - Slightly stable	5
F - Stable	7

The depth of the boundary layer is described by the mixing height and refers to the height above ground within which the plume can mix with ambient air. During stable atmospheric conditions at night, the mixing height is often quite low and the boundary layer is constrained. During the day, solar radiation heats the air at ground level and causes the mixing height to rise and the boundary layer to develop through the growth of convection cells. The air above the mixing height during the day is generally colder. The growth of the mixing height is dependent on how well the air can mix with the cooler upper levels of air and therefore depends on meteorological factors such as the intensity of solar radiation and wind speed.

Mixing height information for Curtis Island has been extracted from CALMET for the modelling period, and is presented in Figure 6 . The figure shows that the mixing height tends to develop around 6-7 am, peaks around 2-3 pm before decreasing gradually around sunset (5-6 pm). The average mixing height is between approximately 350m at night to 1,000m during the middle of the day. The peak height of the mixed layer is just below 2,000m above the site.

5.3 Location of Sensitive Receptors

It is important to consider the proximity of sensitive receptors to project infrastructure that may potentially release air emissions. The Arrow LNG Plant will be situated approximately 1.6km north of the nearest single residence on Tide Island in Port Curtis, 4.5km northwest of the major residential areas in Gladstone City, and 5.5km to the west of the community at South End. The closest sensitive receptors are the accommodation camps identified for the Arrow LNG Plant and the other LNG facilities proposed for Curtis Island. The locations of the workforce accommodation camps have been incorporated in to the area assessed.

The predicted maximum ground-level concentration of each pollutant in each receptor area based on the 250 metre modelling grid resolution has been assessed. The sensitive receptor areas are illustrated in Figure 7.

- Gladstone
- Tannum Sands
-
- Yarwun
- Fishermans Landing
- South End
- Island receptors including: Tide Island, Witt Island, Compigne Island, Quoin Island and Turtle Island
- LNG accommodation camps for the Arrow LNG Plant, APLNG, QCLNG and GLNG

5.4 Existing Air Quality

5.4.1 Emissions Associated with Existing Local Industries

There are a number of existing local industries that have an impact on the Gladstone airshed including a 1,650 MW coal-fired power station, two large alumina refineries, an aluminium smelter, an ammonium nitrate facility, coal handling and port facilities and a cement manufacturing facility. Emissions from industry include NO_X, CO, PM_{10}, SO_2 and VOCs. Further sources of NO_X and SO_2 include heavy site vehicles, machinery and shipping, while general sources of dust in the region include bushfires, landfills, commuter and freight trains including raw material transport, exposed areas of land, construction activities and traffic on public roads.

A summary of the latest edition of the National Pollutant Inventory (NPI) emissions database, detailing emissions for industries operating during the 2008 – 2009 reporting period, is presented in Table 6.

Table 6 Air pollution emissions for existing industries in the Gladstone region for the 2008 to 2009 NPI reporting period

Source	Oxides of nitrogen (t/yr)	Sulfur dioxide (t/yr)	Carbon monoxide (t/yr)	PM_{10} (t/yr)	$PM_{2.5}$ (t/yr)	Total VOCs (t/yr)
Austicks Pty Ltd (Wood product manufacturing)	141	0.52	100	10	8.4	12
Boyne Smelters Ltd (Aluminium smelting)	535	12,431	35,534	850	473	249
BP Australia Gladstone Terminal	--	--	--	--	--	62
Caltex Terminal Gladstone	--	--	--	--	--	160
Cement Australia (Cement production)	2,918	49	755	33	11	4.5
Gladstone Shell Aviation	--	--	--	--	--	0.18
Gladstone Ports Corporation Port Central	29	0.014	11	99	2	4.0
Gladstone Regional Council (All sites combined)	--	--	0.24	--	--	2.7
Jemena Asset Management Pty Ltd, QAL + Boyne Meter Station (Queensland Gas Pipeline)	--	--	--	--	--	3.8
Jemena Asset Management Pty Ltd, Gladstone Meter Station (Queensland Gas Pipeline)	--	--	--	--	--	0.13
NRG Gladstone Operating Services Pty Ltd (Fossil fuel power generation)	43,000	35,000	971	137	27	120
Orica Australia Pty Ltd (basic inorganic chemical manufacturing)	423	0.55	31	15	6	3.8
Orica Meter Station (Queensland Gas Pipeline)	--	--	--	--	--	0.54
Queensland Alumina Limited (Alumina production)	8,448	4,020	1,021	353	47	28
Queensland Rail Barney Point Rail (Fuelling Facility)	--	--	--	--	--	1.8
QR Callemondah Rail Yard (Fuelling facility)	38	0.020	22	3	3	42
Rio Tinto Aluminium Yarwun (Alumina production)	991	1,310	73	117	42	249
UMIMIN Australia Ltd (Construction material mining)	89	6.7	34	90	1.5	8.1
Total	56,611	52,818	38,551	1,708	620	952

Table note:
Gladstone Regional Council emissions are provided as a total for the following sites: Aerodrome Road Tip, Bat Colony Sign, Benaraby Road, Blain Drive, Cemetry Road, Corner Webb Park, Palm Drive Webb Park, Palm Drive Sports Field

5.4.2 Existing Ambient Air Quality

DERM operates a network of ambient air quality monitoring stations in the city of Gladstone and surrounding areas. A summary of DERM monitoring station data relevant to the air quality study is presented in Table 7. Air pollutants presented in Table 7 are those compounds monitored by DERM that may also be emitted from the Arrow LNG Plant. Ozone (O_3), whilst not emitted directly from the Arrow LNG Plant has the potential to be generated as a result of secondary photochemical transformation of primary pre-cursor pollutants such as NO_X and VOCs that are emitted by existing industries and also emitted by the Arrow LNG Plant.

Table 7 Ambient air quality monitoring of NO_2, SO_2, CO, O_3, PM_{10} and $PM_{2.5}$ at DERM monitoring sites in the Gladstone region

Monitoring station	Address	Data analysis period		Air pollutants monitored and analysed
		Start date	End date	
Boat Creek	Mount Larcom – cnr Gladstone & Landing Roads	June 2008	December 2010	NO_2, PM_{10}, $PM_{2.5}$
Clinton	Gladstone Airport	February 2001	December 2010	NO_2, PM_{10}
Targinie	Swanns Road	January 1997	December 2010	NO_2, PM_{10}, $PM_{2.5}$
Targinie	Stupkins Lane	January 2001	December 2010	PM_{10}, O_3
Boyne Island	Beacon Avenue	October 2008	December 2010	CO, NO_2, SO_2, PM_{10}, $PM_{2.5}$
Auckland Point	Auckland Point	July 2009	December 2010	O_3
Memorial Park	Memorial Park	July 2009	December 2010	O_3

5.4.3 Existing Ambient Nitrogen Dioxide Concentrations in the Region

The assessment of ambient concentrations of NO_2 has been carried out through a review of the DERM monthly air quality monitoring reports at Clinton, Boat Creek, and Boyne Island and is presented in Table 8. The monitoring information indicates that there have been no exceedances of the Air EPP objectives for NO_2 in the local area during the past ten years.

Table 8 Existing 1-hour and annual average concentrations of NO_2 in the Gladstone region (µg/m³)

Year	Clinton	Boat Creek	Targinie	Boyne Island
Maximum 1-hour average				
1999	NM	NM	86.3	NM
2000	NM	NM	78.1	NM
2001	141.7	NM	96.5	NM
2002	73.9	NM	98.6	NM
2003	65.7	NM	84.2	NM
2004	78.1	NM	90.4	NM
2005	73.9	NM	96.5	NM
2006	71.9	NM	90.4	NM
2007	78.1	NM	73.9	NM
2008	76.0	55.5	65.7	61.6
2009	69.8	121.2	78.1	90.3
2010	71.8	70.0	78.0	51.3
Annual average				
2007	10.3	NM	6.2	N/M
2008	8.2	N/A	6.2	N/A
2009	8.2	12.3	6.2	4.1
2010	8.2	10.3	6.2	2.1

Table note:
There were no annual averages reported by DERM between 1999 and 2006.
N/A refers to no annual average for NO_2 in these years due to insufficient data.
NM refers to 'No Monitoring' being conducted for these years
Air EPP 1-hour average objective for health and wellbeing is 250 µg/m³
Air EPP annual average objective for health and wellbeing is 62 µg/m³
Air EPP annual average objective for health and biodiversity of ecosystems is 33 µg/m³

5.4.4 Existing Ambient Sulfur Dioxide Concentrations in the Region

The assessment of ambient concentrations of SO_2 has been carried out through a review of the DERM monthly air quality monitoring reports at Clinton, Boat Creek, Targinie and Boyne Island and is presented in Table 9. The monitoring information indicates that there have been no exceedances of the Air EPP objectives for SO_2 in the local area during the past ten years.

Table 9 Existing 1-hour, 24-hour and annual average concentrations of SO_2 in the Gladstone region (µg/m³)

Year	Clinton	Boat Creek	Targinie	Boyne Island
Maximum 1-hour average				
1999	NM	NM	120.1	NM
2000	NM	NM	143.0	NM
2001	377.5	NM	266.0	NM
2002	154.4	NM	203.0	NM
2003	220.2	NM	291.7	NM
2004	137.3	NM	348.9	NM
2005	371.8	NM	148.7	NM
2006	145.9	NM	151.6	NM
2007	308.9	NM	123.0	NM
2008	443.3	125.8	140.1	205.9
2009	211.6	254.5	188.7	185.9
2010	143.0	228.8	125.8	163.0
Maximum 24-hour average				
1999	NM	NM	N\A	NM
2000	NM	NM	N\A	NM
2001	N\A	NM	N\A	NM
2002	N\A	NM	N\A	NM
2003	N\A	NM	N\A	NM
2004	N\A	NM	N\A	NM
2005	N\A	NM	N\A	NM
2006	N\A	NM	N\A	NM
2007	25.7	NM	25.7	NM
2008	28.6	22.9	20.0	51.5
2009	20.0	42.9	28.6	31.5
2010	31.5	31.5	28.6	22.9
Annual average				
1999	NM	NM	5.7	NM
2000	NM	NM	5.7	NM
2001	2.9	NM	5.7	NM
2002	2.9	NM	5.7	NM
2003	5.7	NM	5.7	NM
2004	2.9	NM	5.7	NM
2005	2.9	NM	5.7	NM
2006	2.9	NM	5.7	NM
2007	2.9	NM	5.7	NM
2008	2.9	NA	2.9	NA
2009	2.9	5.7	5.7	2.9
2010	2.9	5.7	5.7	2.9

Table note:
24-hour average SO_2 values not reported between 1999 and 2006
N/A refers to no value for SO_2 in these years.
NM refers to 'No Monitoring' being conducted for these years
Air EPP 1-hour average objective for health and wellbeing is 570 µg/m³
Air EPP 24-hour average objective for health and wellbeing is 230 µg/m³
Air EPP annual average objective for health and wellbeing is 57 µg/m³

5.4.5 Existing Ambient Carbon Monoxide Concentrations in the Region

The assessment of ambient concentrations of CO has been carried out through a review of the DERM monthly monitoring reports at Boyne Island and is presented in Table 10. Monitoring of CO in the Gladstone region has only been carried out at the Boyne Island site since October 2008. The monitoring information indicates that there have been no exceedances of the Air EPP objective for CO in the local area during this period.

Table 10 Existing 8-hour average concentrations of CO in the Gladstone region (µg/m³)

Year	Boyne Island	
	Max	70th percentile
2008	249.8	N/A
2009	2,623.4	15.6
2010	1,249.2	38.8

Table note:
Air EPP 8-hour average objective for health and wellbeing is 11,000 µg/m³
70th percentile values obtained from raw data set

5.4.6 Existing Ambient Particulate Matter Concentrations in the Region

The assessment of ambient concentrations of PM_{10} and $PM_{2.5}$ has been carried out through a review of the DERM monthly monitoring reports at Clinton, Boat Creek, Targinie and Boyne Island and is presented in Table 11 and Table 12. The information presented in Table 11 includes the maximum 24-hour average concentration of PM_{10} at each monitoring station, the sixth highest concentration that is used for the assessment against the Air EPP, and the 70th percentile 24-hour average concentration that is used as a background concentration for the cumulative impact assessment. The 70th percentile 24-hour average concentration is also used as a background concentration for the cumulative impact assessment of $PM_{2.5}$.

The monitoring information indicates that there have been several exceedances of the 24-hour average Air EPP objective of PM_{10} in the local area during the past ten years, particularly during 2009. $PM_{2.5}$ has only been monitored in the area since 2008, with a similar number of exceedances of the Air EPP objective occurring in 2009. In addition to this, the annual average Air EPP objective of $PM_{2.5}$ was also exceeded in 2009.

The DERM monthly monitoring reports indicate that all exceedances of the 24-hour average Air EPP objectives of PM_{10} and $PM_{2.5}$ were caused by dust storms and bushfires. The DERM monthly monitoring reports also indicate that the incidence of dust events throughout Queensland was unusually high during 2009, with the number of exceedances of the 24-hour average Air EPP objectives of PM_{10} and $PM_{2.5}$ significantly higher than those recorded previously. The most significant dust event was the major dust storm that affected much of eastern Australia and most of Queensland during late September 2009, with record concentrations of PM_{10} and $PM_{2.5}$ measured at all monitoring sites.

Table 11 Existing 24-hour average concentrations of PM_{10} in the Gladstone region (µg/m³)

Year	Clinton				Boat Creek				Targinie				Boyne Island			
	Max	6th highest	No. of exceed	70th %ile	Max	6th highest	No. of exceed	70th %ile	Max	6th highest	No. of exceed	70th %ile	Max	6th highest	No. of exceed	70th %ile
2001	63.5	48.7	0	19.3	NM	NM	NM	NM	93.2	39.6	0[1]	20.5	NM	NM	NM	NM
2002	174.6	51.8	1	17.8	NM	NM	NM	NM	194.1	59.0	4[1]	24.0	NM	NM	NM	NM
2003	41.9	32.4	0	16.3	NM	NM	NM	NM	50.0	41.0	0[1]	20.1	NM	NM	NM	NM
2004	44.2	33.2	0	17.5	NM	NM	NM	NM	51.0	42.1	0[1]	20.1	NM	NM	NM	NM
2005	220.4	33.4	0	16.7	NM	NM	NM	NM	223.5	36.2	0[1]	17.9	NM	NM	NM	NM
2006	53.1	35.8	0	17.3	NM	NM	NM	NM	78.8	28.3	0[1]	16.6	NM	NM	NM	NM
2007	28.8	25.8	0	15.7	NM	NM	NM	NM	34.2	29.4	0[1]	15.4	NM	NM	NM	NM
2008	59.8	31.0	0	14.8	42.5	30.5	0	NA	63.0	25.1	0[1]	16.1	37.5	27.6	0	17.4
2009	273.2	97.6	10	23.3	272.6	93.0	10	19.7	310.6	70.0	3[2]	16.0	264.4	78.9	10	16.8
2010	40.5	29.6	0	16.4	37.8	29.4	0	19.0	29.9	24.9	0[2]	11.9	32.3	26.6	0	15.0

Table note:
[1] Targinie monitor was located at Stupkins Lane.
[2] Targinie monitor was located at Swanns Road.
6th highest and 70th percentile values obtained from raw data set
Air EPP objective is 50 µg/m³ with five exceedances allowed.
'Max' refers to the maximum 24-hour average concentration
The '6th highest' concentration is presented for comparison with the Air EPP objective as five exceedances are permitted.
'No. of exceed' refers to the number of exceedances of the 24-hour average Air EPP air quality objective
'NM' No Monitoring
The 2008 dataset for Boat Creek is for the period June to December.
The 2008 dataset for Boyne Island is for the period October to December only
The 2010 datasets for all sites are for the period January to November. December data was not made available by DERM at the time of the study.

Table 12 Existing 24-hour and annual average concentrations of $PM_{2.5}$ in the Gladstone region (µg/m³)

Year	Clinton				Boat Creek				Targinie				Boyne Island			
	Max	No. of exceed	70th %ile	Annual	Max	No. of exceed	70th %ile	Annual	Max	No. of exceed	70th %ile	Annual	Max	No. of exceed	70th %ile	Annual
2008	NM	NM	NM	NM	20.2	0	NA	NA	NM	NM	NM	NM	19.8	0	8.4	NA
2009	39.0	9	8.8	8.7	218.2	13	7.7	9.3	61.5	4	4.8	5.6	105.6	7	6.8	7.3
2010	18.6	0	5.8	5.3	15.2	0	7.1	6.8	12.4	0	3.7	4.0	11.0	0	4.4	3.4

Table note:
Air EPP objective for the 24-hour average is 25 µg/m³ with no exceedances allowed.
Air EPP objective for the annual average is 8 µg/m³.
'Max' refers to the maximum 24-hour average concentration
'No. of exceed' refers to the number of exceedances of the 24-hour average Air EPP air quality objective
'NM' No Monitoring
The 2008 dataset for Boat Creek is for the period June to December.
The 2010 datasets for all sites are for the period January to November. December data was not made available by DERM at the time of the study.
The 2008 dataset for Boyne Island is for the period October to December.

5.4.7 Existing Ambient Air Toxics (Hydrocarbons/VOCs) Concentrations in the Region

The Clean and Healthy Air for Gladstone Project is a Queensland Government initiative, established to gain a better understanding of air pollution in the Gladstone area, and to identify any potential risks to public health. The monitoring program established as part of the program covered a wide range of air pollutants. The Queensland Government published a Human Health Risk Assessment for the Final Public Health Report for the Gladstone Project area in 2010 (Queensland Health, 2010). The report presents monitoring results for several air toxic species measured in the Gladstone region including some of the VOCs that are likely to be emitted from the Arrow LNG Plant. The maximum concentrations of these species were low or very low relative to the air quality objectives.

5.4.8 Existing Ambient Ozone Concentrations in the Region

The assessment of ambient concentrations of O_3 has been carried out through a review of the DERM monthly air quality monitoring reports at Targinnie, Auckland Point and Memorial Park and is presented in Table 13. The monitoring information indicates that there have been no exceedances of the Air EPP objective for O_3 in the local area during the past ten years.

Table 13 Summary of DERM monitoring information for the maximum 1-hour average concentrations of ozone in the Gladstone region for each year (µg/m³)

Date	Targinie Stupkins Lane	Auckland Point	Memorial Park
2001	119.9	NM	NM
2002	98.5	NM	NM
2003	96.4	NM	NM
2004	85.7	NM	NM
2005	81.4	NM	NM
2006	NM	NM	NM
2007	NM	NM	NM
2008	NM	NM	NM
2009	NM	100.7	102.8
2010	NM	83.5	94.2

Table note:
Air EPP objective for the 1-hour average is 210 µg/m^3 with no exceedances allowed.
'NM' No Monitoring

5.5 Background Air Quality used in the Cumulative Assessment

Background air quality for the cumulative impact assessment has been calculated in three ways depending on the pollutant assessed:

1. Modelling of emissions using the GAMSv3 that includes emissions of NO_X and SO_2 released by other major industry in the Gladstone region
2. Analysis of DERM monitoring station observations across the Gladstone region
3. Extrapolation of predicted ground-level concentrations for Arrow LNG Plant to include the potential impacts associated with the development of the other proposed LNG projects

GAMSv3 was used to assess the cumulative impact to air quality through the prediction of ground-level concentrations of NO_2 and SO_2 associated with emissions to air from existing and currently proposed industrial sources. Annual emissions of NO_X and SO_2 for each of the industrial sources included in the GAMSv3 are presented in Table 14.

Table 14 Modelled annual emissions of oxides of nitrogen and sulfur dioxide from industries included in the GAMSv3

Facility	Emission rate (t/yr)	
	Oxides of nitrogen	Sulfur dioxide
NRG Gladstone Power Station	43,621	34,018
Queensland Alumina Ltd	7,973	3,614
Boyne Smelters Ltd	-	6,860
Rio Tinto Aluminium Yarwun Stage 1	3,690	5,229
Rio Tinto Aluminium Yarwun Stage 2[1]	2,886	361
Cement Australia	4,457	17
Orica	300	0.2
Australia Pacific LNG[1]	3,250	N/A
Queensland Curtis LNG[1]	2,562	N/A
Gladstone LNG[1]	2,369	N/A
LNG Limited Fishermans Landing[1]	363	N/A

Table note:
[1] Approved but not built at the time of this EIS study
N/A – Not assessed

NO_X and SO_2 emissions associated with existing industries and proposed LNG plants were included in the dispersion model. The predicted ground-level concentrations at sensitive receptor locations of NO_2 and SO_2 associated with emissions from existing industries and proposed LNG plants, based on GAMSv3 modelling, are presented in Table 15 for the various air quality criteria. Contour plots for the various air quality criteria for predicted background concentrations of NO_2 and SO_2 are presented in Figure 8 to Figure 12.

Table 15 Predicted concentrations of nitrogen dioxide and sulfur dioxide for existing industries and proposed LNG plants based on GAMSv3 modelling (in µg/m³)

Location	Nitrogen dioxide		Sulfur dioxide		
	Maximum 1-hour average	Annual average	Maximum 1-hour average	Maximum 24-hour average	Annual average
Gladstone	257	9	677	171	14.3
Tannum Sands	33	0.5	182	46	2.6
Targinnie	77	7	213	106	18
Yarwun	103	7	311	93	20
Fisherman's Landing	83	6	237	71	15
South End	34	0.4	86	27	0.9
Maximum on isolated islands[1]	45	0.9	119	37	2
LNG construction camps[2]	52	1.3	125	37	2
Maximum % of air quality objective	103	14	119	74	34
Air quality objective	250	62	570	230	57

Table note:
[1] Value represents the maximum ground-level concentration predicted at all of the sensitive receptors situated on islands in Port Curtis, as shown in Figure 7.
[2] Value represents the maximum ground-level concentration predicted at all of the construction camps situated on Curtis Island, as shown in Figure 7.

Background concentrations used in the cumulative impact assessment for air pollutants not included in the GAMSv3, such as CO, PM_{10} and $PM_{2.5}$ have been determined through the analysis of DERM monitoring station observations carried out for the description of the existing air quality across the region (refer to Section 5.4.5 and 5.4.6). The source and value used for background concentrations in the cumulative impact assessment are summarised in Table 16.

Table 16 Summary of background concentrations for carbon monoxide, fine particles and ozone used in the assessment (in µg/m³)

<table>
<tr><th rowspan="2">Sensitive receptor</th><th colspan="8">Pollutant</th></tr>
<tr><th>Carbon monoxide[1,2] 8-hour average</th><th>Source</th><th>PM_{10} [3] 24-hour average</th><th>$PM_{2.5}$ [3] 24-hour average</th><th>$PM_{2.5}$ [4] Annual average</th><th>Source</th><th>Ozone [5] 1-hour average</th><th>Source</th></tr>
<tr><td>Gladstone</td><td rowspan="8">38.8</td><td rowspan="8">Boyne Island</td><td>19.3</td><td>5.8</td><td>5.3</td><td>Clinton</td><td rowspan="8">120</td><td rowspan="8">Targinnie</td></tr>
<tr><td>Tannum Sands</td><td>17.4</td><td>4.4</td><td>3.4</td><td>Boyne Island</td></tr>
<tr><td>Targinnie</td><td>24.0</td><td>3.7</td><td>4.0</td><td>Targinnie</td></tr>
<tr><td>Yarwun</td><td>19.0</td><td>7.1</td><td>6.8</td><td>Boat Creek</td></tr>
<tr><td>Fishermans Landing</td><td>19.0</td><td>7.1</td><td>6.8</td><td>Boat Creek</td></tr>
<tr><td>South End</td><td>24.0</td><td>3.7</td><td>4.0</td><td>Targinnie</td></tr>
<tr><td>Island receptors[6]</td><td>24.0</td><td>3.7</td><td>4.0</td><td>Targinnie</td></tr>
<tr><td>Construction camps[7]</td><td>24.0</td><td>3.7</td><td>4.0</td><td>Targinnie</td></tr>
</table>

Table note:
[1] Carbon monoxide in the Gladstone region is only monitored at Boyne Island.
[2] The 8-hour average CO concentration is based on the highest 70th percentile value for each of the years during the monitoring period.
[3] 24-hour average PM_{10} and $PM_{2.5}$ concentrations are based on the highest 70th percentile value for each of the years during the monitoring period excluding 2009, as 2009 is not considered to be a representative year due to a significant number of dust storms and bushfires.
[4] Annual average $PM_{2.5}$ concentrations are based on the annual average for 2010, since monitoring commenced in 2008 and 2009 is not considered to be a representative year.
[5] 1-hour average ozone concentration is based on the highest maximum value for each of the years during the monitoring period.
[6] Value represents the maximum ground-level concentration predicted at all of the sensitive receptors situated on islands in Port Curtis, as shown in Figure 7.
[7] Value represents the maximum ground-level concentration predicted at all of the construction camps situated on Curtis Island, as shown in Figure 7.
The monitoring station at Targinnie is considered to be removed from the main industry zone and has been used to represent the background concentrations at the construction camps, South End and Island receptors.

The Arrow LNG Plant is the fifth proposed LNG plant in the Gladstone region and one of four LNG plants located within the GSDA on Curtis Island. A similar suite of air toxics will be emitted from each LNG plant. Consequently, a conservative approach was adopted by Katestone Environmental to assess the potential for cumulative impacts of various hydrocarbon emissions released from all of the LNG plants. The method used was to extrapolate the predicted ground-level concentration of each hydrocarbon species at each sensitive receptor area by the number of LNG plants weighted by the facility's proposed LNG production capacity in millions of tonnes of LNG per annum. The nominal LNG production capacities of all of the proposed facilities and the scaling factor applied are presented in Table 17. This scaling factor has also been applied to the cumulative assessment of CO, PM_{10} and $PM_{2.5}$ to account for the other LNG plants.

Table 17 LNG production capacities and emissions scaling factor

Facility	Nominal LNG production capacity (MTPA)
Australia Pacific LNG	18
Queensland Curtis LNG	12
Gladstone LNG	10
LNG Limited	3.2
Total capacity other LNG Plants	*43.2*
Arrow LNG Plant	18
Emissions scaling factor	**3.4**
Table note: The Arrow LNG Plant base case is 16 Mtpa with a potential maximum capacity of 18 Mtpa. This assessment is based on the assumption that the maximum production capacity of 18 Mtpa is achieved.	

The assessment of potential cumulative ground-level concentrations of CO, PM_{10}, $PM_{2.5}$ and hydrocarbons using this approach is considered conservative as it assumes the emissions are released from the same location, i.e., the Arrow LNG Plant gas turbine stacks. The outcome is that the concentration of hydrocarbons in the Arrow LNG Plant emission plumes will be inflated by a factor of 3.4. In reality, the spatial distribution of ground-level concentrations of these air pollutants in the Gladstone region from all of the LNG facilities operating concurrently will be lower and more dispersed.

Due to the location of each LNG plant relative to the worker construction camp sensitive receptor areas, this scaling factor has not been applied to the cumulative assessment of potential impacts at each of the camps. This is due to camps being near-field receptors and downwind of the Arrow LNG Plant under certain meteorological conditions (such as wind direction and atmospheric stability), but not downwind of the other LNG plant emissions under those same conditions at the same time. Additional construction and operation of the LNG plants is unlikely to be simultaneous and so cumulative impacts are unlikely to occur at these camps in practice. The approach estimates the total emissions of CO, PM_{10}, $PM_{2.5}$ and hydrocarbons that are emitted from the LNG precinct and allows for an assessment of the predicted ground-level concentrations at the sensitive receptor areas.

6. Emissions and Modelling Considerations

6.1 Emission Data Sources

Source characteristics information and emission rates have been supplied by Arrow Energy based on a range of plant design specifications. Emission rates of NO_X and CO are based on gas turbine manufacturer design parameters, while emissions of PM_{10}, $PM_{2.5}$ and hydrocarbons have been estimated by Katestone Environmental using the NPI emission factors (NPI, 2008). Emission rates of NO_X, CO and hydrocarbons for the flares have been estimated using USEPA AP 42 emissions factors (USEPA, 1991). Emission rates of NO_X, SO_2, CO, PM_{10}, $PM_{2.5}$ and hydrocarbons for LNG Carriers at port call and supporting tug boats have also been estimated using emission factors. The emission factors used in the study have been sourced from the documents outlined in Table 18.

Table 18 Documents referenced for the determination of PM_{10}, $PM_{2.5}$ and hydrocarbon emissions

Source	Document referenced
Gas turbines	NPI Emission estimation technique manual for Combustion Engines, Version 3.0
Flares	USEPA AP 42 Industrial Flares, Chapter 13.5
LNG Carriers and tug boats	NPI Emission estimation technique manual for Marine Operations, Version 2.0
	Current Methodologies in Preparing Mobile Source Port-Related Emission Inventories (ICF, 2009)

The NPI emission factors used to calculate emission rates for hydrocarbons associated with the gas turbines are based on the chemical composition and lower heating value (LHV) of 38.9 MJ/m^3 of standard natural gas, while the coal seam methane being consumed as a fuel in the Arrow LNG Plant has a LHV of 28.7 MJ/m^3 (Arrow Energy, 2011). The emission factors used in the calculation of emission rates have been adjusted for this difference.

6.2 Overview of Sources of Air Pollutants

The air pollutants assessed for the Arrow LNG Plant air quality assessment are associated with the main sources of emissions. The emission sources and associated air pollutants are summarised in Table 19.

Table 19 Summary of Arrow LNG emission sources and air pollutants assessed

Source	Pollutant group	Compound
Routine operations		
• Gas turbines for LNG compressor drivers • Gas turbines power generation • Flare pilot for five process relief systems	Criteria pollutants	Oxides of nitrogen
		Carbon monoxide
		PM_{10}
		$PM_{2.5}$
	Air toxics	1,3-Butadiene
		Acetaldehyde
		Acrolein
		Benzene
		Ethylbenzene
		Formaldehyde
		Toluene
		Xylene
• LNG carrier and tug boats	Criteria pollutants	Oxides of nitrogen
		Sulfur dioxide
		Carbon monoxide
		PM_{10}
		$PM_{2.5}$
	Air toxics	Benzene
		Ethylbenzene
		Formaldehyde
		Toluene
		Xylene
		Dioxins and furans
Non-routine operations		
• Cold dry flare	Criteria pollutants	Oxides of nitrogen
		Carbon monoxide
	Air toxics	Methane
		Acetylene
		Ethane/ethylene
		Propane
		Propylene

6.3 Routine Operations

The routine operations assessed for the air quality impact assessment are for the all mechanical (base case) scenario which comprises the liquefaction process being driven by gas turbines and power generated for the site through gas turbine generators. This scenario represents the worst case for the Arrow LNG Plant in terms of potential air quality impacts. All other design cases will result in a lower air quality impact. This section describes the emissions associated with the all mechanical (base case) operating in the range between 50% and 100% load.

6.3.1 Gas Turbine Compressor Drivers

The exhaust characteristics of the gas turbines driving the compressors in the liquefaction process are presented in Table 20. Two 100 MW gas turbine units will drive the Propane (C3) and Mixed Refrigerant (MR) compressors in the liquefaction process of each LNG train. The base case includes four LNG trains with two gas turbine units per train, with a total of eight gas turbine compressor drivers being assessed. Each of the gas turbine compressor drivers will be fitted with waste heat recovery systems that will reduce the temperature of the exhaust gas.

Source characteristics are presented for the full range of routine operating conditions with the gas turbine compressor drivers operating at a continuous, nominal minimum capacity of 50% load and a maximum capacity of 100% load. The 100% load represents the worst case emissions scenario, however, during low load operations the lower stack exhaust gas flow results in a reduction in plume buoyancy and a change in plume dispersion and ground-level concentrations.

Table 20 Source characteristics of the gas turbine compressor drivers under routine operating conditions

Parameter	Units	50% load	100% load
Gas turbine input energy per unit	MW	148.1	231.9
Gas turbine thermal efficiency	%	33.9	43.3
Gas turbine output energy per unit - shaft power	MW	50.2	100.4
Number of stacks per train	--	2	
Total number of turbine units (four train case)	--	8	
Stack base ground elevation (above sea level)	m	11-25	
Stack height (above ground level)	m	40	
Stack diameter	m	5	
Exhaust gas temperature	ºC	230[1]	200[1]
Exhaust gas velocity	m/s	10.5	15.0
Exhaust gas flow rate (actual stack conditions)	Am^3/s	205.6	293.6
Normalised exhaust gas flow rate (0^oC, 1 Atm, dry[2], 15% oxygen content[3])	Nm^3/s	111.6	169.5
Exhaust gas mass rate	kg/s	141.5	214.7

Table note:
[1] Gas turbines include a Waste Heat Recovery Unit that result in a reduced exhaust gas temperature[2] Dry gas volume.
[3] Referenced to 15% oxygen content.
Source: Arrow Energy

The location of the stacks associated with each of the eight gas turbine compressor drivers for the four-train case is presented in Table 21.

Table 21 Locations of the gas turbine emission stacks

Compressor Turbine Driver	Train 1		Train 2		Train 3		Train 4	
	Easting	Northing	Easting	Northing	Easting	Northing	Easting	Northing
Unit 1	319729	7368943	319755	7369146	319780	7369345	319808	7369543
Unit 2	319625	7368956	319651	7369160	319675	7369357	319691	7369557

Table note:
MGA coordinates referenced to GDA94 (Zone 56) (in metres)

The concentrations and emission rates for NO_X, SO_2, CO and PM_{10} and $PM_{2.5}$ used in the modelling are presented in Table 22. The NPI emission factors for fine particles indicate that 100% of the fine particles emitted by the gas turbines are in the $PM_{2.5}$ size fraction. The emissions are also presented as total annual emissions for comparison with other industrial sources in the region.

Table 22 Concentration and emission rates of criteria air pollutants from the gas turbine compressor drivers under routine operating conditions

Parameter	Stack concentration[1] (mg/Nm^3)		Emission rate[1] (g/s)[4]		Total annual emissions[2] (t/yr)
	50% load	100% load	50% load	100% load	
Oxides of nitrogen (as NO_2)	51.3 (25ppm)	51.3 (25ppm)	5.7	8.7	1,366 – 2,074
Carbon monoxide	637	408	71.1	69.2	16,505 – 16,958
PM_{10} / $PM_{2.}$[3]	--	--	0.76	0.76	180

Table note:
[1] Information obtained from Arrow Energy unless otherwise stated from NPI emissions factors. Basis is 15% O_2, 0℃, 101.3 kPa
[2] Modelling has assumed that all turbines are operating for 8,760 hours per year, four trains. Total annual emissions based on actual plant utilisation of approximately 94.5% or 345 days per year. Range in total annual emissions accounts for 50% to 100% load. Total annual emissions accounts for eight gas turbine compressor drivers.
[3] Particulate emissions from gas turbines are negligible, i.e. all particulate matter emitted is smaller than 2.5 microns. PM_{10} and $PM_{2.5}$ emission rates are assumed to be equivalent.
[4] Emission rates (g/s) are per turbine

Table 23 Emission rates of hydrocarbons from the gas turbine compressor drivers

Pollutant	Emission factor[1] (kg/kWh)	Stack concentration[1] (mg/Nm^3)		Emission rate[1] (g/s)	
		50% load	100% load	50% load	100% load
1,3-Butadiene	6.65E-10	0.00018	0.00019	0.000020	0.000032
Acetaldehyde	6.19E-08	0.017	0.017	0.0019	0.0029
Acrolein	9.91E-09	0.0027	0.0028	0.00030	0.00047
Benzene	1.86E-08	0.0050	0.0052	0.00056	0.00088
Ethylbenzene	4.95E-08	0.013	0.014	0.0015	0.0023
Formaldehyde	1.10E-06	0.30	0.31	0.033	0.052
Toluene	2.01E-07	0.055	0.056	0.0061	0.0095
Xylene	9.91E-08	0.027	0.028	0.0030	0.0047

Table note:
[1]Source: NPI Emission Estimation Technique Manual – Combustion Engines v3.0 (2008)

6.3.2 Gas Turbine Power Generators

Electrical power for the Arrow LNG Plant all mechanical scenario (base case) will be generated by the combustion of CSG in gas turbines. A total of seven gas turbines are required for the four train scenario. The source characteristics of the gas turbines, used for power generation, are presented in Table 24.

Table 24 Source characteristics of the power generation gas turbines under routine operating conditions at 50% and 100% loads

Parameter	Units	50% load	100% load
Gas turbine input energy per unit	MW	48.6	74.9
Gas turbine thermal efficiency	%	28.2	36.6
Gas turbine output energy per unit - shaft power	MW	13.7	27.4
Number of stacks per turbine unit	--	1	
Total number of turbine units (four train case)	--	7	
Stack base ground elevation (above sea level)	m	16-24	
Stack height (above ground level)	m	25	
Stack diameter	m	4	
Exhaust gas temperature	℃	525.2	527.1
Exhaust gas velocity	m/s	11.5	15.4
Exhaust gas flow rate (actual stack conditions)	Am^3/s	144.2	193.5
Normalised exhaust gas flow rate (0^oC, 1 Atm, dry[1], 15% oxygen content[2])	Nm^3/s	49.3	66.1
Exhaust gas mass rate	kg/s	62.5	83.7

Table note:
[1] Assumed to be dry gas volume.
[2] Assumed to be reference to 15% oxygen content.
Source: Arrow Energy

The locations of the stacks associated with each of the seven gas turbines for power generation for the four-train case are presented in Table 25.

Table 25 Locations of the power generation gas turbine stacks

Turbine unit	Easting	Northing
1	319919	7369096
2	319923	7369126
3	319927	7369155
4	319931	7369185
5	319935	7369215
6	319943	7369277
7	319945	7369298

Table note:
MGA coordinates referenced to GDA94 (Zone 56) (in metres)

The concentrations and emission rates for NO_X, SO_2, CO and $PM_{10}/PM_{2.5}$ used in the modelling are presented in Table 26. The emissions are also presented as total annual emissions for comparison with other industrial sources in the region.

Table 26 Concentration and emission rates of air pollutants from power generation gas turbines under routine operating conditions

Parameter	Concentration (mg/Nm^3)		Emission rate (g/s)[3]		Total annual emissions[3] (t/yr)
	50% load	100% load	50% load	100% load	
Oxides of nitrogen (as NO_2)	51.3[1] (25ppm)	51.3[1] (25ppm)	2.5	3.4	528 - 707
Carbon monoxide	63.6[1]	63.6[1]	3.1	4.2	655 - 877
PM_{10} / $PM_{2.5}$	--	--	0.76[1]	0.76[1]	158

Table note:
[1] Information supplied by Arrow Energy. Basis is 15% O_2, 0℃, 101.3 kPa
[2] Modelling has assumed that all turbines are operating for 8,760 hours per year, four trains. Total annual emissions based on actual plant utilisation of approximately 94.5% or 345 days per year. Range in total annual emissions accounts for 50% to 100% load. Total annual emissions accounts for seven power generation gas turbines.
[3] Emission rates (g/s) are per turbine

Table 27 Breakdown of emission rates of hydrocarbons from the gas turbines for power generation

Pollutant	Emission factor[1] (kg/kWh)	Stack concentration (mg/Nm^3)		Emission rate (g/s)	
		50% load	100% load	50% load	100% load
1,3-Butadiene	6.65E-10	0.00013	0.00015	0.0000066	0.000010
Acetaldehyde	6.19E-08	0.012	0.014	0.00062	0.00095
Acrolein	9.91E-09	0.0020	0.0023	0.000099	0.00015
Benzene	1.86E-08	0.0037	0.0043	0.00018	0.00028
Ethylbenzene	4.95E-08	0.010	0.011	0.00049	0.00076
Formaldehyde	1.10E-06	0.22	0.26	0.011	0.017
Toluene	2.01E-07	0.041	0.047	0.0020	0.0031
Xylene	9.91E-08	0.020	0.023	0.00099	0.0015

Table note:
[1] Source: NPI Emission Estimation Technique Manual – Combustion Engines v3.0 (2008)

6.3.3 Flare Relief System Pilot

Five flare headers associated with different process relief systems will operate with a constant pilot light during routine operations. The five flare headers will be located on a single 110m tall stack. The source characteristics associated with each of the five relief systems are presented in Table 28, while the emission factors and emission rates are detailed in Table 29. The AP 42 emission factors document for industrial flares (chapter 13.5) provides an average distribution by volume for the total hydrocarbon fraction, and is reproduced here as Table 30. The location of the flare stack assessed in the modelling is presented in Table 31.

USEPA SCREEN3 method for flare modelling

To enable a dispersion model to adequately model the flare, the characteristics of the plume need to be modified to account for the buoyancy correctly. The nominal stack height and diameter are the actual height and diameter of the physical stack, while the effective height is the stack height entered into the model, along with the effective stack diameter, to account for the thermal buoyancy generated by the flare combustion zone at the flare tip. The USEPA approved SCREEN3 method has been used in conjunction with information supplied by Arrow Energy in calculating source and emission characteristics required for the modelling of the process relief system flare during both routine (pilot) and non-routine (upset/maintenance) conditions.

The SCREEN3 method calculates plume rise for flares based on an effective buoyancy flux parameter. It is assumed that 55% of the total heat is lost due to radiation, with the remaining 45% released as sensible heat that contributes to the buoyancy of the plume. Plume dispersion is consequently calculated by the CALPUFF dispersion model from the top of the combustion zone (i.e., effective height). The height of the combustion zone is equivalent to the difference between the effective and nominal stack heights. The effective diameter accounts for the assumption that the flame may be bent over to a 45 degree angle from the vertical due to the wind. This provides for a potential worst case plume extent at its release point.

Table 28 Energy release and plume buoyancy characteristics of the flare process relief system under pilot conditions during routine operations

Parameter	Units	Cold Dry 1 and 2 (F-CD)	Warm Wet, Operational (F-WW, F-OP)	Storage and Loading (F-LP)
Peak energy out[1,2]	GW	0.002063	0.000811	0.000744
Nominal stack height above ground[1]	m	110		
Nominal stack diameter[1]	m	1.37		
Effective stack height above ground[2]	m	111.6	111.0	111.0
Effective flare tip diameter[2]	m	0.47	0.29	0.28
Plume temperature after combustion[3]	^{o}C	1,000		
Plume vertical velocity at stack top after combustion[3]	m/s	20		
Percentage of total heat loss not due to radiation[3]	%	45	45	45

Table note:
[1] Information provided by Arrow Energy
[2] Calculated by Katestone Environmental using USEPA SCREEN3 Method
[3] USEPA SCREEN3 Method assumption

Table 29 Emission rates for the flare process relief systems pilot during routine operations

Parameter	Emission Factor[1] (g/GJ)	Cold Dry 1 and 2 (F-CD) (g/s)	Warm Wet, Operational (F-WW, F-OP) (g/s)	Storage and Loading (F-LP) (g/s)	Total annual emissions[2] (t/yr)
Oxides of nitrogen (as NO_2)	29.235	0.06	0.02	0.02	6
Carbon monoxide	159.073	0.33	0.13	0.12	31
Total hydrocarbons	60.190	0.12	0.05	0.04	12

Table note:
[1] From AP 42 Emission Factors
[2] The total emissions are based on the pilot flares operating during routine operations for the proposed plant availability of 345 days per year. It can be expected that plant shut downs may require gas to be disposed of through the flare system for train depressurisation. This will increase the quantity of air pollutants released for a short duration (typically approximately 15 minutes). Flare characteristics for non routine operations are provided in Table 35.
Emissions of fine particulate matter are assumed to be zero due to the use of smokeless flares.

Table 30 Composition of hydrocarbon emissions from the cold dry gas flare based on USEPA AP 42 emission factors

Composition	Volume (%)	
	Average	Range
Methane	55	14 - 83
Ethane/Ethylene	8	1 - 14
Acetylene	5	0.3 - 23
Propane	7	0 - 16
Propylene	25	1- 65

Table note:
The composition presented is an average of a number of test results obtained under the following sets of test conditions: steam-assisted flare using high-Btu-content feed; steam-assisted using low-Btu-content feed; and air assisted flare using low-Btu-content feed. In all tests, “waste” gas was a synthetic gas consisting of a mixture of propylene and propane.

Table 31 Location of the flare stack

Source	Easting	Northing
Flare stack	319775	7368688

Table note:
MGA coordinates referenced to GDA94 (Zone 56) (in metres)

6.3.4 LNG Carriers and Tug Boats

Emissions from shipping have been assessed based on air pollutants released from LNG carriers and tug boats while consuming Marine Diesel Oil (MDO) at port call (i.e. when LNG carriers are in berth). Emissions have been calculated using emission factors based on the number of engines operating per LNG carrier and tug boat and the engine capacity, as provided by Arrow Energy. Source characteristics for LNG carriers and tug boats at port call are described in Table 32, while emission rates, that have been calculated based on a combination of engine specifications and USEPA (2009) and NPI (2008) emission factors, are presented in Table 33.

Table 32 Source characteristics of LNG Carriers and tug boats during port call

Parameter	Units	LNG carrier		Tug boat
		Main engine	Auxiliary engine	Main engine
Number of engines per ship[1]	-	2	2	2
Number of engines operating per ship during port call[1]	-	1	1	2
Engine power per engine unit[1]	kW	11,400	8,550	2,000
Number of stacks per ship[1]	--	1		2
Stack height (above water level)[2]	m	37		6
Stack diameter[2]	m	1.7		0.65
Exhaust gas temperature[2]	℃	155		554.3
Exhaust gas velocity[2]	m/s	6.7		22.3
Exhaust gas flow rate (actual stack conditions) [2]	Am^3/s	15.2		7.4
Normalised exhaust gas flow rate (0^oC, 1 Atm)[2]	Nm^3/s	9.7		2.44

Table note:
[1] Technical specification information supplied by Arrow Energy. Oxygen reference conditions not available.
[2] QCLNG (2009)

Table 33 Emission rates of air pollutants from LNG Carriers and tug boats during port call

Parameter	Emission factor (g/kWh)	LNG carrier[1]		Tug boat[2]
		Main engine (g/s)	Auxiliary engine (g/s)	Main engine (g/s)
Oxides of nitrogen (as NO_2)	13.9	44.02	33.01	8.3[3]
Sulfur dioxide	6.16	19.5	14.6	6.84
Carbon monoxide	1.1	3.48	2.61	0.96[3]
PM_{10}	0.75	2.4	1.8	0.42
$PM_{2.5}$	0.28	0.89	0.67	0.16
Benzene	0.00762	0.024	0.018	0.0042
Ethylbenzene	0.000247	0.00078	0.00059	0.00014
Formaldehyde	0.000353	0.0011	0.00084	0.00020
Toluene	0.000201	0.00064	0.00048	0.00011
Xylene	0.00388	0.012	0.0092	0.0022
Dioxins and furans	2.41E-15	7.63E-12	5.72E-12	1.34E-12

Table note:
[1] LNG Carrier emissions are presented on a per engine basis. One Main Engine and one Auxiliary Engine are assumed to be operating at all times during a port call. The total emission rate from the LNG Carrier is the sum of the Main and Auxiliary Engines released from the single stack. One LNG Carrier is assumed to be at port at a time for the assessment.
[2] Tug boat emissions are presented on a per engine basis. Two engines are assumed to be operating at all times. Four tug boats operating at the port at all times have been assessed.
[3] Emission rates for NO_X and CO for the tug boats are based on engine specifications information.
All emission rates are based on USEPA and NPI emissions factors except where indicated in note 3.

6.3.5 Summary of Total Annual Emissions for Routine Operations

A summary of the range in potential total annual emissions from the Arrow LNG Plant during routine operations based on the 50% and 100% load scenarios is presented in Table 34. The summary is based on plant availability of 345 days per year (i.e., 94.5% availability) and four port calls for LNG carriers per week (52 weeks per year). Tug boats are assumed to operate during the LNG carrier port calls.

Table 34 Summary of the range in total annual emissions for criteria pollutants from the Arrow LNG Plant during routine operations (in t/yr)

Parameter	Gas turbines[1]				LNG carriers and tug boats[2]	Flare pilot	Total Arrow LNG Plant[3]	
	Compressor drivers		Power generation					
	50% load	100% load	50% load	100% load			Min	Max
Oxides of nitrogen (as NO_2)	1,366	2,074	528	707	3,066	6	4,966	5,853
Sulfur dioxide	0	0	0	0	1,350	0	1,350	1350
Carbon monoxide	13,215	13,577	655	877	253	31	14,154	14,738
PM_{10} / $PM_{2.5}$	180	180	158	158	164	0	502	502

Table note:
[1] Based on plant availability of 345 days (94.5% of year).
[2] Based on LNG Carrier port calls and tug boat operation of 208 days per year (1 LNG carrier for 24 hours per port call, 4 port calls per week, 52 weeks per year).
[3] Range in emissions based on plant operating loads (i.e., minimum based on 50% load and maximum based on 100% load for 345 days availability per year).

6.4 Non-routine Operations

Non-routine production processes operate on an intermittent and occasional basis for a short duration and may be planned or unplanned. Planned non-routine plant processes may include:

- Gas flares, including the Cold Dry Flare 1 (F-CD1), Cold Dry Flare 2 (F-CD2), Warm Wet Flare (F-WW), Storage and Loading Flare (F-LP) and Operational Flare (F-OP), are used for LNG process train and gas pipeline pressure management during –
  - Cold plant start up
  - Plant shutdown for maintenance
  - Disposal of boil-off gas not returned to the feed gas line due to issues with the boil-off gas compressor
- Plant construction phase-related emissions such as dust associated with earthworks and land clearing and combustion gas emissions from motor vehicles and earth moving equipment engines

Unplanned non-routine plant processes may include:

- Upset or emergency conditions that requires depressurisation of a liquefaction train or the gas pipeline entering the LNG plant

Other activities of the LNG plant occur intermittently for a short duration, are mobile or are transient in nature. These activities are likely to be intermittent sources of air pollutants. Emission sources in this category include:

- Variable emissions from routine operating equipment during start up and shut down
- Vehicle emissions
- Diesel generators
- Fire water pumps

The assessment of the potential affect of non-routine operations on air quality has been conducted selectively to identify worst-case conditions. Consequently, a quantitative assessment has been conducted for emissions associated with the gas flares during maintenance and upset or emergency conditions of the LNG plant. The worst-case emergency conditions for a release from the cold dry gas flare (F-CD) has been assessed and presented in this report.

6.4.1 Cold Dry Gas Flare

The principle function of the cold dry flare is to dispose of excess gases safely by controlled combustion in the event of an upset or plant maintenance in the liquefaction unit of each LNG train. A summary of the source characteristics for the cold dry flare (F-CD) during emergency operations for the depressurisation of the liquefaction unit of a single LNG train are presented in Table 35.

The USEPA SCREEN3 method has been used to calculate the effective height and diameter of the flare during the design maximum energy release. Due to the diminishing release rate of energy as the gas pressure is reduced in the plant, the characteristics presented are for the average plume dimensions over the 15 minute depressurisation period. The effective stack height, diameter and energy release rate will diminish with time. A linear decay rate over the 15-minute flaring period has been assumed as a worst-case scenario.

Table 35 Energy release and plume buoyancy characteristics of the Cold Dry Flare system

Parameter	Units	Cold dry gas flare (F-CD)
Peak energy out[1]	GJ/hr	63,000
Peak energy out[1] (per 15 minute depressurisation period)	GJ/15 min	15,750
Peak energy out[2]	GJ/s	17.50
Plume temperature after combustion[2]	^{o}C	1,000
Nominal stack height above ground[1]	m	110
Nominal stack diameter[1]	m	1.37
Effective stack height above ground[3]	m	234
Effective flare tip diameter[3]	m	43
Flare heat/radiation ratio[2]	%	45
Table note: [1] Information provided by Arrow LNG [2] USEPA SCREEN3 Method assumption [3] Calculated by Katestone Environmental using USEPA SCREEN3 Method		

Only limited information is available for flare emissions and consequently emission factors have been employed based on USEPA AP 42 documents (Chapter 13.5, Industrial Flares) in conjunction with information supplied by Arrow Energy. The emission factors for industrial flares and the emission rates used in the assessment for each of the pollutants are presented in Table 36. The USEPA AP 42 emission factors for industrial flares also consider particulate emissions for a range of flare types. The use of smokeless flares with negligible particulate emissions is proposed for the Arrow LNG Plant.

The assessment for the flare considers the 1-hour average ground-level concentrations of air pollutants during each hour of the year. Based on advice from Arrow LNG, an emergency LNG depressurisation event is likely to be approximately fifteen minutes in duration, with the gas flow rate and energy release diminishing with time, only 25% of the hourly emissions have been input to the model to represent the emissions in grams per second for fifteen minutes.

Table 36 Emission factors and emission rates for the Cold Dry Flare (F-CD) during emergency conditions

Parameter	Oxides of nitrogen	Carbon monoxide	Total hydrocarbons
Emission factor (g/GJ)	29.3[1]	159.1[1]	60.2[1]
Emission rate (g/s)	128[2]	696[2]	263[2]
Table note: [1] From AP 42 Emission Factors [2] Calculated from data supplied by Arrow Energy assuming duration of flaring event is 15 minutes			

6.4.2 LNG Train Start Up and Shutdown Conditions

The compressor driver gas turbine start-up procedure generally takes about fifteen to thirty minutes. During this period, operational capacity will be less than full load resulting in lower NO_X emissions than that released at full routine production.

A planned shutdown also requires a systematic procedure of taking units off-line and some flaring will take place to depressurise the liquefaction train. In a similar way to a start-up, lower quantities of emissions will be released during a shutdown than during full load operations. The disposal of gases through the flare also changes the suite of hydrocarbons released to that emitted from the gas turbines. Consequently, shutdown conditions also do not constitute the worst case emissions scenario and have not been presented in the assessment report.

6.5 Construction Activities

Emissions generated during construction activities are likely to consist of engine exhausts from vehicles and diesel generators and from dust generated by earthworks and vehicle movements on sealed and unsealed roads. A small concrete batching plant will be operated on the site for a short period during the construction phase. The composition of engine exhaust emissions is expected to be primarily NO_X and CO with small quantities of hydrocarbons.

Due to the relatively low emission rates of mobile vehicles in comparison to the gas turbines (during operations), the short duration and transient nature of these emissions during project construction in such an isolated area on Curtis Island, these emissions have not been considered further in this assessment. It is not expected that gaseous emissions to air during the construction phase will exceed those from the routine conditions of the full-scale operating four-train LNG plant.

Particulate matter impacts associated with earthworks, concrete batching, material handling and truck movements will be mainly restricted to the site. Control strategies to minimise the emission rate of air pollutants from construction activities such as the generation of dust from vehicle movements, earthworks and concrete batching will be addressed in the Environmental Management Plan. Emissions during decommissioning activities such as the generation of dust from vehicle movements and earthworks will be similar to the construction phase and will be addressed in the Decommissioning Phase Environmental Management Plan, which will be developed closer to the time of decommissioning.

During commissioning of each train the disposal of gases will be carried out through process flares. The emissions for the flares during commissioning will be less than the worst case modelled for the non-routine operating scenario. Therefore flaring during plant commissioning has not been presented in the assessment report.

6.6 Odour Impact Assessment

LNG facilities are not normally regarded as odour emitting activities. Mercaptan is the odorous chemical that is added to gas consumed in domestic and commercial applications that gives it its distinctive smell. Mercaptan is not added to coal seam gas or export LNG. Coal seam gas and export LNG are colourless and odourless gases.

The primary gaseous air pollutants emitted during the LNG production process are NO_X and CO, with trace quantities of reduced sulfur compounds and hydrocarbons found naturally in the CSG being removed during the production process before liquefaction or combustion in the gas turbines. Therefore SO_2 will not be emitted from the gas turbines. SO_2 emissions associated with the Arrow LNG Plant are limited to those emitted from fuel burning associated with shipping. Trace quantities of hydrocarbons formed from the combustion of methane in the gas turbines and MDO in the ship engines are released, with a few of the compounds being minor odorants.

The assessment of potential odour impacts associated with emissions from the Arrow LNG Plant has been conducted based on the odour thresholds and predicted ground-level concentrations of the odorous compounds identified. The odour threshold of odorous air pollutants has been used to convert the ground-level concentration in micrograms per cubic metre to an odour concentration in odour units for comparison with the DERM odour guideline. A conservative approach has been adopted for the calculation of the total ground-level odour concentration of the mixture of pollutants in the plume by summing the odour concentrations of each of the odorous compounds.

Six of the air pollutants emitted by the gas turbines and ships during routine operations are considered odorous and have been included in the odour impact assessment. The compounds assessed are nitrogen dioxide, sulfur dioxide, formaldehyde, acetaldehyde, benzene and toluene.

All stack emission points at the Arrow LNG Plant are relatively tall and hot with a high vertical velocity, giving the plume enough thermal and mechanical buoyancy at the release point to generate sufficient momentum for the plume to penetrate any low night time inversions, resulting in good plume dispersion conditions and plume rise in the order of some hundreds of metres. These source characteristics also reduce the potential for building wake turbulence to affect plume dispersion. Conversely, the plumes from LNG Carriers and tug boats are less buoyant than the gas turbine plumes and released from a lower height, as the ships are located at sea level while the base elevation of the gas turbines is between 11–25 m above sea level. Consequently, the ship emissions are less likely to penetrate any temperature inversion layer and will not disperse as efficiently during neutral and slightly stable atmospheric conditions by comparison with the gas turbine plumes.

7. Results of Air Quality Impact Assessment

This section presents the results of the air quality impact assessment for the most critical air pollutants, being NO_2 and SO_2, for the routine and non-routine operating conditions. The results for all other pollutants, including CO, PM_{10}, $PM_{2.5}$ and hydrocarbons, for the routine and non-routine operating conditions are provided in Appendix C.

7.1 Routine Operations

7.1.1 Nitrogen Dioxide

The predicted 99.9th percentile 1-hour and annual average ground-level concentrations of NO_2 at sensitive receptors areas for the Arrow LNG Plant operating at 50% load and 100% load in isolation are presented in Table 37, while the 1-hour average ground-level concentrations of NO_2 for the Arrow LNG Plant operating at 50% load and 100% load in isolation are also presented as contour plots in Figure 13 and Figure 14. Figure 15 shows the annual average ground-level concentrations of NO_2 for the Arrow LNG Plant operating in isolation at 100% load. The results for the Arrow LNG Plant operating in isolation show that there is no significant difference between the Arrow LNG Plant operating at 50% load or 100% load because the higher emission rate at 100% load is offset by more favourable dispersion characteristics that occur due to the higher exhaust exit velocity and greater exhaust volume.

Table 37 Predicted 1-hour (99.9th percentile) and annual average ground-level concentrations of nitrogen dioxide at 50% and 100% load for the Arrow LNG plant in isolation (in µg/m^3)

Location	50% load		100% load	
	1-hour average[3]	Annual average	1-hour average[3]	Annual average
Gladstone	45.6	0.4	45.6	0.4
Tannum Sands	10.1	0.1	9.7	0.1
Targinnie	54.0	0.9	54.0	1.0
Yarwun	49.8	0.6	49.5	0.6
Fishermans Landing	30.3	0.5	30.3	0.5
South End	29.5	0.2	30.0	0.2
Island receptors[4]	60.5	1.0	60.5	1.0
Construction camps[5]	147.8	6.7	147.5	6.7
Maximum % of air quality objective	59	11	59	11
Air quality objective	250	62[1] /33[2]	250	62[1] /33[2]

Table notes:
[1] Objective for health and wellbeing
[2] Objective for health and biodiversity of ecosystems
[3] 99.9th percentile, 1-hour average
[4] Value represents the maximum ground-level concentration predicted at all of the sensitive receptors situated on islands in Port Curtis, as shown in Figure 7
[5] Value represents the maximum ground-level concentration predicted at all of the construction camps situated on Curtis Island, as shown in Figure 7

The assessment of the 99.9th percentile 1-hour average and the annual average ground-level concentrations of NO_2 for the Arrow LNG Plant with the inclusion of background during routine operations at 100% load are presented in Table 38, while the 1-hour and annual average ground-level concentrations of NO_2 are presented as contour plots in Figure 16 and Figure 17, respectively.

Table 38 Predicted 1-hour (99.9th percentile) and annual average ground-level concentrations of nitrogen dioxide for the Arrow LNG Plant with background during routine operations at 100% load (in µg/m³)

Sensitive receptor area	1-hour average[1]	Annual average
Gladstone	257.7	8.8
Tannum Sands	34.8	0.6
Targinie	76.8	8.1
Yarwun	106.2	7.6
Fishermans Landing	82.8	6.3
South End	39.3	0.5
Island receptors[4]	65.0	1.9
Construction camps[5]	148.3	7.9
Maximum % of air quality objective	103	14
Air quality objective	250	62[2] /33[3]

Table notes:
[1] 99.9th percentile, 1-hour average
[2] Air EPP objective for health and wellbeing
[3] Air EPP objective for health and biodiversity of ecosystems
[4] Value represents the maximum ground-level concentration predicted at all of the sensitive receptors situated on islands in Port Curtis, as shown in Figure 7.
[5] Value represents the maximum ground-level concentration predicted at all of the construction camps situated on Curtis Island, as shown in Figure 7.

The assessment indicates that the predicted 99.9th percentile 1-hour and annual average ground-level concentrations of NO_2 associated with emissions from the Arrow LNG Plant in isolation are well below the air quality objectives. The cumulative impact assessment shows that predicted NO_2 concentrations in the region are dominated by existing industrial sources such as the power station. The elevated NO_2 concentration of 257.7µg/m³ (Table 38), that was predicted to occur in Gladstone in close proximity to the NRG Gladstone Power Station, is predominantly associated with emissions from the power station and other existing industry rather than the Arrow LNG Plant. The introduction of the Arrow LNG Plant to the cumulative dispersion model does not change the peak concentrations in most locations (with the exception of the construction camps). This is due to:

- The Arrow LNG Plant's emissions are relatively small compared to the total airshed emissions
- The relative locations of the Arrow LNG Plant and existing industries from sensitive receptors are such that the plumes will not overlap.

The contour plots also indicate that the 1-hour (99.9th percentile) average ground-level concentrations due to the Arrow LNG Plant are predicted to occur close to the northwest of the site.

7.1.2 Sulfur Dioxide

The predicted 1-hour (99.9th percentile), 24-hour (maximum) and annual average ground-level concentrations of SO_2 for the Arrow LNG Plant in isolation and with background at sensitive receptors are presented in Table 39. Contour plots are presented in Figure 18, Figure 19 and Figure 20 for the Arrow LNG Plant in isolation and in Figure 21, Figure 22 and Figure 23 for the Arrow LNG Plant operating in conjunction with background. Emissions of SO_2 are associated with the combustion of MDO in the engines of the LNG carriers and tug boats only.

Table 39 Predicted 1-hour (99.9th percentile), 24-hour and annual average ground-level concentrations of sulfur dioxide (in µg/m³)

Sensitive receptor area	Arrow LNG Plant in isolation			Arrow LNG Plant with background		
	1-hour average[3]	24-hour average	Annual average	1-hour average[3]	24-hour average	Annual average
Gladstone	66.0	18.9	0.6	677.0	175.0	14.4
Tannum Sands	14.2	2.7	0.1	184.0	46.6	2.7
Targinnie	77.7	19.3	1.2	213.0	106.0	18.2
Yarwun	72.9	19.1	0.8	311.0	93.4	19.8
Fishermans Landing	44.7	14.0	0.6	237.0	70.6	14.9
South End	43.6	14.3	0.2	86.8	27.9	1.0
Island receptors[4]	89.4	31.8	1.3	119.1	36.5	3.5
Construction camps[5]	216.6	46.1	8.8	216.6	59.4	11.2
Maximum % of air quality objective	38	20	40	119	76	90
Air quality objective	570[1]	230[1]	57[1]/22[2]	570[1]	230[1]	57[1]/22[2]

Table notes:
[1] Objective for health and wellbeing
[2] Objective for health and biodiversity of ecosystems
[3] 1-hour 99.9th percentile
[4] Value represents the maximum ground-level concentration predicted at all of the sensitive receptors situated on islands in Port Curtis, as shown in Figure 7
[5] Value represents the maximum ground-level concentration predicted at all of the construction camps situated on Curtis Island, as shown in Figure 7

The assessment indicates that the predicted 1-hour (99.9th percentile) , 24-hour (maximum) and annual average concentrations of SO_2, based on Arrow LNG Plant shipping-related emissions in isolation, are low and well below the Air EPP objectives. In a similar way to predicted concentrations of NO_2, the existing air quality with regard to SO_2 concentrations in the region is dominated by existing industrial sources such as the NRG Gladstone Power Station. The introduction of the Arrow LNG Plant to the cumulative dispersion model does not change the peak concentrations in most locations (with the exception of the construction camps). This is due to:

- The Arrow LNG Plant's emissions are relatively small compared to the total airshed emissions
- The relative locations of the Arrow LNG Plant and existing industries from sensitive receptors are such that the plumes will not overlap.

The assessment also indicates that the 1-hour (99.9th percentile), 24 hour maximum and annual average concentrations due to the Arrow LNG Plant are predicted to occur close to the site:

- On elevated terrain on Curtis Island to the north and northeast of the LNG carrier and loading facilities
- Over Port Curtis to the northwest of the LNG carrier and loading facilities

7.2 Non-routine Operations

This section summarises the results for the non-routine operations at the Arrow LNG Plant. This scenario comprises emissions from the routine operations plus the operation of the cold dry flare (F-CD1) under the worst case plant upset or emergency conditions where a liquefaction train is depressurised with feed gas disposed of through combustion at the flare. This assessment scenario is a conservative worst case flaring scenario due to the very low probability of occurrence. Additionally, the gas turbine emissions during routine operations of the LNG processing train being depressurised have also been included in the non-routine operations scenario, which is unrealistic as the gas turbines will not operate while a train is being depressurised.

As this is a short-term operating scenario annual averages have not been assessed. It should also be noted that particulate emissions are not expected from the flares.

7.2.1 Nitrogen Dioxide

The predicted 1-hour average (99.9th percentile) ground-level concentrations of NO_2 at sensitive receptor areas for the Arrow LNG Plant during a non-routine flare event (F-CD) are presented in Table 40.

The assessment indicates that impacts associated with NO_2 emissions from the Arrow LNG Plant with the flare in operation during worst case conditions are low and well below the Air EPP objective. The assessment illustrates that the stack flare does not significantly contribute to ground-level concentrations of NO_2 beyond that of the existing background and the Arrow LNG Plant. Of the Arrow LNG Plant sources, the flares do not contribute to peak concentrations of NO_2 because of the extremely buoyant plume characteristics of the flare that provides for a significant amount of plume rise and consequent dispersion. Hence, the results that are presented in Table 40 for the Arrow LNG Plant in isolation are dominated by the gas turbines that have been conservatively included in this scenario.

Table 40 Predicted maximum 1-hour average ground-level concentrations of nitrogen dioxide for the Arrow LNG Plant during worst case, non-routine flare (F-CD) operations at 100% load

Sensitive receptor area	Arrow LNG Plant in isolation	Arrow LNG Plant with background
Gladstone	46	258
Tannum Sands	10	35
Targinnie	54	77
Yarwun	50	106
Fishermans Landing	30	83
South End	30	39
Island receptors[1]	61	65
Construction camps[2]	148	148
Maximum % of air quality objective	59.0	103.1
Air quality objective	250	

Table note:
Maximum value is 99.9th percentile, 1-hour average
[1] Value represents the maximum ground-level concentration predicted at all of the sensitive receptors situated on islands in Port Curtis, as shown in Figure 7
[2] Value represents the maximum ground-level concentration predicted at all of the construction camps situated on Curtis Island, as shown in Figure 7

8. Avoidance, Mitigation and Management Measures

The Arrow LNG design philosophy is based on the following principle:

> *Minimisation through abatement at source of gaseous emissions that have the potential of causing negative impact on the environment (Arrow LNG Project: Basis of Design Report)*

The following specifications and requirements are applicable to emissions:

- Compliance with all relevant national ambient air quality standards and objectives including the Air NEPM, Air Toxics NEPM and the Air EPP (as detailed in Section 4).
-
- During start-up and shutdown controlled flaring is part of the operational procedure. The operations philosophy shall cover all situations where gas flaring is needed as a consequence of operational upsets.
    - The flare shall be luminous and bright (i.e., show smokeless combustion at operating design gas flow rate). The relative density of emitted smoke shall not exceed No. 1 Ringelmann Number. Maximum allowed exceedence is 5 min/hr with an aggregated 15 min/24 hrs.
- To minimise fugitive emissions from sources such as pumps, seals, valves, connectors and pipe work. The latest proven stage of development of processes, facilities and methods of operation shall be applied, including closed draining, minimising the number of flanges, installation of dry gas seals on compressors, vapour recovery systems and where applicable, double seals for hydrocarbon pumps. The project shall develop and include the new equipment in the existing leak detection and maintenance plan.
- The Arrow LNG Plant will only use low sulfur diesel (max 0.01% sulfur by mass) in diesel powered generators
- Boil off gas originating from stored LNG (including return vapours from the LNG carrier) shall be collected using an appropriate vapour recovery system (e.g. compressor system) and not be released to air
- Low emissions technology (e.g. Dry Low-NO_X (DLN) burners shall be applied throughout for significant combustion equipment (e.g. gas turbines).
- The design shall include provisions to install adequate equipment to monitor and record stack emissions for which regulatory limits exist and/or for which performance statistics are required. All monitoring and recording shall in principle be based on automatic on-line technology, in line with current best practice. All stacks shall be fitted with emissions monitoring ports suitable for continuous monitoring even if continuous monitoring is not recommended/possible, in order to facilitate future monitoring if required.
- Ground-level concentrations of air pollutants at the construction camp shall not exceed the relevant ambient air quality standards and objectives identified for the air quality assessment.
- New installations shall not use chlorofluorocarbons (CFC), halogens or related materials listed as banned under the Montreal Protocol.

9. Conclusions

An air quality impact assessment has been conducted for the Arrow LNG Plant to be constructed and operated on Curtis Island on the northern shoreline of Port Curtis near the city of Gladstone in central Queensland.

The air quality impact assessment has investigated the potential for impacts associated with emissions to air from stack sources during routine and non-routine operating scenarios. The impacts of air pollutants for the Arrow LNG Plant in isolation and with background concentrations have been considered. These scenarios represent the worst-case potential for impacts associated with the proposal.

The assessment was carried out using the Gladstone Airshed Modelling System version 3, a regional airshed dispersion model developed by Katestone Environmental for the Department of Infrastructure and Planning for use in planning studies to evaluate cumulative impacts on air quality. The model includes emissions of NO_X and SO_2 from major existing and approved (but yet to be built) industrial sources in the Gladstone region such as the other proposed LNG plants at Curtis Island and Fishermans Landing. The model was used to predict the impacts of NO_2 and SO_2 for the Arrow LNG Plant during routine and non-routine operating scenarios. For air pollutants not included in the GAMSv3 model such as fine particles (PM_{10} and $PM_{2.5}$), carbon monoxide and hydrocarbons, alternative approaches were adopted for the cumulative assessments including the addition of a representative regional background concentration for CO, PM_{10} and $PM_{2.5}$, and the extrapolation of predicted hydrocarbon concentrations for the Arrow LNG Plant to account for the other LNG plants.

Emissions associated with the Arrow LNG Plant during routine operations are mainly due to the consumption of coal seam gas as a fuel in the gas turbines to drive the LNG compressors and for site power generation. Consequently, the primary pollutant of interest is NO_X. Small quantities of PM_{10}, $PM_{2.5}$, CO, SO_2 and hydrocarbons are also released during routine plant operations. NO_X is also the key pollutant emitted during non-routine operations with small quantities of CO and hydrocarbons. The proposed stack flares will be smokeless and consequently emissions of fine particles will be near zero.

NO_X and CO emission information for gas turbines was provided by Arrow Energy from manufacturer specifications, while emission rates for PM_{10}, $PM_{2.5}$, SO_2 and hydrocarbons have been estimated using NPI (2008) emissions factors. A summary of the total annual emissions of criteria air pollutants for existing industry in Gladstone and for the Arrow LNG Plant is presented in Table 41.

Table 41 Summary of annual emissions from existing Gladstone industries and the Arrow LNG Plant

Source	Units	NO_X	CO	$PM_{10}/PM_{2.5}$	SO_2
Existing Gladstone[1]	t/yr	56,611	38,551	2,328	52,818
Arrow LNG Plant[2]	t/yr	5,853	14,738	502	1,350
Arrow LNG Plant as a percentage of total emissions	%	9.3	27.7	17.7	2.5

Table note:
[1] Based on NPI reports for 2008-2009 period for existing industries only (no natural or anthropogenic emissions included)
[2] Total plant emissions for routine operations at plant design availability (94.5%).

The following conclusions may be drawn from the air quality impact assessment.

In relation to dispersion meteorology:

- The Arrow LNG Plant site is dominated by moderate winds with an average wind speed of 3.9 m/s (at 10 metres above ground). This provides for relatively good dispersion conditions for stack sources.
- The prevailing wind direction at the site is from the southeast quadrant which will transport the plumes away from the main population centre of Gladstone located to the southeast
- Winds from the southwest during the winter months and at night are predicted to transport the plume to the northeast where the plume may come in contact with elevated terrain areas of Curtis Island
- Winds likely to carry emissions from the Arrow LNG Plant over the population centre of Gladstone city occur very infrequently

A cumulative air quality impact assessment was undertaken that included all existing industrial sources in Gladstone and proposed future LNG plants on Curtis Island and at Fishermans Landing, and has shown the following:

- All air quality objectives are met for routine and non-routine operation of the Arrow LNG Plant (inclusive of background levels) at sensitive receptors for NO_2, CO, PM_{10}, $PM_{2.5}$, odour, O_3, SO_2 and hydrocarbons

For all pollutants considered, the regional air quality is dominated by existing sources, which include industrial, anthropogenic and natural sources. The assessment indicates that there are no significant constraints to air quality in the Gladstone airshed. Industrial sources such as the existing NRG Gladstone Power Station are the most important contributors to the airshed. The introduction of the Arrow LNG Plant to the cumulative dispersion model does not change the peak concentrations in most locations. This is due to:

- The Arrow LNG Plant's emissions are relatively small compared to the total airshed emissions
- The relative locations of the Arrow LNG Plant and existing industries from sensitive receptors are such that the plumes will not overlap.

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Figure 1 Map showing the Arrow LNG Plant air quality assessment area in the Gladstone region

Location: Gladstone region, QLD	**Type:** Project area terrain contour map	**Date:** June 2011	**Prepared by:** S. Menzel

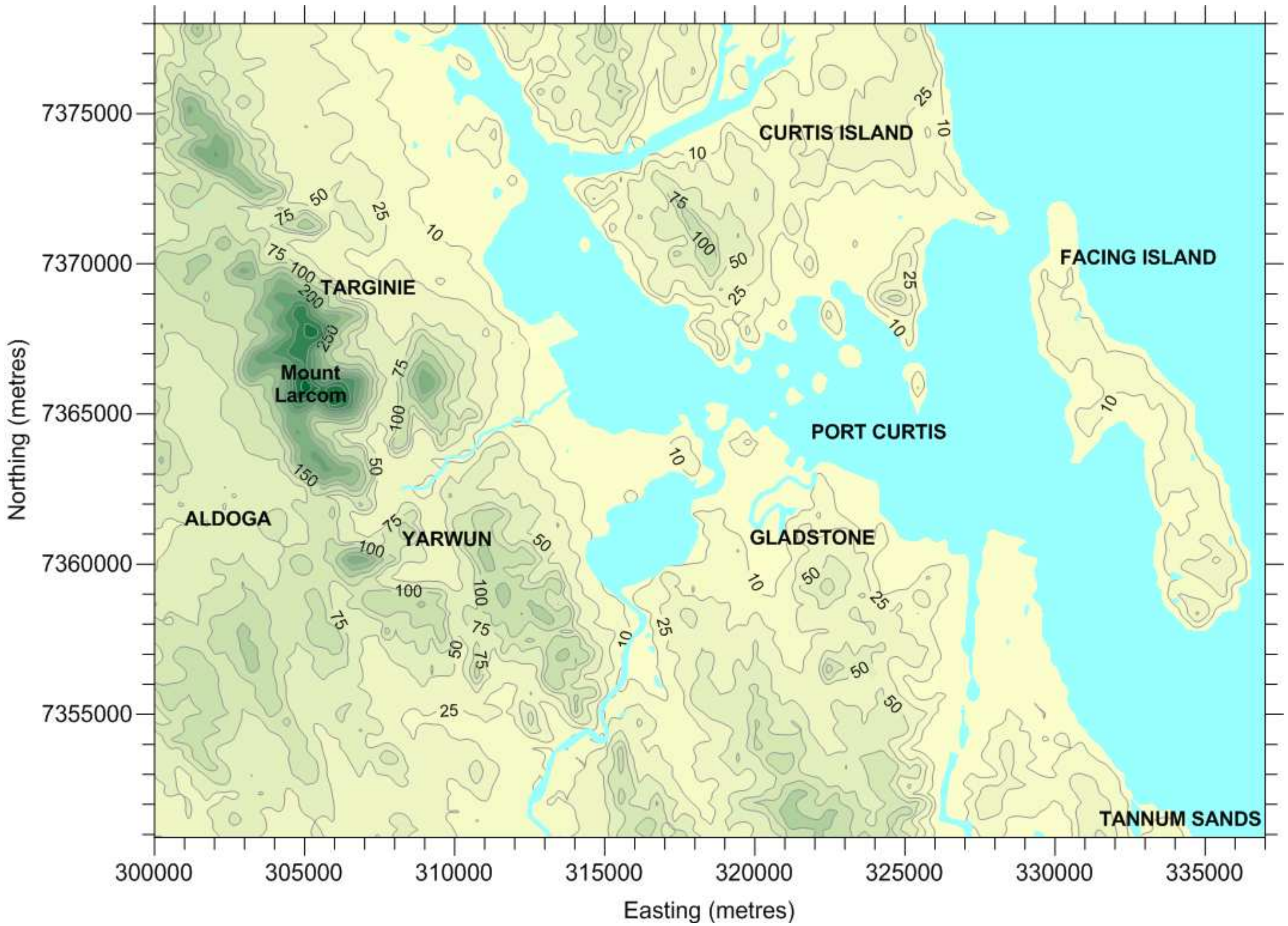

Figure 2 Map showing the terrain in the Arrow LNG Plant air quality assessment area			
Location: Gladstone region, QLD	**Type:** Project area terrain contour map	**Date:** September 2011	**Prepared by:** A. Vernon

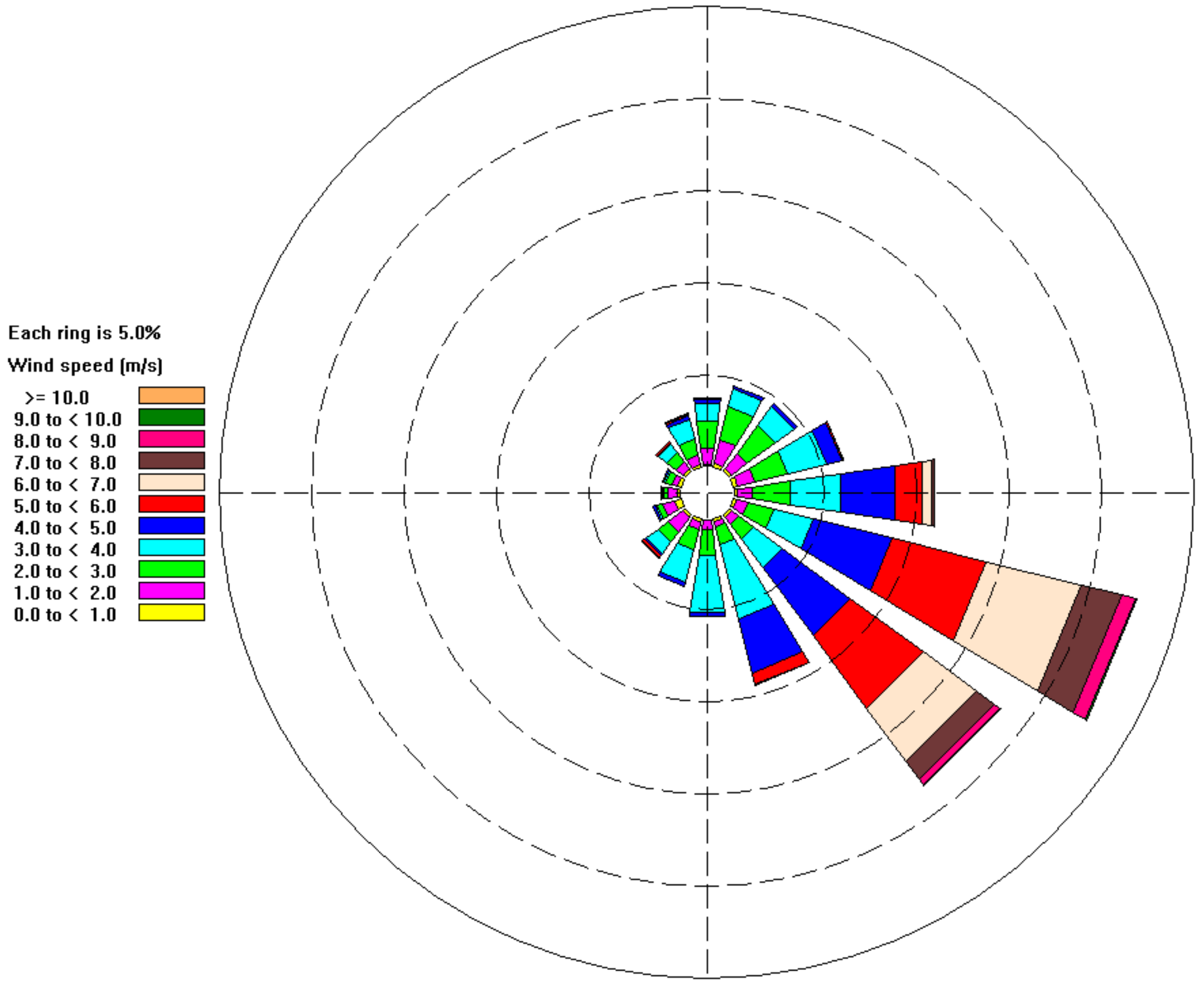

Figure 3 Annual distribution of wind direction and speed at the Arrow LNG Plant used in the dispersion modelling

Location: Arrow LNG Plant, Curtis Island	**Period:** 1 April 2006 – 31 March 2007	**Data source:** Generated by CALMETv6.3	**Units:** m/s and degrees
Type: Wind rose diagram		**Prepared by:** A. Schloss	**Date:** June 2011

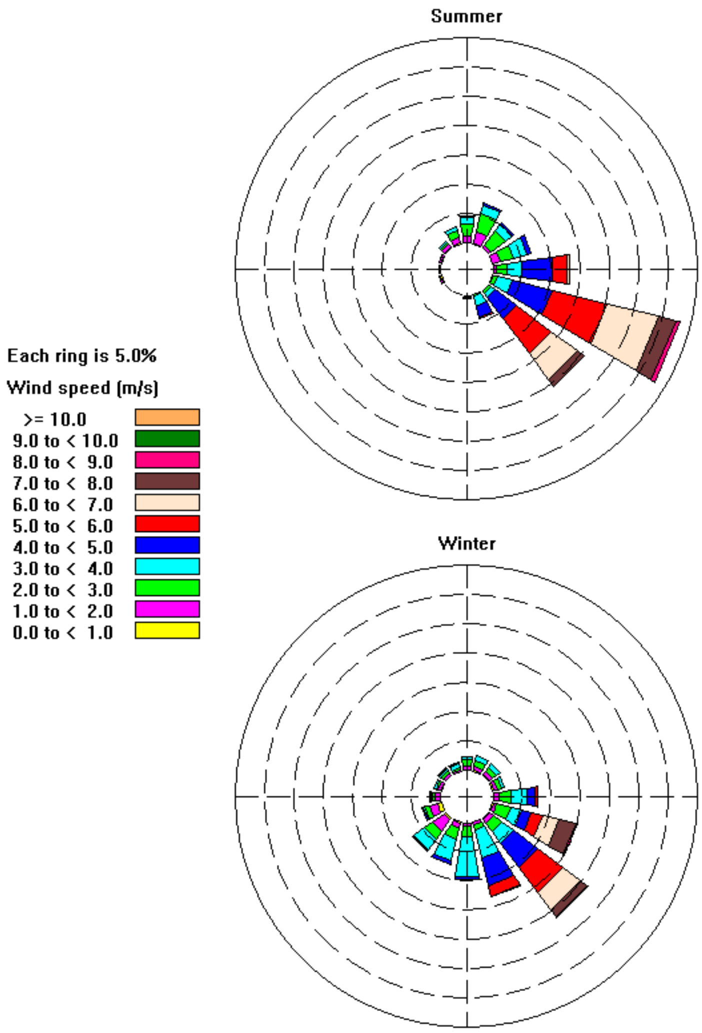

Figure 4 Seasonal distribution of wind direction and speed at the Arrow LNG Plant used in the dispersion modelling

Location: Arrow LNG Plant, Curtis Island	**Period:** 1 April 2006 – 31 March 2007	**Data source:** Generated by CALMETv6.3	**Units:** m/s and degrees
Type: Wind Rose		**Prepared by:** A. Schloss	**Date:** June 2011

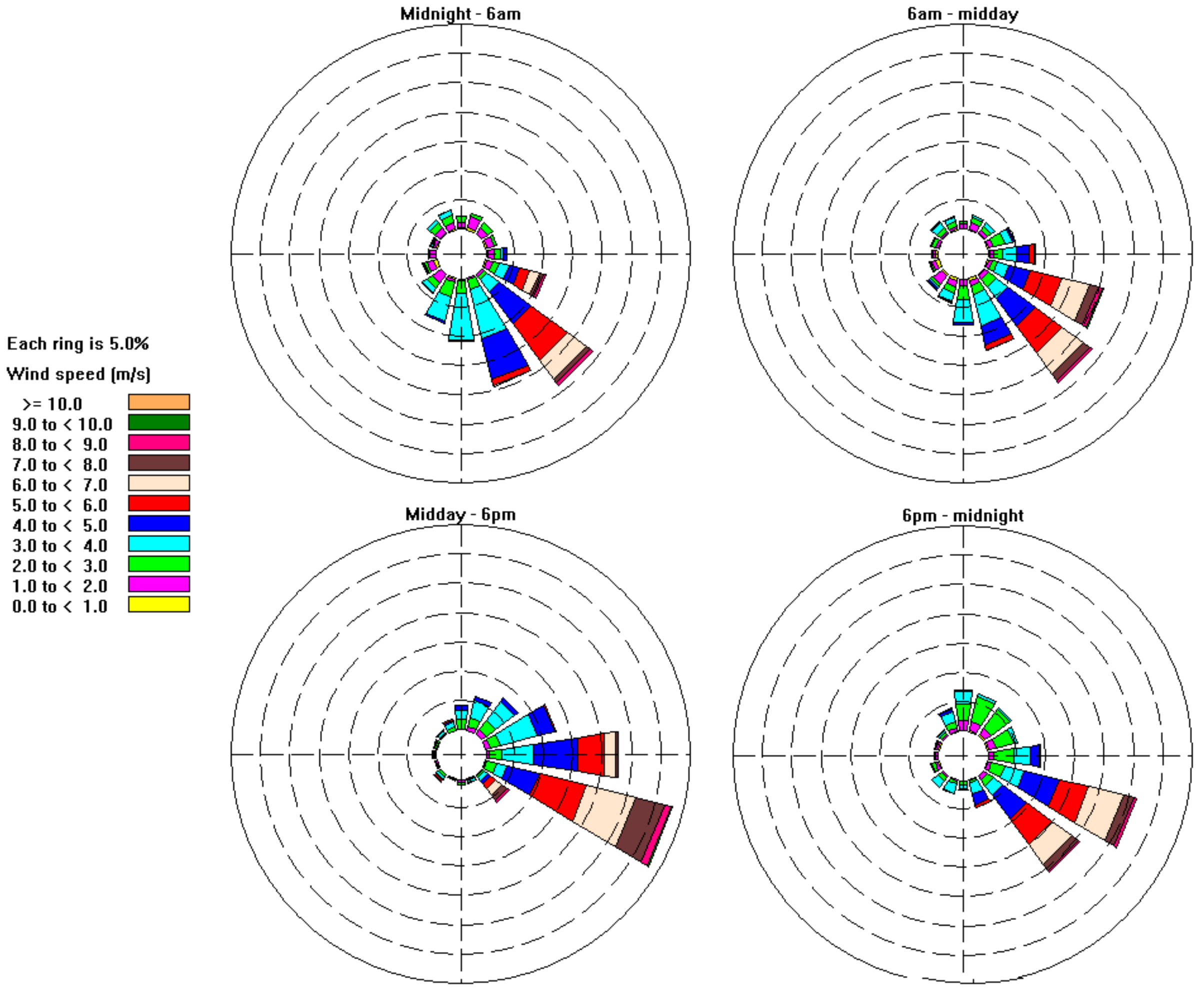

Figure 5 Daily distribution of wind direction and speed at the Arrow LNG Plant used in the dispersion modelling

Location: Arrow LNG Plant, Curtis Island	**Period:** 1 April 2006 – 31 March 2007	**Data source:** Generated by CALMETv6.3	**Units:** m/s and degrees
Type: Wind Rose		**Prepared by:** A. Schloss	**Date:** June 2011

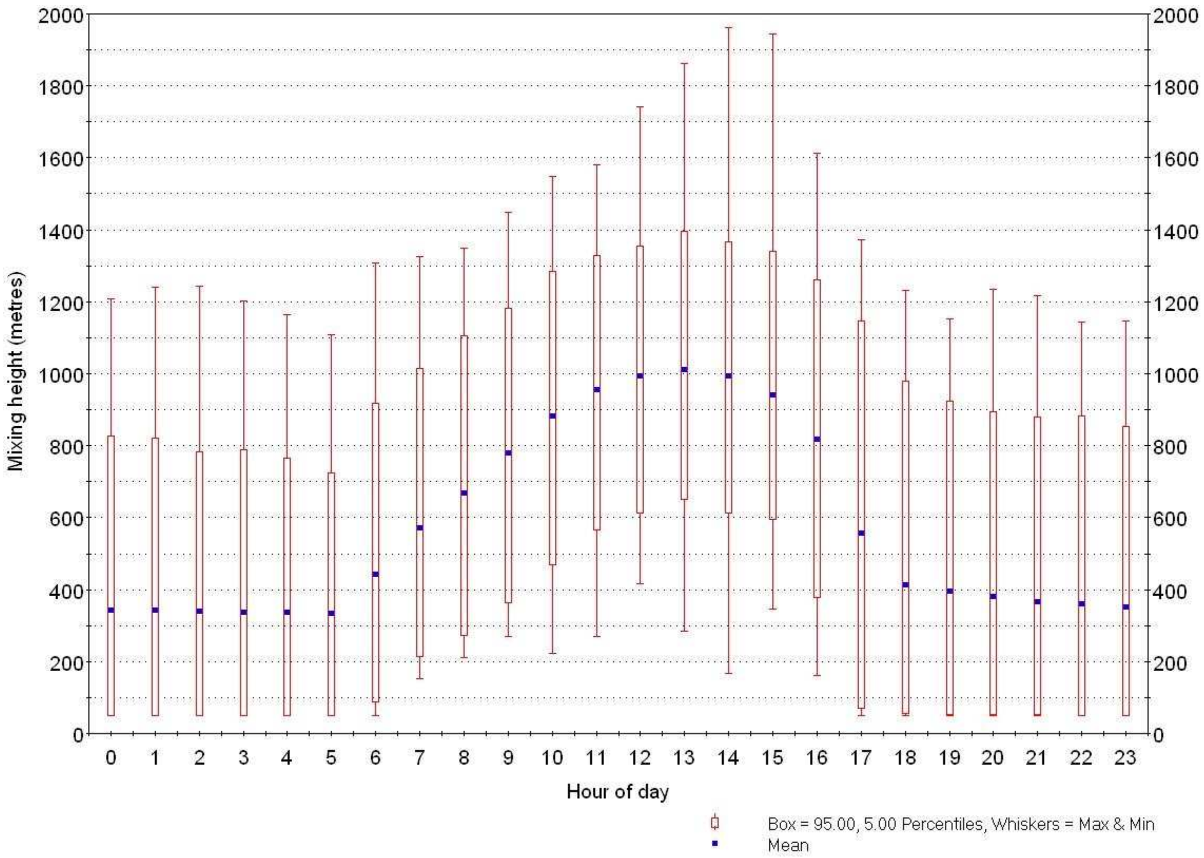

Figure 6 **Hourly distributions of mixing height**			
Location: Arrow LNG Plant, Curtis Island	**Period:** 1 April 2006 – 31 March 2007	**Data source:** GAMSv3	**Units:** Metres above ground
Type: Box and Whisker Plot		**Prepared by:** A. Schloss	**Date:** June 2011

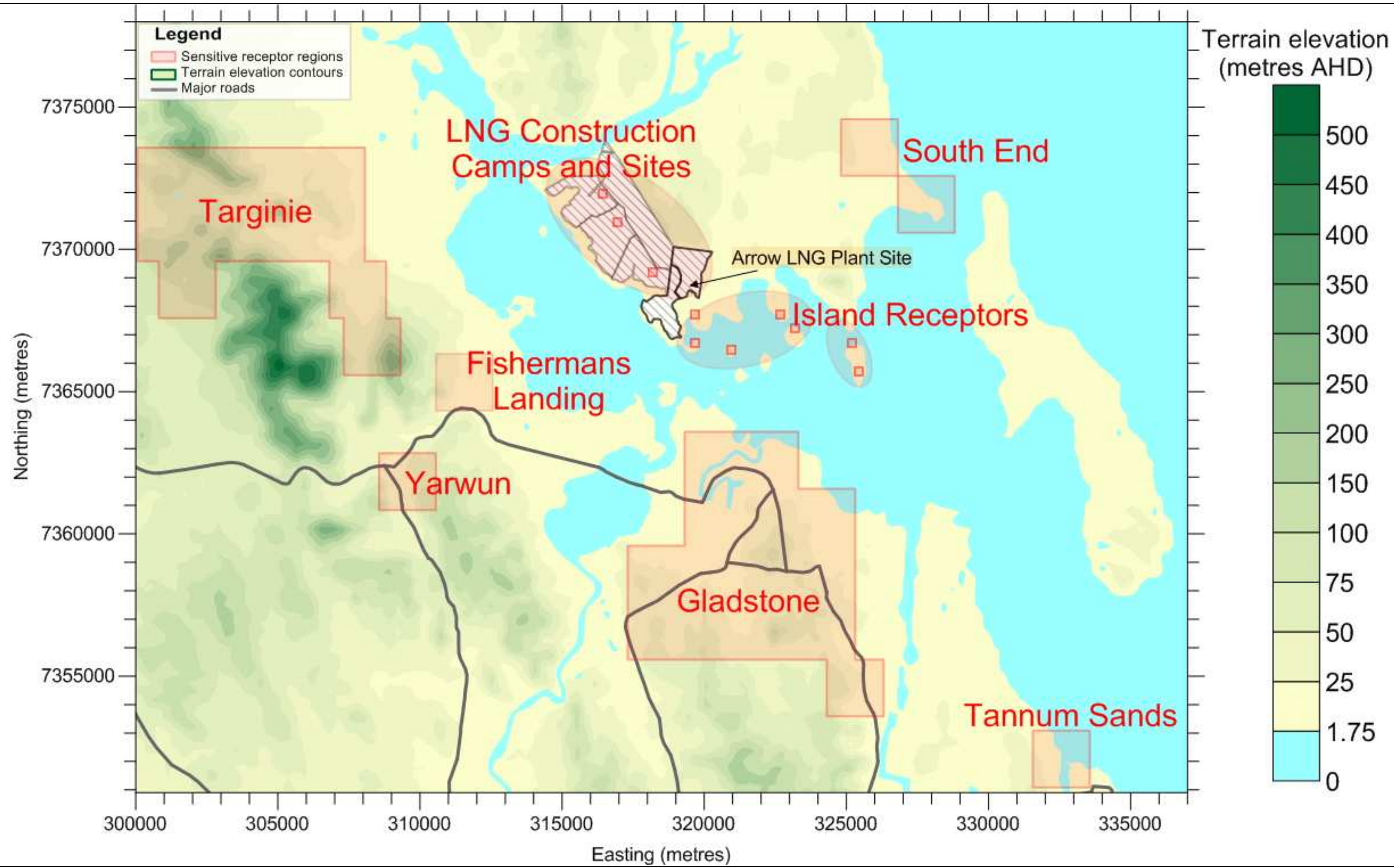

Figure 7 Location of sensitive receptor assessment areas

Location: Gladstone region, QLD	**Type:** Map	**Date:** June 2011	**Prepared by:** S. Menzel

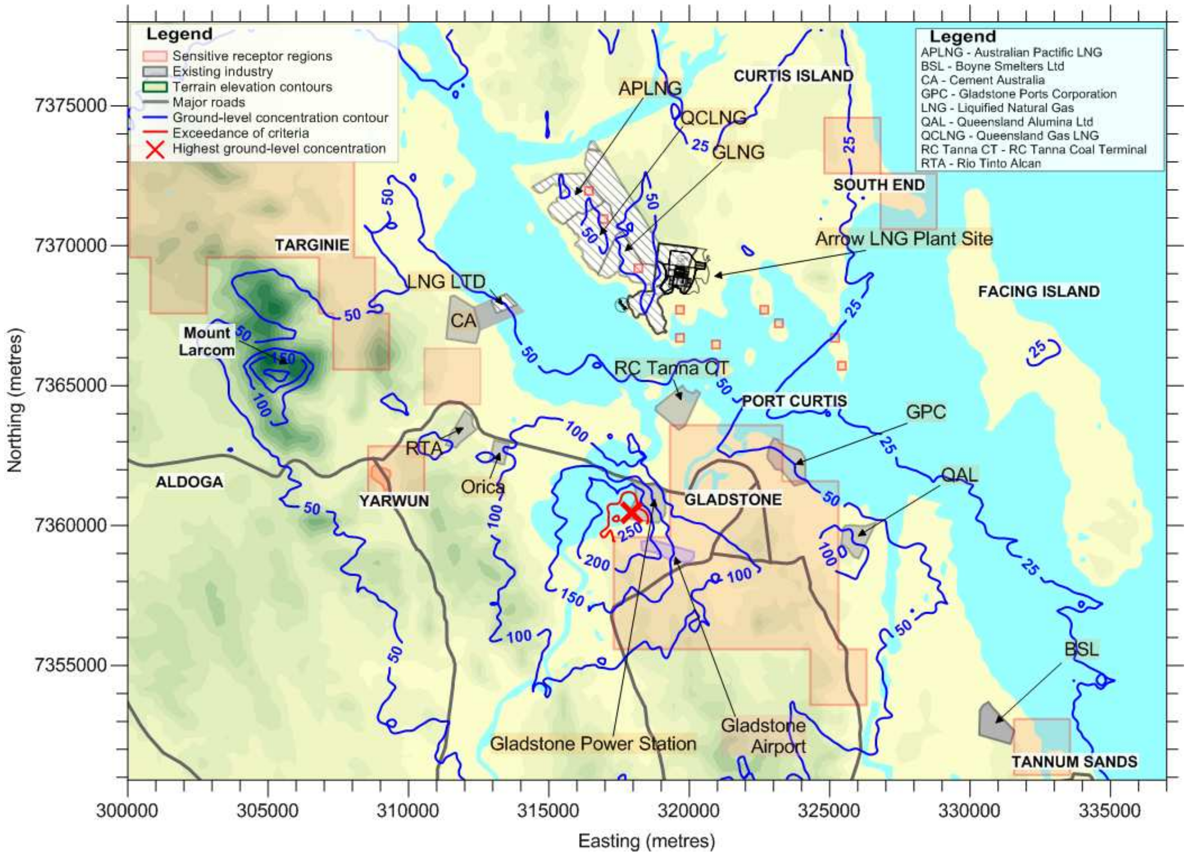

Figure 8	**Predicted 99.9th percentile 1-hour average ground-level concentrations of nitrogen dioxide for background sources including other proposed LNG plants**		
Location: Arrow LNG Plant area, Gladstone	**Averaging period:** 1-hour	**Data source:** GAMSv3	**Units:** µg/m³
Type: 99.9th percentile 1-hour average contour plot	**Air quality objective:** Health and wellbeing: 250 µg/m³	**Prepared by:** A. Vernon, S. Menzel	**Date:** June 2011

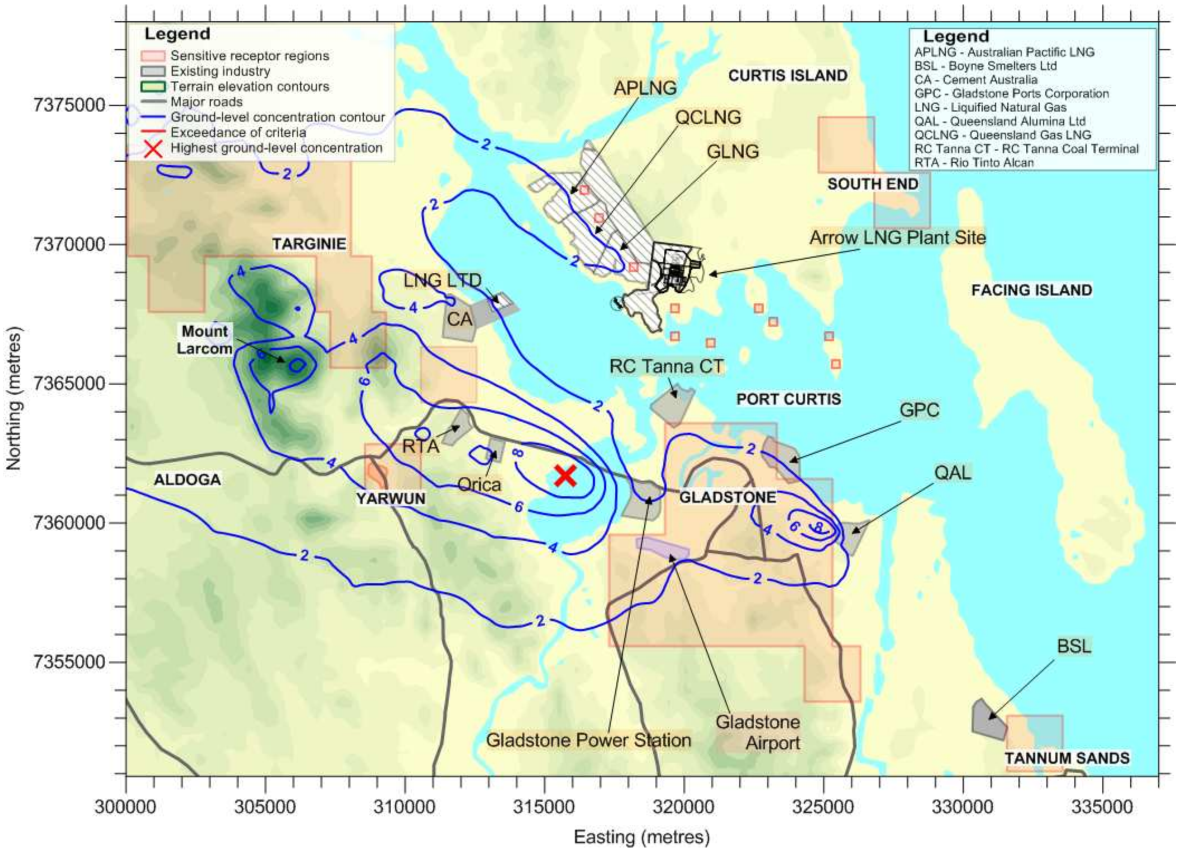

Figure 9 Predicted annual average ground-level concentrations of nitrogen dioxide for background sources including other proposed LNG plants

Location:	**Averaging period:**	**Data source:**	**Units:**
Arrow LNG Plant area, Gladstone	Annual	GAMSv3	µg/m³
Type: NO$_2$ annual average contour plot	**Air quality objectives:** Health and wellbeing: 62 µg/m³ Health and Biodiversity of ecosystems: 33 µg/m³	**Prepared by:** A. Vernon, S. Menzel	**Date:** June 2011

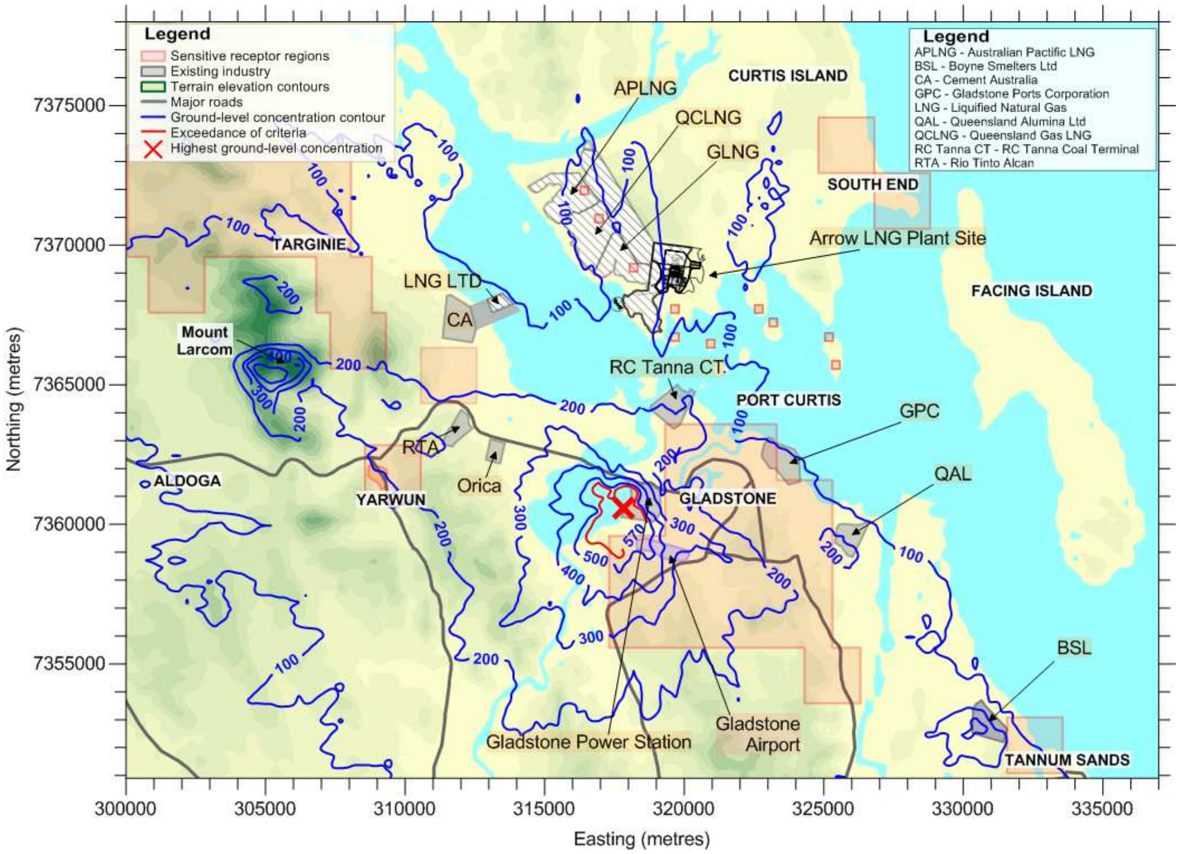

Figure 10 Predicted 99.9th percentile 1-hour average ground-level concentrations of sulfur dioxide for background sources

Location: Arrow LNG Plant area, Gladstone	**Averaging period:** 1-hour	**Data source:** GAMSv3	**Units:** µg/m³
Type: 99.9th percentile 1-hour average contour plot	**Air quality objective:** Health and wellbeing: 570 µg/m³	**Prepared by:** A. Vernon, S. Menzel	**Date:** June 2011

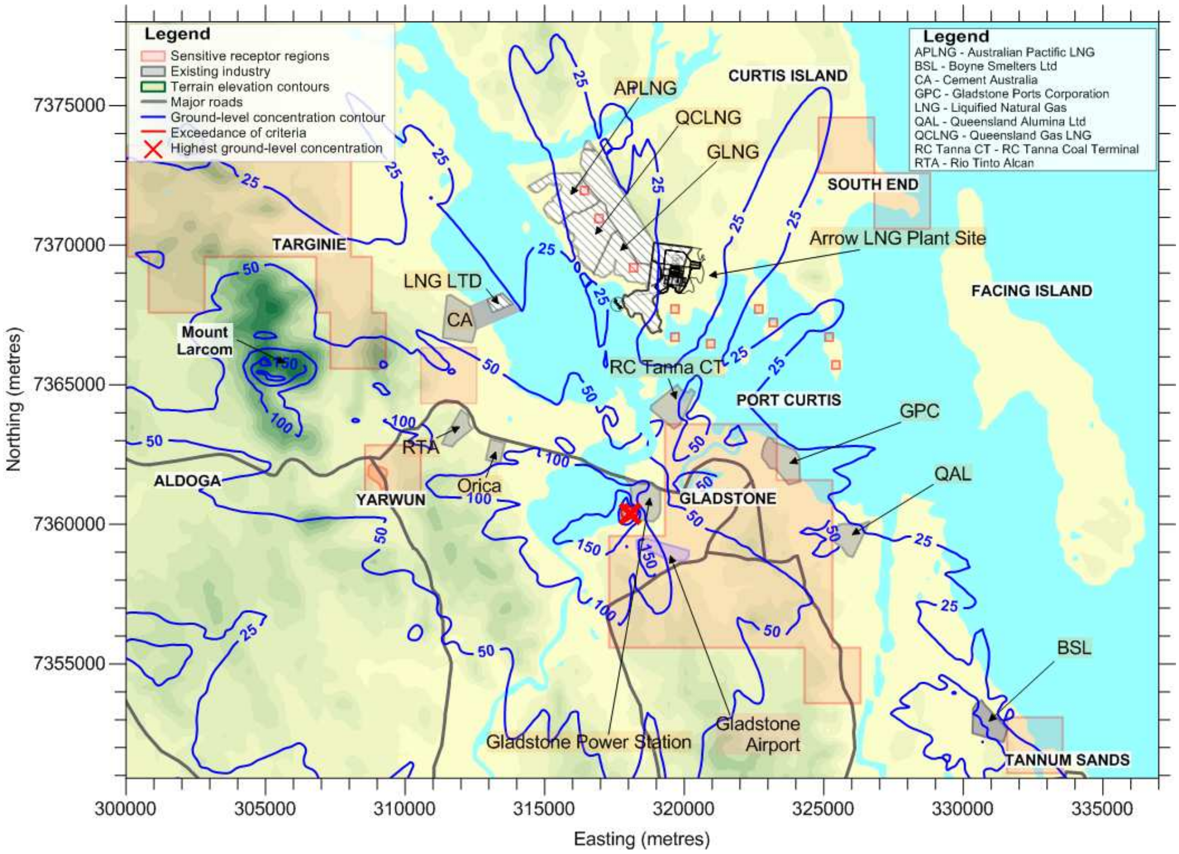

Figure 11 Predicted maximum 24-hour average ground-level concentrations of sulfur dioxide for background sources

Location: Arrow LNG Plant area, Gladstone	**Averaging period:** 24-hour	**Data source:** GAMSv3	**Units:** µg/m³
Type: SO_2 maximum 24-hour average contour plot	**Air quality objective:** Health and wellbeing: 230 µg/m³	**Prepared by:** A. Vernon, S. Menzel	**Date:** June 2011

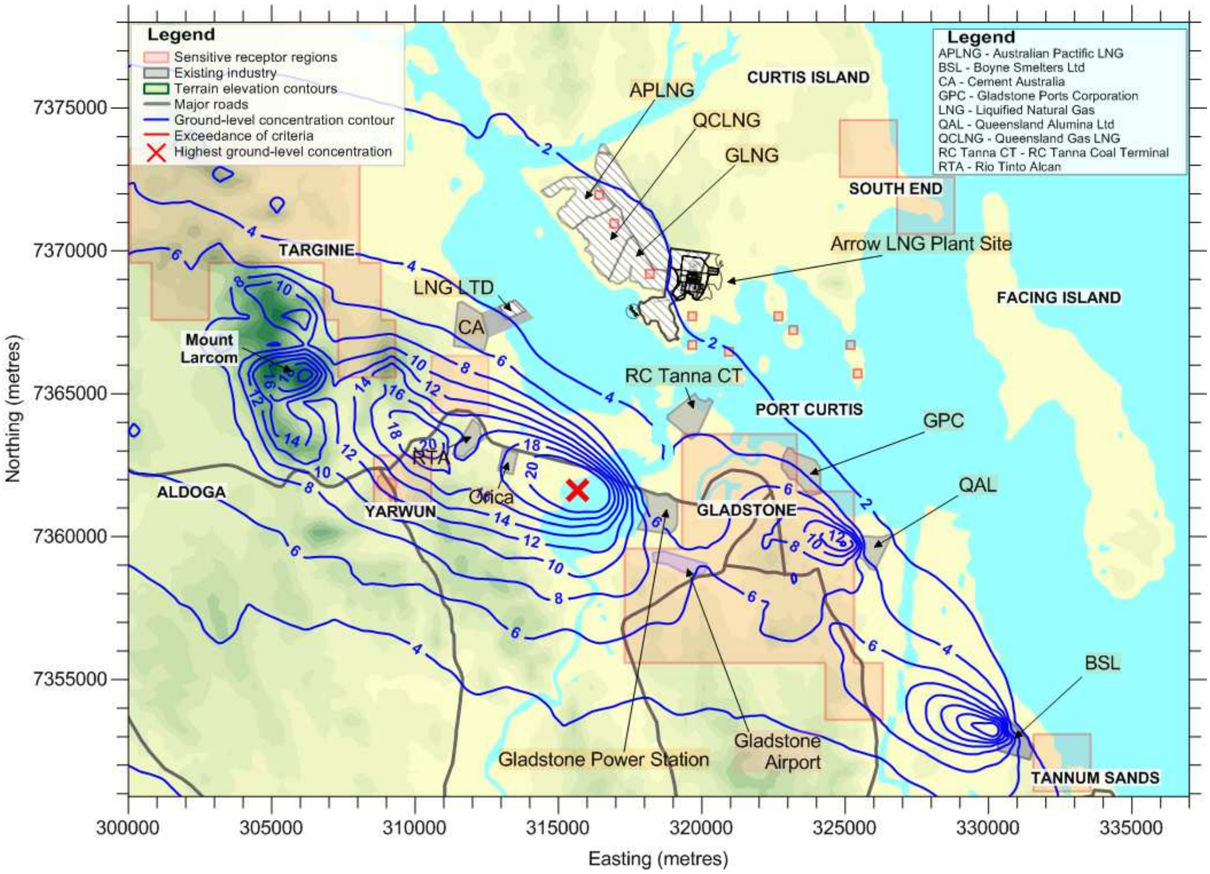

Figure 12 Predicted annual average ground-level concentrations of sulfur dioxide for background sources

Location: Arrow LNG Plant area, Gladstone	**Averaging period:** Annual	**Data source:** GAMSv3	**Units:** µg/m³
Type: SO_2 annual average contour plot	**Air quality objectives:** Health and wellbeing: 57 µg/m³	**Prepared by:** A. Vernon, S. Menzel	**Date:** June 2011

Figure 13 Predicted 99.9th percentile 1-hour average ground-level concentrations of nitrogen dioxide for the Arrow LNG Plant in isolation during routine operations at 50% load

Location: Arrow LNG Plant, Gladstone	**Averaging period:** 1-hour	**Data source:** GAMSv3	**Units:** µg/m³ and metres
Type: 99.9th percentile 1-hour average contour plot	**Air quality objective:** Health and wellbeing: 250 µg/m³	**Prepared by:** A. Vernon, S. Menzel	**Date:** June 2011

Figure 14	**Predicted 99.9th percentile 1-hour average ground-level concentrations of nitrogen dioxide for the Arrow LNG Plant in isolation during routine operations at 100% load**

Location: Arrow LNG Plant, Gladstone	**Averaging period:** 1-hour	**Data source:** GAMSv3	**Units:** µg/m³ and metres
Type: 99.9th percentile 1-hour average contour plot	**Air quality objective:** Health and wellbeing: 250 µg/m³	**Prepared by:** A. Vernon, S. Menzel	**Date:** June 2011

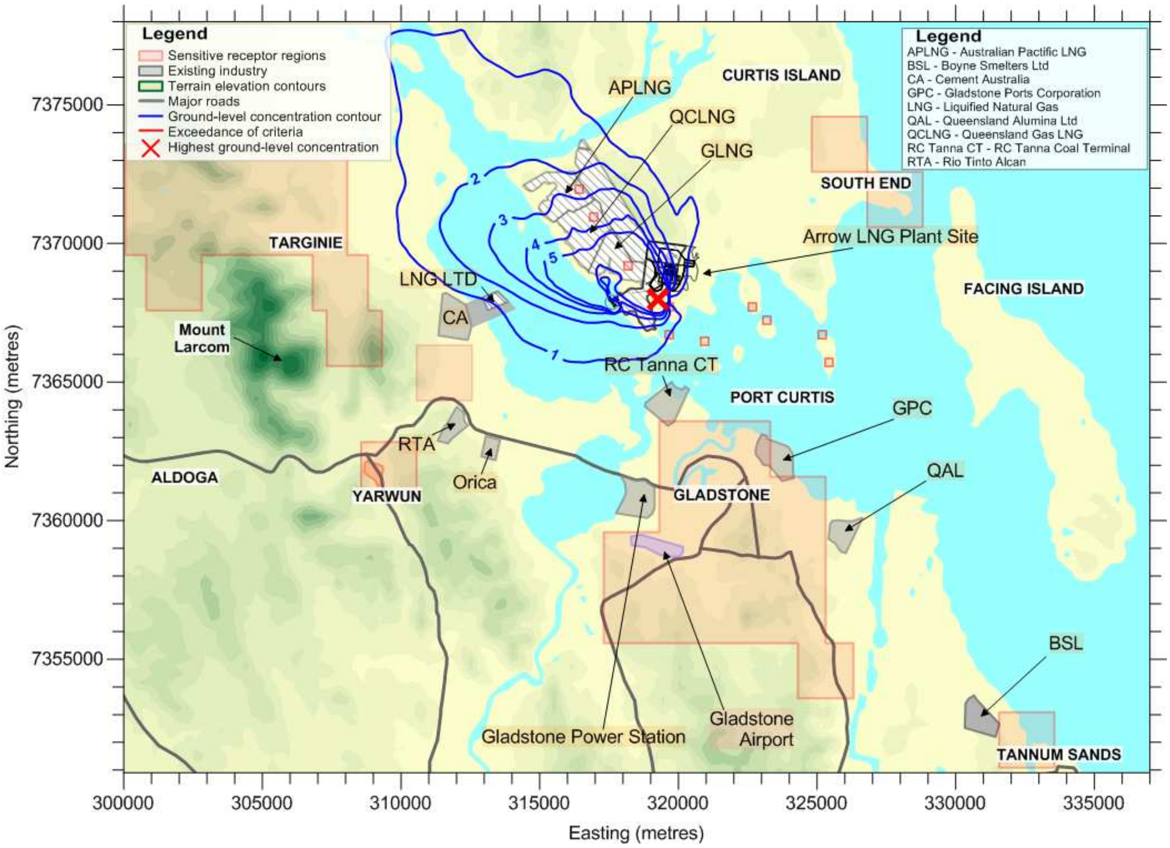

Figure 15	**Predicted maximum annual average ground-level concentrations of nitrogen dioxide for the Arrow LNG Plant in isolation during routine operations at 100% load**		
Location: Arrow LNG Plant, Gladstone	**Averaging period:** Annual	**Data source:** GAMSv3	**Units:** µg/m³
Type: NO_2 annual average contour plot	**Air quality objectives:** Health and wellbeing: 62 µg/m³ Health and Biodiversity of ecosystems: 33 µg/m³	**Prepared by:** A. Vernon, S. Menzel	**Date:** June 2011

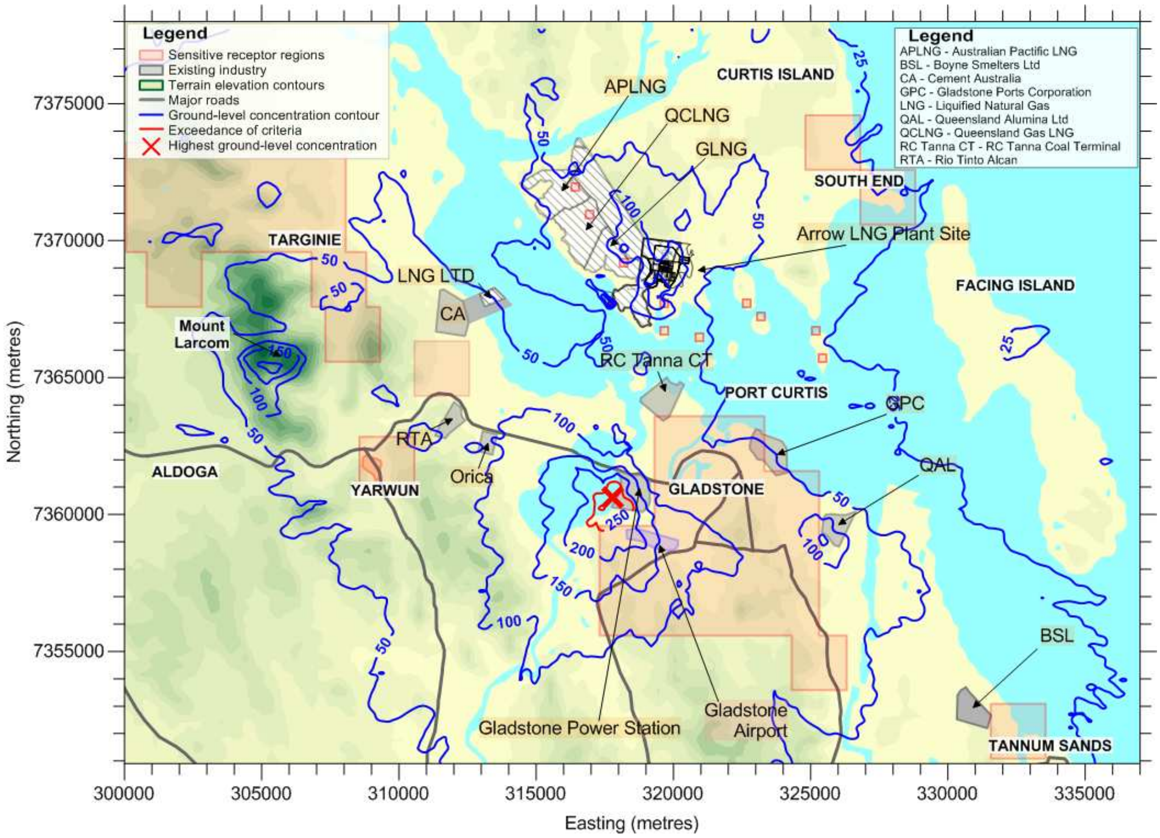

Figure 16 Predicted 99.9th percentile 1-hour average ground-level concentrations of nitrogen dioxide for the Arrow LNG Plant with background during routine operation at 100% load

Location: Arrow LNG Plant, Gladstone	**Averaging period:** 1-hour	**Data source:** GAMSv3	**Units:** µg/m³ and metres
Type: 99.9th percentile 1-hour average contour plot	**Air quality objective:** Health and wellbeing: 250 µg/m³	**Prepared by:** A. Vernon, S. Menzel	**Date:** June 2011

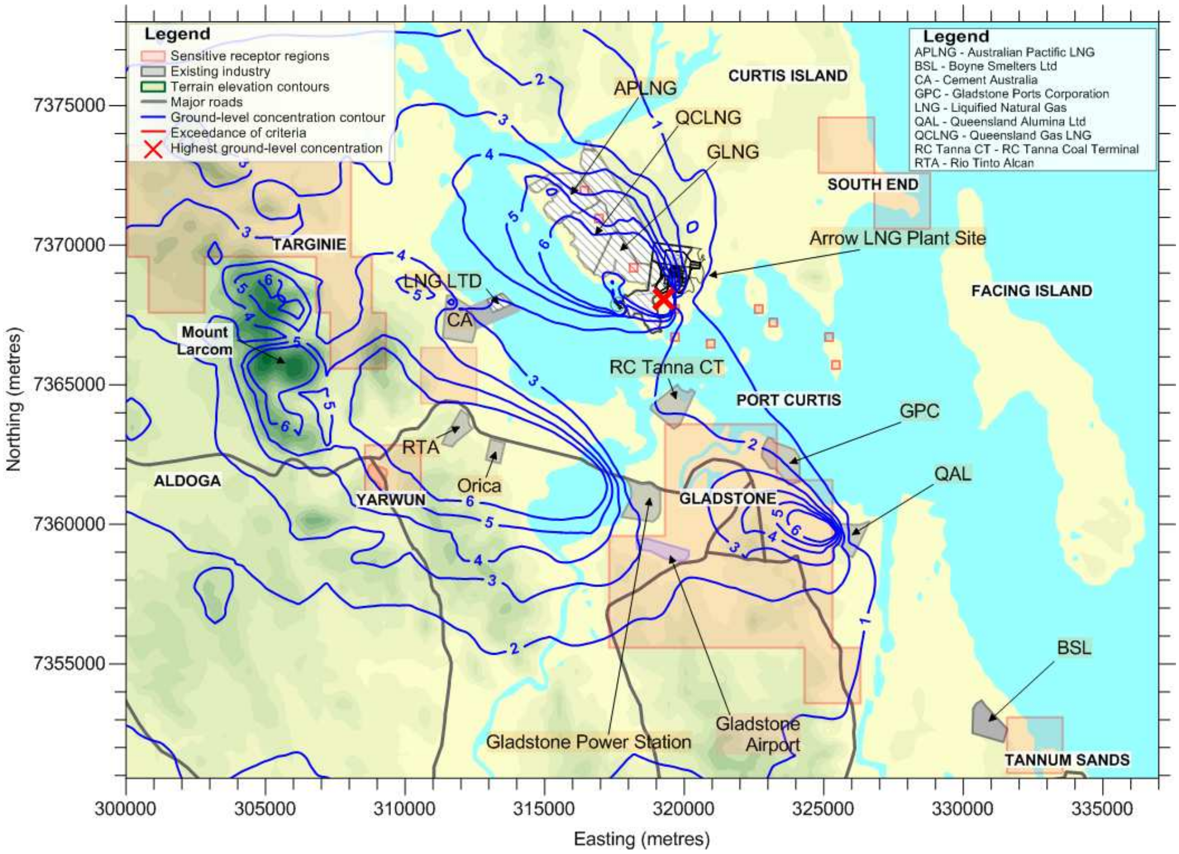

Figure 17 **Predicted cumulative annual average ground-level concentrations of nitrogen dioxide for the Arrow LNG Plant with background during routine operation at 100% load**

Location: Arrow LNG Plant, Gladstone	**Averaging period:** Annual	**Data source:** GAMSv3	**Units:** µg/m³
Type: NO_2 annual average contour plot	**Air quality objectives:** Health and wellbeing: 62 µg/m³ Health and Biodiversity of ecosystems: 33 µg/m³	**Prepared by:** A. Vernon, S. Menzel	**Date:** June 2011

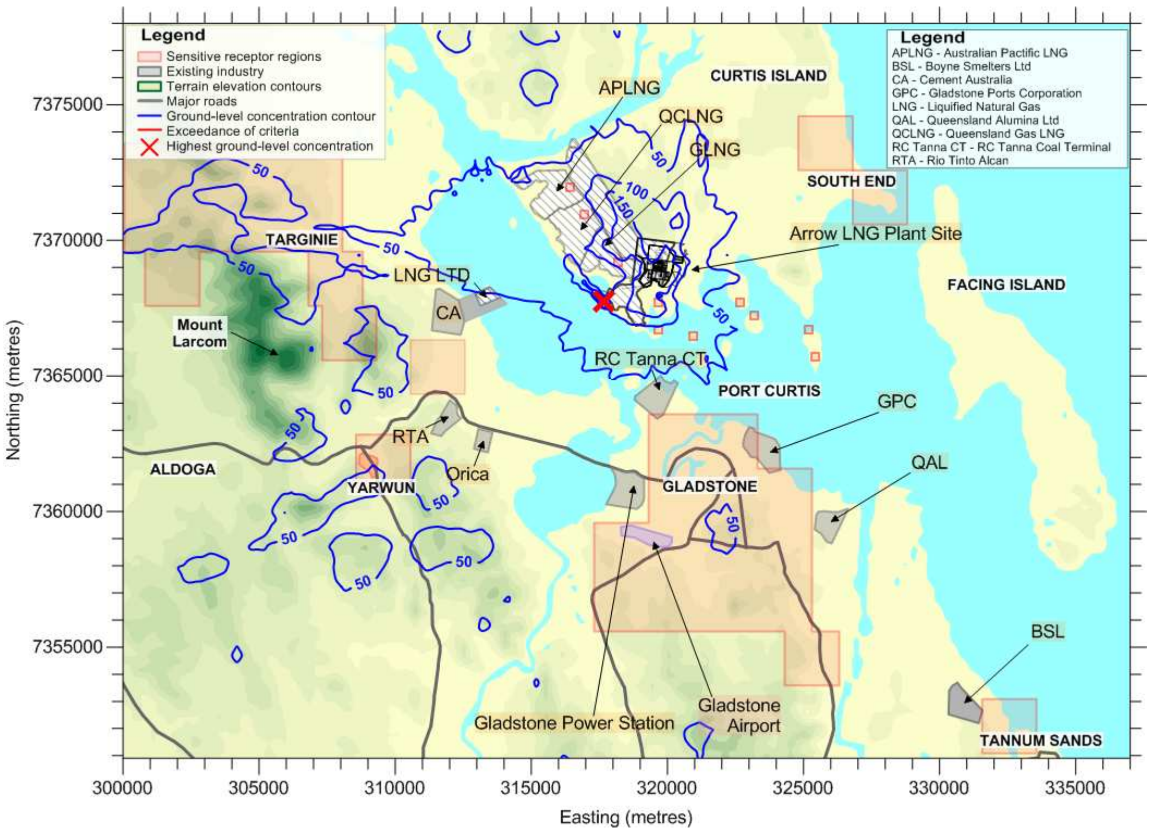

Figure 18	**Predicted 99.9th percentile, 1-hour average ground-level concentrations of sulfur dioxide for the Arrow LNG Plant in isolation**

Location: Arrow LNG Plant, Gladstone	**Averaging period:** 1-hour	**Data source:** GAMSv3	**Units:** µg/m³
Type: 99.9th percentile, 1-hour average contour plot	**Air quality objective:** Health and wellbeing: 570 µg/m³	**Prepared by:** A. Vernon, S. Menzel	**Date:** June 2011

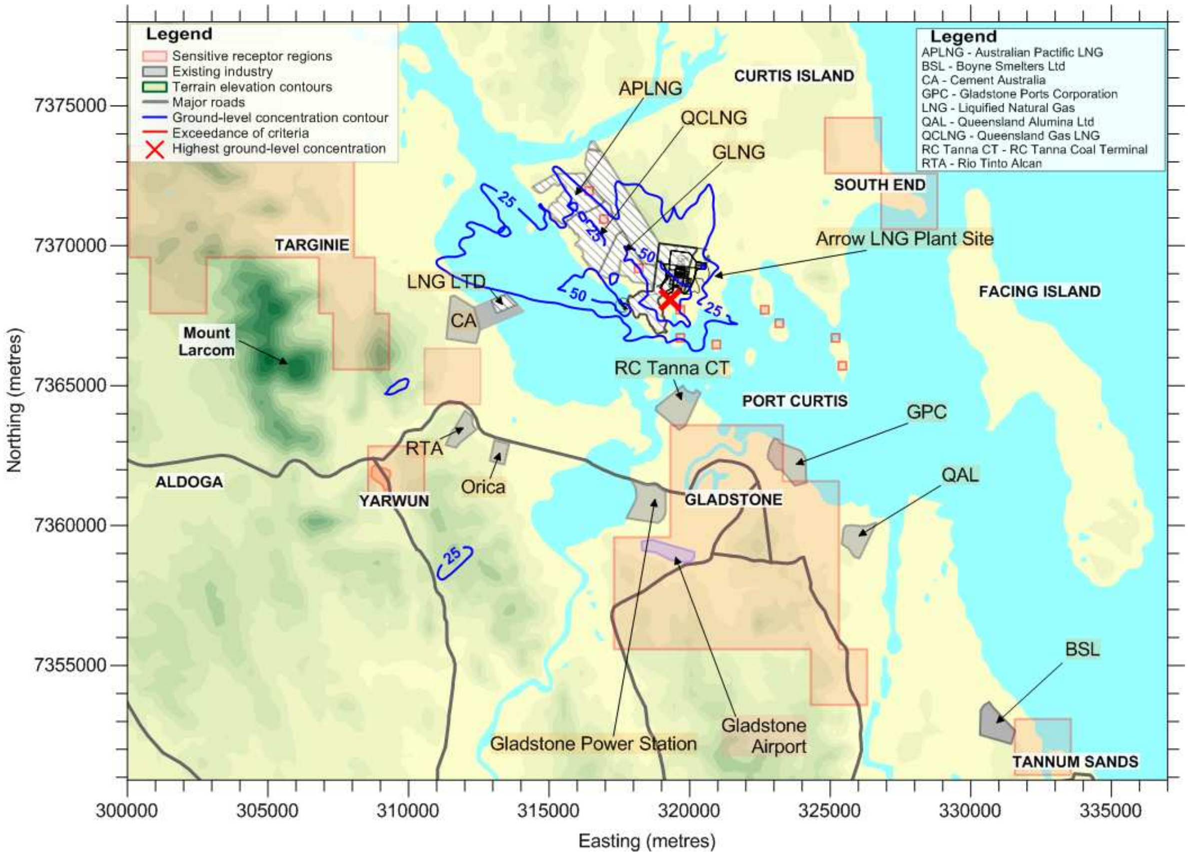

Figure 19	**Predicted maximum 24-hour average ground-level concentrations of sulfur dioxide for the Arrow LNG Plant in isolation**

Location: Arrow LNG Plant, Gladstone	**Averaging period:** 24-hour	**Data source:** GAMSv3	**Units:** µg/m³
Type: SO_2 maximum 24-hour average contour plot	**Air quality objective:** Health and wellbeing: 230 µg/m³	**Prepared by:** A. Vernon, S. Menzel	**Date:** June 2011

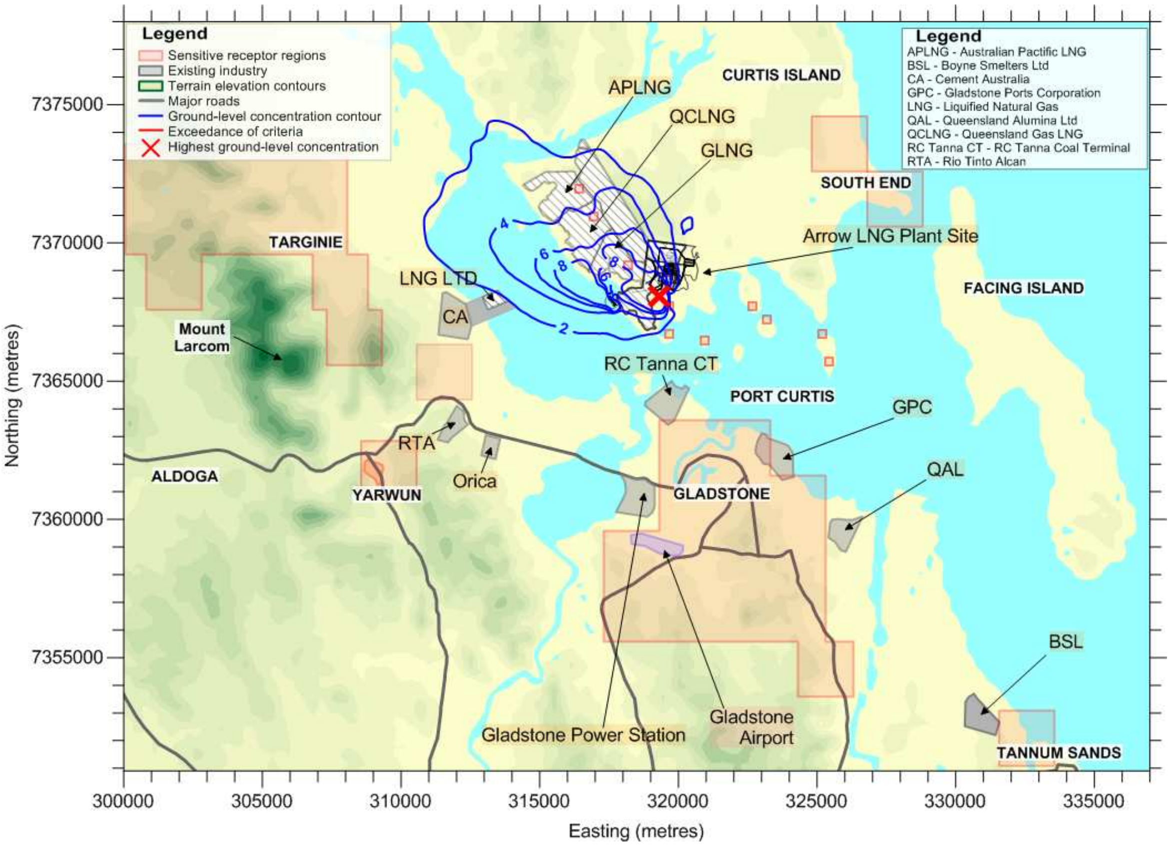

Figure 20 Predicted annual average ground-level concentrations of sulfur dioxide for the Arrow LNG Plant in isolation during routine operation at 100% load

Location: Arrow LNG Plant, Gladstone	**Averaging period:** Annual	**Data source:** GAMSv3	**Units:** µg/m³
Type: SO_2 annual average contour plot	**Air quality objectives:** Health and wellbeing: 57 µg/m³	**Prepared by:** A. Vernon, S. Menzel	**Date:** June 2011

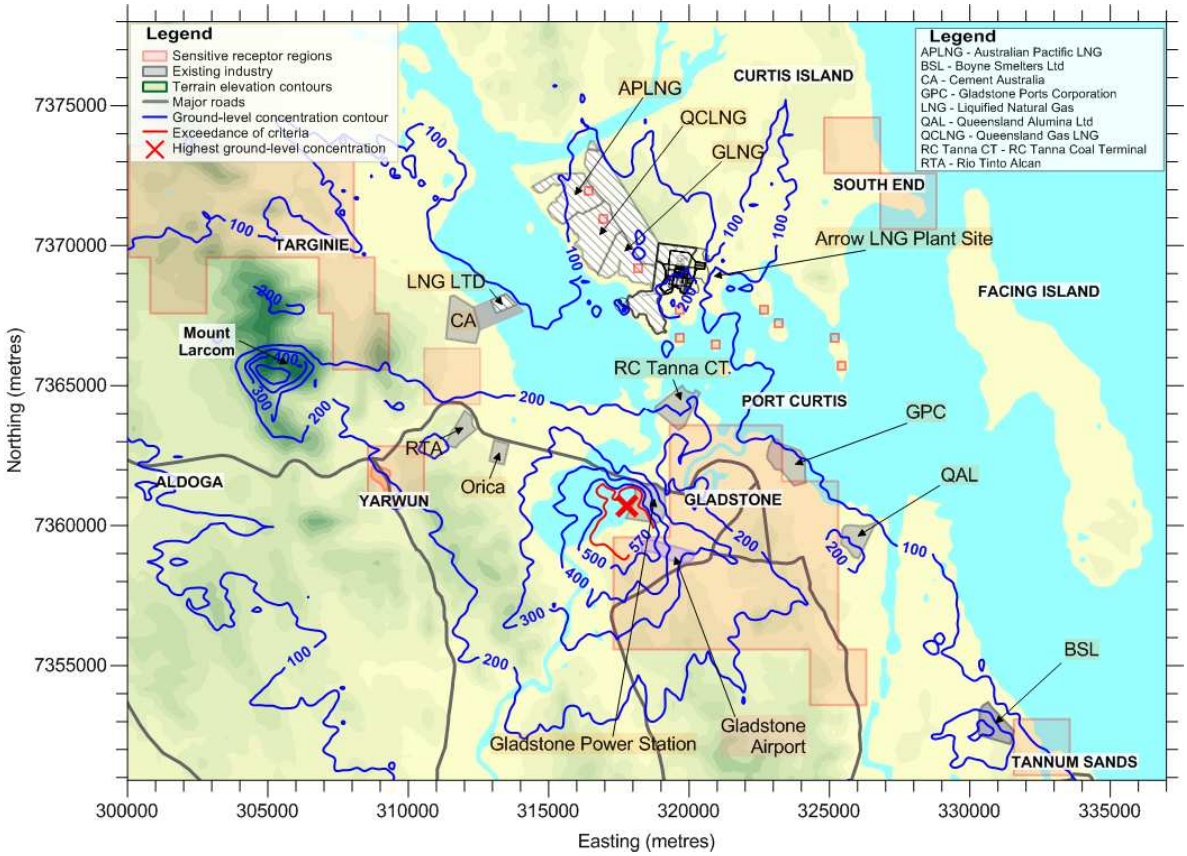

Figure 21 **Predicted 99.9th percentile, 1-hour average ground-level concentrations of sulfur dioxide for the Arrow LNG Plant with background during routine operation at 100% load**

Location: Arrow LNG Plant, Gladstone	**Averaging period:** 1-hour	**Data source:** GAMSv3	**Units:** µg/m³
Type: 99.9th percentile, 1-hour average contour plot	**Air quality objective:** Health and wellbeing: 570 µg/m³	**Prepared by:** A. Vernon, S. Menzel	**Date:** June 2011

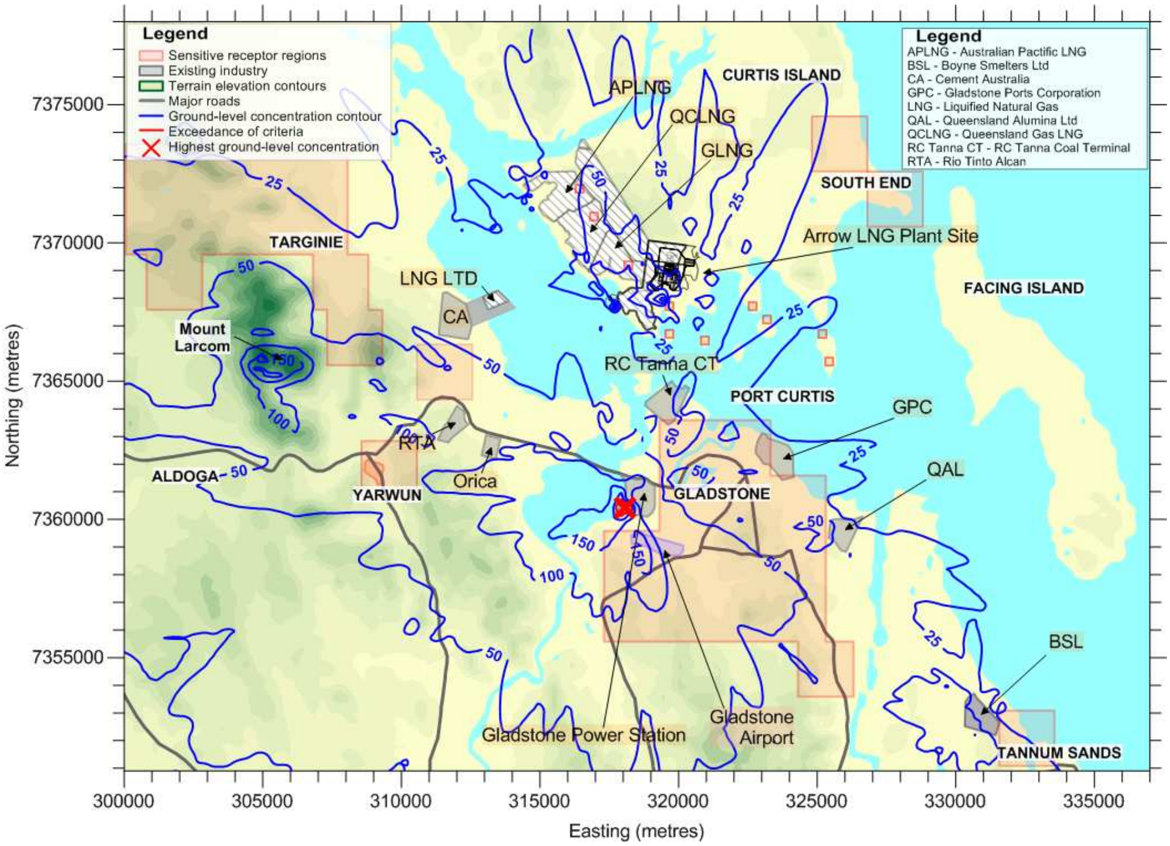

Figure 22	**Predicted maximum 24-hour average ground-level concentrations of sulfur dioxide for the Arrow LNG Plant with background during routine operation at 100% load**		
Location: Arrow LNG Plant, Gladstone	**Averaging period:** 24-hour	**Data source:** GAMSv3	**Units:** µg/m³
Type: SO_2 maximum 24-hour average contour plot	**Air quality objective:** Health and wellbeing: 230 µg/m³	**Prepared by:** A. Vernon, S. Menzel	**Date:** June 2011

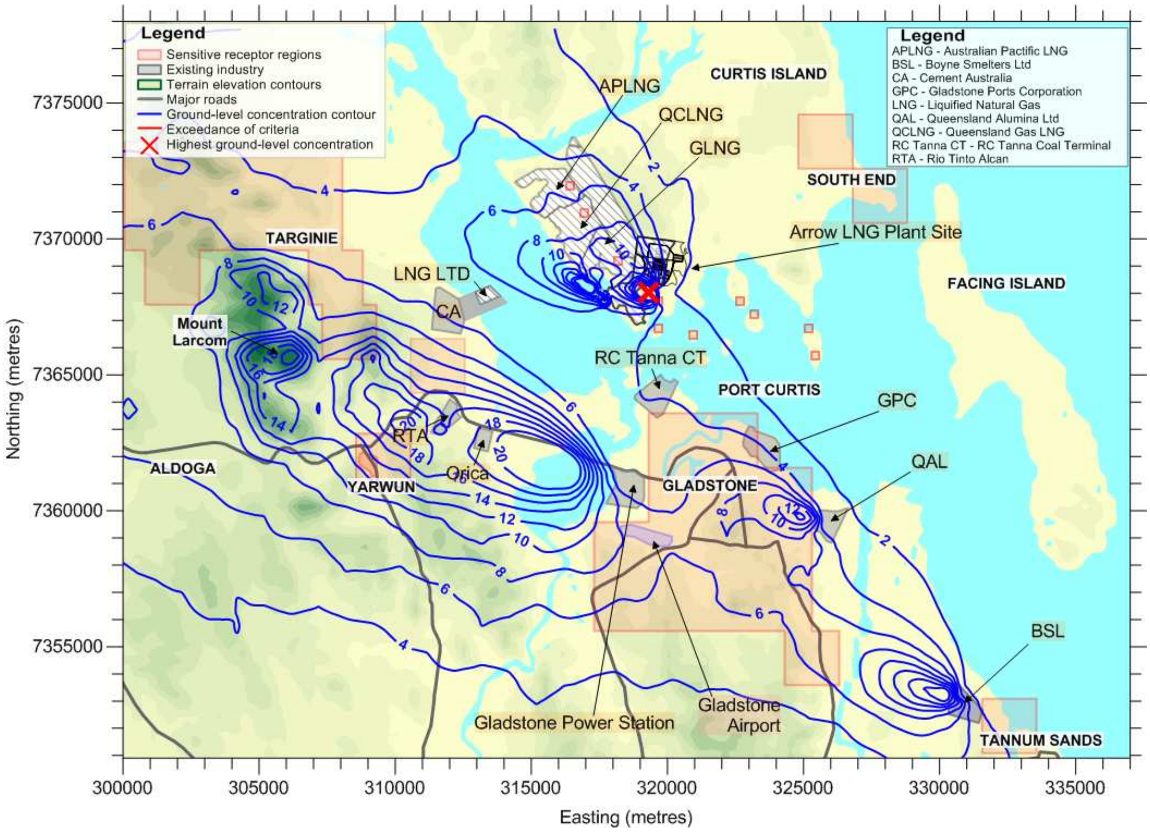

Figure 23	**Predicted cumulative annual average ground-level concentrations of sulfur dioxide for the Arrow LNG Plant with background during routine operation at 100% load**		
Location: Arrow LNG Plant, Gladstone	**Averaging period:** Annual	**Data source:** GAMSv3	**Units:** µg/m³
Type: SO_2 annual average contour plot	**Air quality objectives:** Health and wellbeing: 57 µg/m³	**Prepared by:** A. Vernon, S. Menzel	**Date:** June 2011

Appendix A

Terms of Reference Cross Reference Table

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Terms of Reference Cross Reference Table

This Appendix presents a summarised cross reference (Table A1) of the methodology and findings of the air quality impact assessment of the Arrow LNG Plant against the requirements of the Project Terms of Reference.

Table A1 Terms of Reference Cross Reference Table for the Air Quality Impact Assessment Technical Study

Terms of reference Section	EIS requirement	Technical Study Name	Technical specialist report section	How the component is addressed in the study
3.6.1 Description of environmental values	Summary of environmental values and indicators of air quality as described in the Air EPP and other air quality standards, used in the assessment	Katestone Environmental	Air Quality Impact Assessment Report, Section 3	The air quality criteria used in the assessment has been summarised.
	Identification of sensitive receptor areas in the Gladstone region	Katestone Environmental	Air Quality Impact Assessment Report, Section 7.3	The sensitive receptor areas have been identified and illustrated on an aerial image.
	Description of existing air quality in the Gladstone region and at sensitive receptor areas	Katestone Environmental	Air Quality Impact Assessment Report, Section 6.2	The existing air quality in the region has been assessed against the Air EPP objectives for NO_2, SO_2, CO, PM_{10}, $PM_{2.5}$ and ozone.
	Description of meteorological variables used in the modelling assessment that influence the dispersion of air pollutants	Katestone Environmental	Air Quality Impact Assessment Report, Section 8, and Climate Desktop Study Report (Katestone Environmental, 2011)	The meteorological variables have been analysed and presented based on the meteorological modelling outputs over the site and in the Gladstone airshed. The meteorological variables and climate for the region has been analysed and presented in the Climate Desktop Study Report.
3.6.2 Potential impacts and mitigation measures	Air pollutants and emission rates expected to be generated by project routine and non-routine operational activities	Katestone Environmental	Air Quality Impact Assessment Report, Section 7.2, 7.5.2 – 7.5.5	Air pollutants expected to be released from sources at the plant have been identified, emission rates quantified and source characteristics described for routine and non-routine operational activities.

Table A1 Terms of Reference Cross Reference Table for the Air Quality Impact Assessment Technical Study (continued)

	Air pollutants, emission rates and impacts expected to be generated by project construction activities	Katestone Environmental	Air Quality Impact Assessment Report, Section 7.5.6	The generation, management and expected impact of gaseous and particulate emissions associated with construction activities have been addressed
	Identification of climatic patterns that could affect dust and pollutant generation and movement	Katestone Environmental	Air Quality Impact Assessment Report, Section 8	Climatic variables including extreme weather are discussed in the Climate Desktop Study Report, while an analysis of the dispersion meteorology is presented in Section 8. The majority of air pollutants emitted from the project will be associated with the process and fuel burning activities. Minor dust emissions associated with wind erosion during construction will be addressed in the Environmental Management Plan.
	Impacts on terrestrial flora and fauna	Katestone Environmental	Air Quality Impact Assessment Report, Section 9	The impacts associated with terrestrial flora and fauna have been assessed by comparison of predicted ground-level concentrations of important air pollutants with the objectives for the health and biodiversity of ecosystems.
	Impacts on air quality from greenhouse gas emissions	Not Katestone Environmental's discipline	PAE GHG Emissions Report	Addressed in the PAE GHG Emissions Report
	Impacts on air quality ozone depleting substances	Katestone Environmental	Air Quality Impact Assessment Report, Section 4.3	No ozone depleting substances will be released.
	Standards of emissions	Katestone Environmental	Air Quality Impact Assessment Report, Section 7.5.1	Identification of the NSW POEO Clean Air Regulation standards of emissions
	Atmospheric dispersion modelling methodology	Katestone Environmental	Air Quality Impact Assessment Report, Section 7.1, Appendix B	The modelling methodology is discussed and an evaluation of the modelling system is presented.

Table A1 Terms of Reference Cross Reference Table for the Air Quality Impact Assessment Technical Study (continued)

3.6.2 Potential impacts and mitigation measures	Assessment of air quality impacts associated with emissions from the plant during normal and maximum operating conditions	Katestone Environmental	Air Quality Impact Assessment Report, Section 9, Appendix C	The assessment has been made for the maximum operating condition – 100% load. A sensitivity analysis has also been carried out to assess the difference in impacts of NO_2 for the plant operating at 50% and 100% load. No significant difference in the plant operating at 50% and 100% load was identified. The predicted 99.9th percentile ground-level concentration has been assessed for all pollutants with a 1-hour average air quality criteria. The 99.5th percentile ground-level odour concentration has been assessed against the odour guideline. A cumulative assessment has been carried out for all criteria air pollutants. The cumulative impact associated with hydrocarbon emissions from the entire LNG precinct on the Gladstone region has been assessed.
	Description of assumptions used in the calculation of emissions, source characteristics and modelling assessment	Katestone Environmental	Air Quality Impact Assessment Report, Section 7	All inputs to the modelling assessment have been described.
	Reference of DERM and Queensland Health studies in the Gladstone region with respect to air quality	Katestone Environmental	Air Quality Impact Assessment Report, Section 6	The existing air quality in the region has been described using monthly DERM air quality monitoring reports and the raw monitoring data supplied by DERM. The Queensland Health Clean and Healthy Air For Gladstone studies have also been reference.
3.6.2 Potential impacts and mitigation measures	Description of plant activities	Katestone Environmental	Air Quality Impact Assessment Report, Section 4.2 – 4.4	The activities at the LNG Plant have been described in terms of emissions to air. The design philosophy for the project with respect to air emissions has also been described.

Table A2 Terms of Reference Cross Reference Table for the Air Quality Impact Assessment Technical Study (continued)

	Description of air pollution control and mitigation measures	Katestone Environmental	Air Quality Impact Assessment Report, Section 4.4, 7.5.2.1, 7.5.2.2	The project design philosophy outlines the air pollution control and mitigation measures. Best practice emissions technology will be adopted for gas turbines including Dry Low NO_X burners with an emissions concentration of 25ppm.
	Description of the back up measures to be incorporated that will act in the event of failure of primary measures to minimise the likelihood of plant upsets and adverse air impacts	Katestone Environmental	Air Quality Impact Assessment Report, Section 7.5.4	Description and assessment of process relief system flares during non-routine upset or maintenance conditions.
	Air pollutant inventory and emission characteristics for the plant during normal and maximum operating conditions	Katestone Environmental	Air Quality Impact Assessment Report, Section 7.5.2	Emission concentrations, rates and stack exhaust characteristics have been detailed for all sources.

APPENDIX B

GAMS V3 Modelling Methodology and Performance Evaluation

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B1. The GAMSv3 Model

The Gladstone Airshed Modelling System version 3 (GAMSv3) was designed using a two-stage approach. Firstly, the CSIRO's meteorological model, TAPM (The Air Pollution Model) (Hurley 2005), was used to simulate the regional meteorology in the Gladstone region. Further refinement of the wind field was then made through the CALMET meteorological pre-processor. Secondly, the CALPUFF plume dispersion model was configured with the source characteristics and emissions relating to existing industries in the Gladstone region.

The meteorological modelling performance evaluation was carried out using statistical techniques to correlate observations and predictions of important meteorological parameters at several monitoring stations across the region. In a similar way, the pollution model evaluation study was carried out using statistical techniques to correlate observations and predictions of sulfur dioxide and oxides of nitrogen emissions at several monitoring stations across the region.

B1.1 TAPM Meteorological Simulations

TAPM was developed by the CSIRO and has been validated by the CSIRO, Katestone Environmental and others for many locations in Australia, Southeast Asia and in North America (see www.dar.csiro.au/TAPM/ for more details on the model and validation results from the CSIRO). The model has generally performed well in simulating regional winds for the purposes of air quality modelling studies.

TAPM required synoptic meteorological information for the Gladstone region. This information was generated by a global model similar to the large-scale models used to forecast the weather. The data are supplied by the BOM on a grid resolution of approximately 75 km, and at elevations of between one hundred metres to five kilometres above the ground. TAPM uses this synoptic information, along with specific details of the location such as surrounding terrain, land-use, soil moisture content and soil type to simulate the meteorology of a region as well as at a specific location.

TAPM solves the fundamental fluid dynamics equations to predict meteorology at a mesoscale (20 kilometre to 200 kilometre) and at a local scale (down to a few hundred metres). TAPM includes parameterisations for cloud/rain micro-physical processes, urban/vegetation canopy and soil, and radiative fluxes. TAPM is skilled at simulating the flows important to regional and local scale meteorology, such as the southeast trade winds and sea breezes.

TAPM (version 3.0.7) was configured as follows:

- Mother domain of 30 km with 3 nested daughter grids of 10 km, 3 km and 1 km
- 48 x 34 grid points for all modelling domains resulting in a 40 x 40 km grid at 1 kilometre resolution
- 25 vertical levels, from the surface up to an altitude of 8000 metres above ground level
- Geosciences Australia 9 second DEM terrain data
- The TAPM defaults for sea surface temperature
- Default options selected for advanced meteorological inputs
- Year modelled: 1 April 2006 to 31 March 2007
- Landuse and coastline data was refined based on high resolution images sourced from Google Earth and vegetation maps obtained from the DERM
- Local data assimilation using observations from three regionally representative sites

The land use for the inner grid required significant modification due to the coarseness of the TAPM dataset. Representative data was derived from vegetation maps obtained from DERM and from aerial imaging by Google Earth. The coastline was also re-defined in the database to better represent the complex coastline around Curtis Island. Detailed 3-second arc DEM elevation data (resolution approximately 100 metre) was obtained from Geosciences Australia for refining this modelling domain.

TAPM was used as the prognostic mesoscale meteorological model to provide three-dimensional hourly meteorological fields to CALMET, a diagnostic meteorological model and wind field pre-processor for the CALPUFF air dispersion model. The CALMET modelling grid was positioned within the TAPM simulation, effectively becoming a fifth nested grid. The three-dimensional meteorological fields generated by TAPM were then input into CALMET model to generate a fine resolution meteorological field.

B1.2 CALMET Meteorological Simulations

CALMET (version 6.3) is an advanced non-steady-state diagnostic three-dimensional meteorological model with micro-meteorological modules for overwater and overland boundary layers. The model is the meteorological pre-processor for the CALPUFF dispersion model. CALMET is capable of assimilating hourly meteorological data from multiple sites within the modelling domain, and can also be initialised with the gridded three-dimensional prognostic output from other meteorological models such as TAPM. This can improve dispersion model output, particularly over complex terrain as the near surface meteorological conditions are calculated for each grid point.

CALMET was used to simulate meteorological conditions around Curtis Island. The modelling domain was setup to be nested within the one kilometre TAPM domain. CALMET treats the prognostic model output as the initial guess field for the diagnostic model wind fields. CALMET then adjusts the initial guess field for the kinematic effects of terrain, slope flows, blocking effects and 3-dimensional divergence minimisation. The coupled approach unites the mesoscale prognostic capabilities of TAPM with the refined terrain and land use capabilities of CALMET.

The use of the three-dimensional wind field provides a complete set of meteorological variables for every grid point and vertical level for each hour of the simulation period. This is a significant improvement in modelling approach to the method of data assimilation from discrete surface stations. No data assimilation was used in CALMET, however regionally representative sites were assimilated into TAPM.

The model was set up with twelve vertical levels with heights at 20 m, 60 m, 100 m, 180 m, 260 m, 360 m, 460 m, 600 m, 800 m, 1600 m, 2600 m and 4600 m at each grid point. The terrain and land use were further refined from those used in the TAPM model to account for the increased resolution. The terrain was generated from the Geosciences Australia 9-second arc DEM dataset at a resolution of 1000 m. All default options and factors were selected except where noted below.

Key features of CALMET used to generate the wind fields are as follows:

- Domain area of 48 by 34 km with 1000 m grid spacing
- 1 year time scale (1 April 2006 to 31 March 2007), divided into individual months for analysis
- Prognostic wind fields input as MM5/3D.Dat "initial guess" field only (as generated from TAPM)
- Step 1 wind field options include kinematic effects, divergence minimisation, Froude adjustment to a critical Froude number of 1 and slope flows
- Terrain radius of influence set at 2 kilometre
- Cloud cover calculated from prognostic relative humidity

B1.3 CALPUFF Dispersion Modelling Methodology

Atmospheric dispersion modelling was carried out using the CALPUFF (version 6.113) dispersion model. CALPUFF is a non-steady-state puff dispersion model, and is accepted for use by DERM for application in environments where wind patterns and plume dispersion is strongly influenced by complex terrain and the land-sea interface. The Gladstone region consists of highly complex meteorology, and includes complex terrain, highly variable land uses and a land-sea interface and coastal islands.

The CALPUFF dispersion model was used to predict ground-level concentrations of air contaminants downwind of this source. Due to increased computational resources available when undertaking the Arrow LNG Plant air quality impact assessment since GAMSv3 was developed, a higher grid resolution of 250 metres was used for the dimensions of the CALPUFF domain.

B2. Description of the Statistical Methods used in the Model Performance Evaluation

The following section describes the statistics used in the evaluation of model performance for the prediction of ground-level concentrations.

B2.1 Root Mean Square Error

The Root Mean Square Error (RSME) can be described as the standard deviation of the difference for hourly predicted and observed pairings at a specific point. The RMSE is a quadratic scoring rule, which measures the average magnitude of the error. The difference between predicted and corresponding observed values are each squared and then averaged over the sample. Finally, the square root of the average is taken. Since the errors are squared before they are averaged, the RMSE gives a relatively high weight to large errors. This means the RMSE is most useful when large errors are particularly undesirable. Overall, the RSME is a good overall measure of model performance, but since large errors are weighted heavily (due to squaring), its value can be distorted. RMSE is equal to the unit of the values being analysed i.e., an RMSE of 1.2 for wind speed = 1.2 m/s^{-1}.

The RMSE is defined as:

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)^2}$$

Ultimately, for good model performance, the RMSE should be a low value, with most of the variation explained in the observations. Here, the systematic error $\mathrm{RMSE_s}$ should approach zero and the unsystematic error, $\mathrm{RMSE_u}$, should approach the RMSE since:

$$\mathrm{RMSE}^2 = \mathrm{RMSE}_\mathrm{S}^2 + \mathrm{RMSE}_\mathrm{u}^2$$

The Systematic and Unsystematic Root Mean Square Error are described as follows.

B2.1.1 Systematic Root Mean Square Error

The Systematic Root Mean Square Error ($\mathrm{RMSE_s}$) is calculated as the square root of the mean square difference of hourly predictions from the regression formula and observation pairings, at a specific point. The regressed predictions are taken from the least squares formula. The $\mathrm{RMSE_s}$ estimates the model's linear (or systematic) error. The systematic error is a measure of the bias in the model due to user input or model deficiency, i.e., data input errors, assimilation variables, and choice of model options. The $\mathrm{RMSE_s}$ is a metric for the model's accuracy.

The $\mathrm{RMSE_s}$ is defined as:

$$\mathrm{RMSE_S} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\hat{P}_i - O_i)^2}$$

B2.1.2 Unsystematic Root Mean Square Error

The Unsystematic Root Mean Square Error ($RMSE_u$) is calculated as the square root of the mean square difference of hourly predictions from the regression formula and model prediction value pairings, at a specific point. The $RMSE_u$ is a measure of how much of the difference between predictions and observations result from random processes or influences outside the legitimate range of the model. This error may require model refinement, such as new algorithms or higher resolution grids, or that the phenomena being simulated cannot be fully resolved by the model. The $RMSE_u$ is a metric for the model's precision.

The $RMSE_u$ is defined as:

$$\mathrm{RMSE_U} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\hat{P}_i - P_i)^2}$$

B2.2 Index of agreement

The Index of Agreement (IOA) is calculated using a method described in Willmott (1982). The IOA can take a value between 0 and 1, with 1 indicating perfect agreement. The IOA is the ratio of the total RMSE to the sum of two differences, i.e., the difference between each prediction and the observed mean, and the difference between each observation and observed mean. From another perspective, the IOA is a measure of the match between the departure of each prediction from the observed mean and the departure of each observation from the observed mean.

The IOA is defined as:

$$\mathrm{IOA} = 1 - \frac{\sum_{i=1}^{N}(P_i - O_i)^2}{\sum_{i=1}^{N}(|P_i - O_{mean}| + |O_i - O_{mean}|)^2}$$

Where: N is the number of observations,
P_i are the hourly model predictions,
O_i are the hourly observations,
O_{mean} is the observed observation mean, and $\hat{P}_i = a + bO_i$ is the linear regression fitted with intercepts *a* and slope *b*.

B2.3 Skill measures

Skill measure statistics are given in terms of a score, rather than in absolute terms. A model's skill can be measured by the difference in the standard deviation of the modelled and observed values.

B2.3.1 Skill E

The Skill_E (SE) is indicative of how much of the standard deviation in the observations is predicted to be due to random/natural processes (unsystematic) in the atmospheric boundary layer. i.e., turbulence/chaos. For good model performance, the value for Skill_E should be less than one.

B2.3.2 Skill V

Skill_V (SV) is ratio of the standard deviation of the model predictions to the standard deviation of the observations. For good model performance, the value for Skill_V should be close to one.

B2.3.3 Skill R

SKILL_R (SR) takes into account systematic and unsystematic errors in relation to the observed standard deviation. For good model performance, the value for Skill_E should be less than one.

B2.3.4 Skill ratios

SKILL_E = (RMSE_U/ STDEV OBS) < 1 shows skill
SKILL_V = (STDEV_MOD/ STDEV _OBS) close to 1 shows skill
SKILL_R = (RMSE/ STDEV _OBS) < 1 shows skill

B2.4 Mean Error and Mean Absolute Error

The Mean Error (ME) is simply the average of the hourly modelled values minus the hourly observed values. It contains both systematic and unsystematic errors and is heavily influence by high and low errors.

The Mean Absolute Error (MAE) measures the average magnitude of the errors in a set of predictions, without considering their direction. It measures accuracy for continuous variables. Expressed in words, the MAE is the average of the absolute values of the differences between predictions and the corresponding observation. The MAE is a linear score, which means that all the individual differences are weighted equally in the average. The MAE and the RMSE can be used together to diagnose the variation in the errors in a set of predictions. The RMSE will always be larger or equal to the MAE; the greater difference between them, the greater the variance in the individual errors in the sample. If the RMSE=MAE, then all the errors are of the same magnitude. Both the MAE and RMSE can range from 0 to ∞. They are negatively-oriented scores, i.e., lower values are better.

B2.5 Complex Vector Correlation

A vector requires both magnitude and phase to define the relationship between two sets of vector quantities. Wind direction is a vector as well as a circular function with a cross over point at 0º and 360º. Thus negating any attempt to characterise the relationship between predicted and observed wind direction measurements using standard linear correlation techniques. However vectors can be represented by their scalar components in a Cartesian or Spherical coordinate system. In the case of wind direction this decomposition results in the scalar quantities of *u* (east-west) and *v* (north-south) thereby allowing independent statistical analyses to take place. Scalar decomposition however, is limited by confining the analysis to individual scalar components not the vector as a whole, as well as, its inherent reliance on the subjective choice of coordinate system used in the decomposition process (Crosby, Breaker and Gemmill 1993). An alternative method is to incorporate the effects of magnitude and direction directly thereby yielding a scalar quantity defining the degree of association between the two datasets (Kundu 1976).

The complex correlation coefficient following the methods described in Kundu (1976) are as follows:

$$p = \frac{\langle u_1 u_2 + v_1 v_2 \rangle}{\langle u_1^{\ 2} + v_1^{\ 2} \rangle^{1/2} \langle u_2^{\ 2} + v_2^{\ 2} \rangle^{1/2}} + i \frac{\langle u_1 v_2 - u_2 v_1 \rangle}{\langle u_1^{\ 2} + v_1^{\ 2} \rangle^{1/2} \langle u_2^{\ 2} + v_2^{\ 2} \rangle^{1/2}}$$

where *u* and *v* are the scalar components of the vector and *i* = $\sqrt{-1}$ yielding the complex conjugate of the vector components. Therefore, the complex correlation coefficient (*p*) can be defined as the normalised inner product between the two vector quantities.

The phase angle is then defined by:

$$\alpha_{av} = \tan^{-1} \frac{\langle u_1 v_2 - v_1 u_2 \rangle}{\langle u_1 u_2 + v_1 v_2 \rangle}$$

Where the resulting quantities are independent of coordinate system and a complex number whose magnitude gives the measure of correlation and whose phase angle gives the average counter clockwise angle of the second vector in relation to the first. Of course phase angle is only meaningful if the correlation coefficient is high. The magnitudes of the instantaneous vectors are used to weight the averaging process in order to estimate the mean angular displacement between the two datasets.

B2.6 Fractional Bias

The Fractional Bias (FB) refers to the mean systematic difference between C_p and C_o, defined as:

$$\text{FB} = \frac{(\overline{C_o} - \overline{C_p})}{0.5(\overline{C_o} + \overline{C_p})}$$

The FB is used when the data sets show a linear relationship. Consequently, the FB is strongly influenced by infrequently occurring high observed and predicted concentrations. For the FB, good model performance is reflected when the value approaches zero. Chang and Hanna (2004) found that for acceptable performing models, the mean bias is within ±30% of the mean (approximately |FB| < 0.3).

B2.7 Normalised Mean Square Error

In a similar manner to the FB, the Normalised Mean Square Error (NMSE) is used when the data sets show a linear relationship, and are strongly influenced by infrequently occurring high observed and predicted concentrations. For the NMSE, good model performance is also reflected when the value approaches zero. Chang and Hanna (2004) found that for acceptable performing models, the random scatter is about a factor of two to three of the mean (i.e., approximately NMSE < 1.5).

The normalised mean squared error (NMSE) is the squared difference between C_p and C_o, given by:

$$NMSE = \frac{\overline{(C_o - C_p)^2}}{\overline{C_o}\,\overline{C_p}}$$

B2.8 Factor of 2

The Factor of 2 (FAC2) is a more robust measure than the FB and NMSE because it is not overly influenced by high and low outliers. For the FAC2, good model performance is reflected when the value approaches one. Chang and Hanna (2004) found that for acceptable performing models, the fraction of predictions within a factor of two of observations is about 50% or greater (i.e., FAC2 > 0.5).

The fraction of predictions within a FAC2 of the observed is defined as:

$$FAC2 = 0.5 \leq \frac{C_p}{C_o} \leq 2.0$$

B2.9 Fractional Bias – Ratio of False Negatives and False Positives

The Ratio of False Negatives (FB_{fn}) can be considered as the under-predicting (false-negative) component of the fractional bias, i.e., only those (C_o, C_p) pairs with $C_p < C_o$ are considered in the calculation. Therefore, the value of FB_{fn} represents the percentage of under-predictions that are likely to be false.

In a similar manner, the Ratio of False Positives (FB_{fp}) can be considered as the over-predicting (false-positive) component of the fractional bias, i.e., only those (C_o, C_p) pairs with $C_p > C_o$ are considered in the calculation. Therefore, the value of FB_{fp} represents the percentage of over-predictions that are likely to be false.

The fractional bias of false negatives is defined as:

$$FB_{fn} = \frac{\frac{1}{2}\sum_i\left[\left|C_{oi} - C_{pi}\right| + \left(C_{oi} - C_{pi}\right)\right]}{\frac{1}{2}\cdot\sum_i\left(C_{oi} + C_{pi}\right)}$$

The fractional bias of false positives is defined as:

$$FB_{fp} = \frac{\frac{1}{2}\sum_i\left[\left|C_{oi} - C_{pi}\right| + \left(C_{pi} - C_{oi}\right)\right]}{\frac{1}{2}\cdot\sum_i\left(C_{oi} + C_{pi}\right)}$$

B2.10 Robust Highest Concentration

The robust highest concentration (RHC) is the mean of the eleven highest concentrations.

B3. Model Performance Evaluation Methodology and Outcomes

The performance of the dispersion and meteorological modelling methodology was extensively evaluated for accuracy and precision in regards to predicting the meteorological parameters and ground-level concentrations of air pollutants. The GAMSv3 meteorological fields show exceptional skill in simulating the wind fields and dispersion characteristics throughout the modelled Gladstone airshed.

Seven meteorological stations, summarised in Table B1, were used in the evaluation of the GAMSv3. Three sites, Gladstone Radar (GLR), Boyne Smelter (BOY), and Targinie Swanns Road (YAR) were assimilated into the TAPM model, while the remaining sites, Auckland Point (AUP), Aldoga (ALD), South Gladstone (QAL) and Clinton (CLI), were used for evaluation purposes. The locations of the assimilation and evaluation monitoring stations used in the development and validation of the GAMSv3 are presented in Figure B1.

Table B1 Meteorological monitoring stations used in the development of the GAMSv3

Station	Code	Easting (km)	Northing (km)	Height (m)	Elevation (m)
Auckland Point (GPC)	AUP	322.065	7362.865	10	10
Gladstone Airport/Clinton (BoM/DERM)	CLI	318.719	7359.178	10	15
South Gladstone Ann St (DERM)	QAL	323.742	7359.988	10	5
Targinie Swanns Rd (DERM)	YAR	306.949	7369.454	10	47
Aldoga (DERM)	ALD	302.697	7362.093	10	62
Gladstone Radar (BoM)	GLR	322.005	7359.024	10	98
Boyne Smelter (BSL)	BOY	331.879	7352.131	30	2

B3.1 Meteorological Modelling

The performance statistics of the GAMSv3 meteorology at the four evaluation sites are summarised in Table B2. Wind direction has been separated into its vector components of easting (u) and northing (v) by:

u = - wind speed x sine (wind direction)
and
v = - wind speed x cosine (wind direction)

The vector correlation method described by Breaker *et al*. (1994) to measure the accuracy of wind direction was also applied. The method accounts for the magnitude (wind speed) and phase (wind direction) in unison, where a magnitude of 1 is a 100% correlation, and the phase is the counter clockwise rotation of the wind direction in degrees, as described in Section B2.

Table B2 Performance statistics of predicted versus observed wind speed (WS) and wind direction vector components U and V

Location	Variable	rmse	rmse_s	rmse_u	IOA	SE	SV	SR	MAE	Vector correlation (magnitude, phase)
AUP	WS	2	1.5	1.3	0.82	0.5	0.8	0.8	1.6	0.92, -12.46
	U	1.9	1.3	1.4	0.93	0.3	0.8	0.5	1.5	-
	V	2	1.5	1.3	0.87	0.4	0.7	0.6	1.5	-
ALD	WS	1.8	1.5	0.9	0.75	0.4	0.5	0.7	1.5	0.8, -7.3
	U	1.6	1.1	1.2	0.85	0.5	0.7	0.6	1.3	-
	V	1.5	1.1	1.03	0.73	0.6	0.8	0.9	1.2	-
CLI	WS	1.2	0.9	0.8	0.87	0.4	0.7	0.6	1	0.92, 3.26
	U	1.2	1.3	1.4	0.94	0.5	0. 9	0.5	0.97	-
	V	1.1	1	1.3	0.93	0.7	1.1	0.6	0.83	-
QAL	WS	0.9	0.4	0.8	0.86	0.7	1.1	0.8	0.7	0.86, 16
	U	1.3	0.6	1.1	0.86	0.7	1.2	0.8	1.01	-
	V	1.2	0.7	1	0.85	0.5	0.8	0.7	0.9	-

AUP: Auckland Point
ALD: Aldoga
CLI: Clinton
QAL: South Gladstone near QAL
rmse: root mean square error
rmse_s: root mean square error
rmse_u: root mean square error
ioa: index of agreement
se: unsystematic RMSE/obs standard deviation
sv: mod standard deviation/obs standard deviation
sr: RMSE/obs standard deviation
MAE: Mean Absolute Error

The performance evaluation shows that the model accurately characterises the meteorology within the modelling domain, with high correlations and indexes of agreement between observed and modelled variables. Model error has been minimised and is well within the recommended factor of two evaluation threshold (NIWA, 2004). The RMSE error was also found below the standard deviation of the observed variables indicating that the model errors are within the natural degree of variability to be expected in the observations.

These results give confidence the modelled wind fields and dispersion characteristics in areas where observational data is sparse or non-existent, such as Curtis Island, would be reliable and accurate representation of reality.

Figure B2 and Figure B3 illustrate the refined terrain and land use data files respectively, adapted for input to the GAMSv3.

B3.2 Pollution Dispersion Modelling

A similar approach for assessing the accuracy of model predictions for wind speed and direction was employed for ground-level concentration of SO_2 and NO_x. Particular attention was paid to the high end of the distribution as these predictions are most relevant to intended use of GAMSv3.

Table B3 and Table B4 show the summary statistics of the observed and modelled datasets. It is apparent that the model tends to over predict average ground-level concentrations at CLI and QAL, while YAR shows a slight under prediction of the mean. The observed standard deviation of SO_2 at the CLI is 17 while the model results indicate a standard deviation of 83, this means that the modelled concentrations display a large amount of variability and partially explains the abnormally high maximum one hour concentration of 600 $\mu g/m^3$ compared to the observed maximum of 207 $\mu g/m^3$. The NO_X statistics display a similar relationship as does the results of for NO_X at the QAL monitor, where an over prediction of the standard deviation appears to coincide with an over prediction of the mean and maximum.

Table B3 Summary statistics for observed and modelled sulfur dioxide

Site	Variable	Mean	Standard deviation	Min	Max	Number of Observations
CLI	OBS_SO2	19.3	17.01	10.01	207.4	600
	MOD_SO2	58.1	83.1	15.2	600.9	600
QAL	OBS_SO2	31.2	31.1	10.01	266.01	1577
	MOD_SO2	45.2	18.8	24.7	215.1	1577
YAR	OBS_SO2	29.6	18.7	10.01	130.2	1282
	MOD_SO2	24.2	20.5	6.4	154.5	1282

Table B4 Summary statistics for observed and modelled oxides of nitrogen

Site	Variable	Mean	Standard deviation	Min	Max	Number of Observations
CLI	OBS_NOx	34.2	21	18.7	173.6	1056
	MOD_NOx	51.3	88.5	10.01	805.9	1056
QAL	OBS_NOx	31.8	29.1	10.1	245.2	2861
	MOD_NOx	63.9	46.2	6.9	467	2861
YAR	OBS_NOx	31.1	20.5	10.2	237.4	2241
	MOD_NOx	27.9	21.9	8.3	190.5	2241

Figure B4 and Figure B5 show the mean, 95^{th}, 98^{th}, 99^{th}, 99.9^{th} percentiles, robust highest concentration (RHC) and the maximum one hour observed and modelled ground-level concentration at the three sites. GAMSv3 does a good job of simulating the distribution at the top end of the concentration spectrum at the three sites. Modelled SO_2 and NO_X is significantly higher than the observations at the CLI location, while SO_2 is slightly under predicted at QAL but NO_X is significantly over predicted. YAR shows the closest relationship with means, standard deviations and maximum being very close to the observed.

Table B5 shows the performance statistics of the model predictions of ground-level SO_2 and NO_X concentrations at YAR, CLI and QAL. The RMSE for CLI and QAL were quite high, with the majority of the error being systematic. This means that errors in the model prediction are due to inherent limitations of the model set up or the emission inventory. The relatively coarse final resolution of the model and the proximity of the monitoring stations to significant sources are most likely responsible for these large errors. YAR scored a relatively low RMSE with an SO_2 systematic error of 5.7 $\mu g/m^3$ and an unsystematic error of 2.9 $\mu g/m^3$. The reverse situation was found for NO_X errors with the unsystematic error being nearly twice that of the systematic. This implies that there is a small but significant amount of variability in the observed NO_X that is not being taken into account by the model. It is thought that this may be due to ship emissions originating from the port. QAL and YAR both scored IOA's for SO_2 and NO_x close 0.8 and 0.9. CLI scored an IOA's of 0.5 and 0.6 for SO_2 and NO_X, respectively. Skill measures showed encouraging results for QAL and YAR with good SE and SR scores. Skill measures for CLI indicate that the model predictions vary significantly from the observed dataset, particularly at the high end of the distribution where the model is consistently a factor of 2 above the observed.

The model displayed a good ability to predict hourly averaged ground-level concentrations throughout the modelling domain within a factor of the 2 of the observations (FAC2). YAR performed the best with nearly 80% of SO_2 to 100% of NO_X predictions falling within a factor of 2 of the observations. CLI also performed well with 68% and 92% of SO_2 and NO_x predictions also being within a factor of two. QAL showed the poorest performance with less than 50% of the predictions being with a factor of 2. The derivation of false negative and false positive scores helps illustrate the conservative nature of the model. The FBfn is the fractional bias of all predictions that are below the observations while the FBfp is the fractional bias of predictions that are above the predictions. Simply this gives a better interpretation of the fractional bias by determining what proportion of the bias is an under prediction and what is an over prediction. For a conservative model a bias towards a false positive is desirable. YAR has a very low FBfn and FBfp meaning that the under and over predictions are minimal, illustrated by the low (0.5, -3.3 µg/m^3) ME for SO_2 and NO_x respectively. QAL and CLI have significantly larger proportion of false positives and a large ME values (QAL NO_X ME = 54 4 µg/m^3), indicating a mean over prediction of 54 µg/m^3.

Table B5 Performance statistics predicted versus observed sulphur dioxide (SO_2) and nitrogen oxide (NO_x)

Parameter	CLI_SO2	QAL_SO2	YAR_SO2	CLI_NOx	QAL_NOx	YAR_NOx
intercept	-32.68	26.86	-7.97	-86.95	17.31	-4.29
slope	4.70	0.59	1.09	4.04	1.47	1.03
rmse	77.24	19.52	6.37	70.71	39.07	6.55
rmse_s	73.88	18.96	5.67	66.14	34.85	3.32
rmse_u	22.54	4.64	2.91	24.99	17.69	5.64
IOA	0.48	0.86	0.97	0.59	0.78	0.98
SE	1.32	0.15	0.16	1.19	0.61	0.28
SV	4.88	0.61	1.10	4.22	1.59	1.07
SR	4.54	0.63	0.34	3.37	1.34	0.32
MAE	38.75	18.51	5.90	23.92	54.46	7.96
FB	1.23	0.37	-0.20	1.17	0.67	-0.11
ME	38.75	4.71	0.53	17.15	54.46	-3.25
NMSE	5.33	0.26	0.06	2.85	1.49	0.10
FAC2	0.68	0.43	0.78	0.92	0.44	1.00
FBfn	0	0.06	0.211	0.08	0.003	0.133
FBfp	1	0.425	0.009	0.48	0.674	0.023

Cumulative frequency distribution plots (Figure B6 and Figure B7) show the 99.99th , 99.97th, 99.93th, 99.9th, 99.84th, 99.75th, 99.6th, 99.5th, 99.37th, 99th, 98.3th, 97.1th, 95th, 93th, 90th, 80th percentile observed versus modelled SO_2 and NO_X concentrations. There is good agreement at the YAR and QAL sites, with predictions at CLI being consistently high by a factor of 2 above the observed.

B4. Conclusion

The performance of the Gladstone Airshed Modelling System Version 3 (GAMSv3) dispersion and meteorological modelling predictions were extensively evaluated for accuracy and precision in predicting meteorology parameters and ground-level concentrations of air pollutants.

Overall GAMSv3 provides a reliable basis for representing dispersion meteorology and for predicting ground-level concentrations of air pollutants. The majority of variation between modelled and observed concentrations of air pollutants was found in the highest percentile concentrations. With GAMSv3 tending to be high compared to the observations, indicating that GAMSv3 is a conservative model.

B5. References

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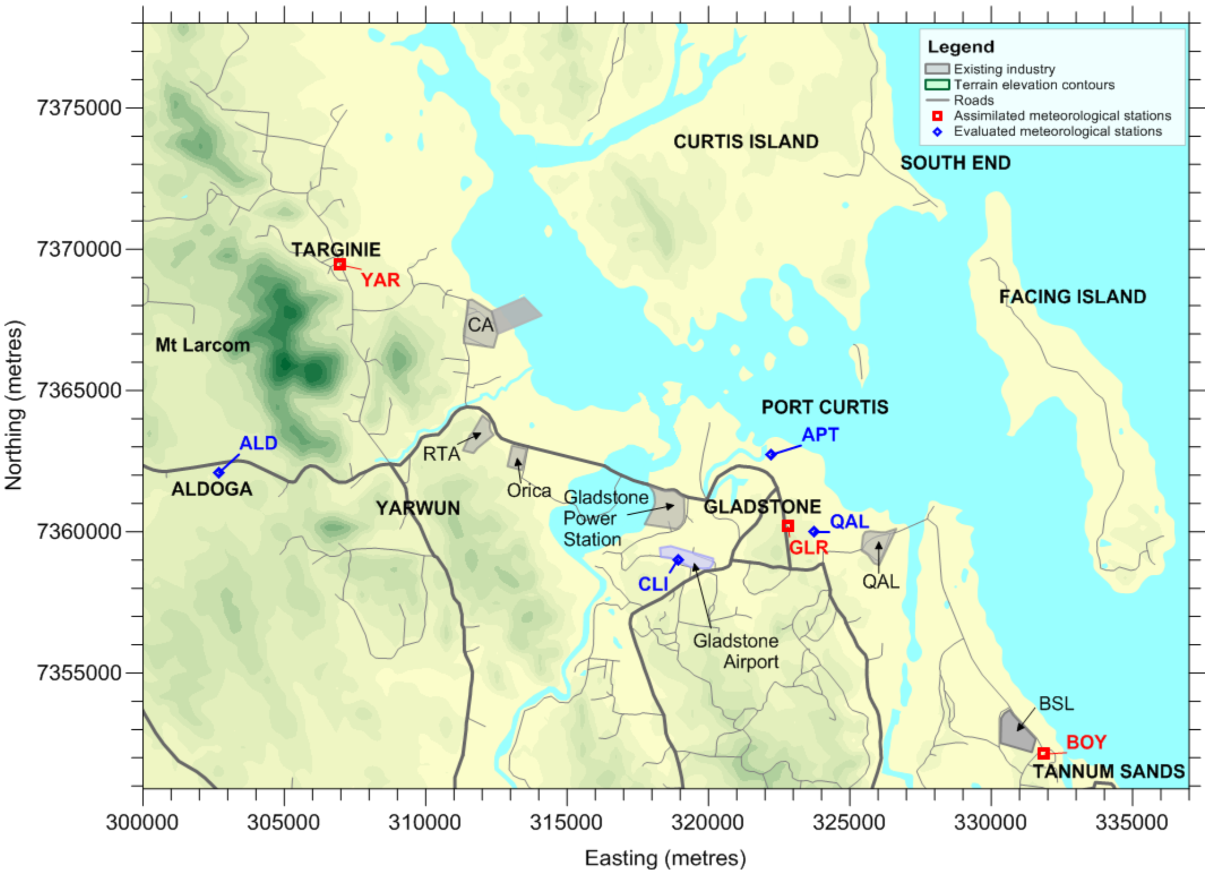

Figure B1 Locations of meteorological monitoring stations used for model assimilation and performance evaluation

Location: Gladstone region	**Data source:** ArcGIS and Google Earth	**Units:** AGD66 coordinates in metres
Type: Map	**Prepared by:** A. Balch	**Date:** July 2010

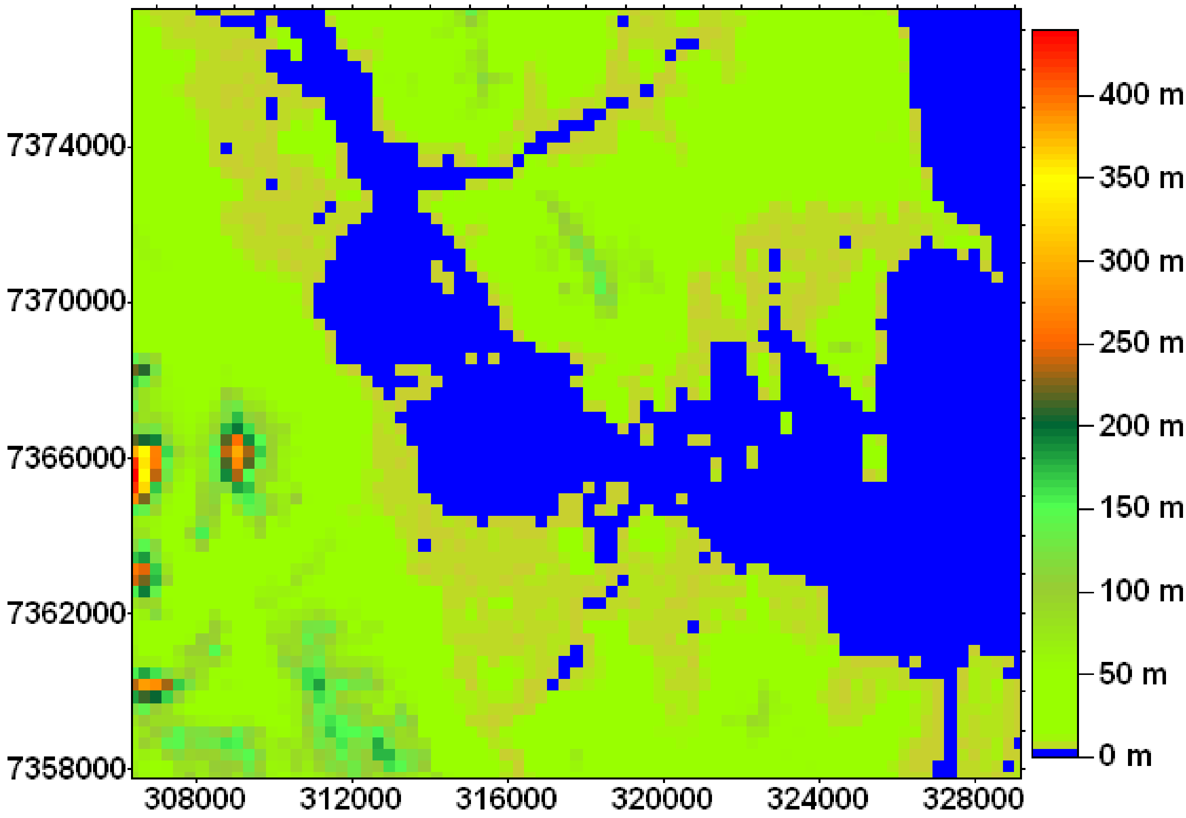

Figure B2 Refined CALMET terrain used in the meteorological model

Location: Gladstone	**Data source:** Generated by CALMETv6.4 and Surfer	**Units:** Metres (m) above sea level
Type: Image map	**Prepared by:** A. Wiebe	**Date:** March 2009

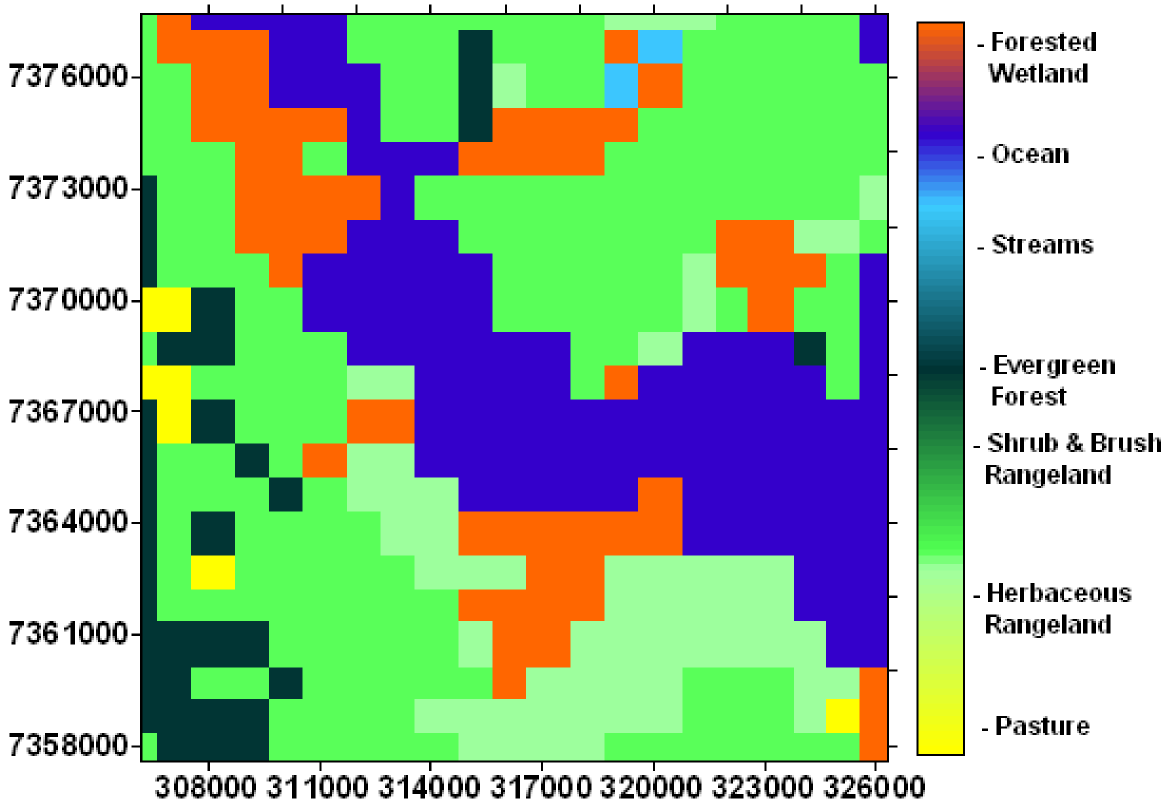

Figure B3 Refined CALMET Level II land use classifications used in the meteorological model

Location: Gladstone	**Data source:** Generated by CALMETv6.3 and Surfer	**Units:** CALMET Level II land use classifications
Type: Image map	**Prepared by:** A. Wiebe	**Date:** March 2009

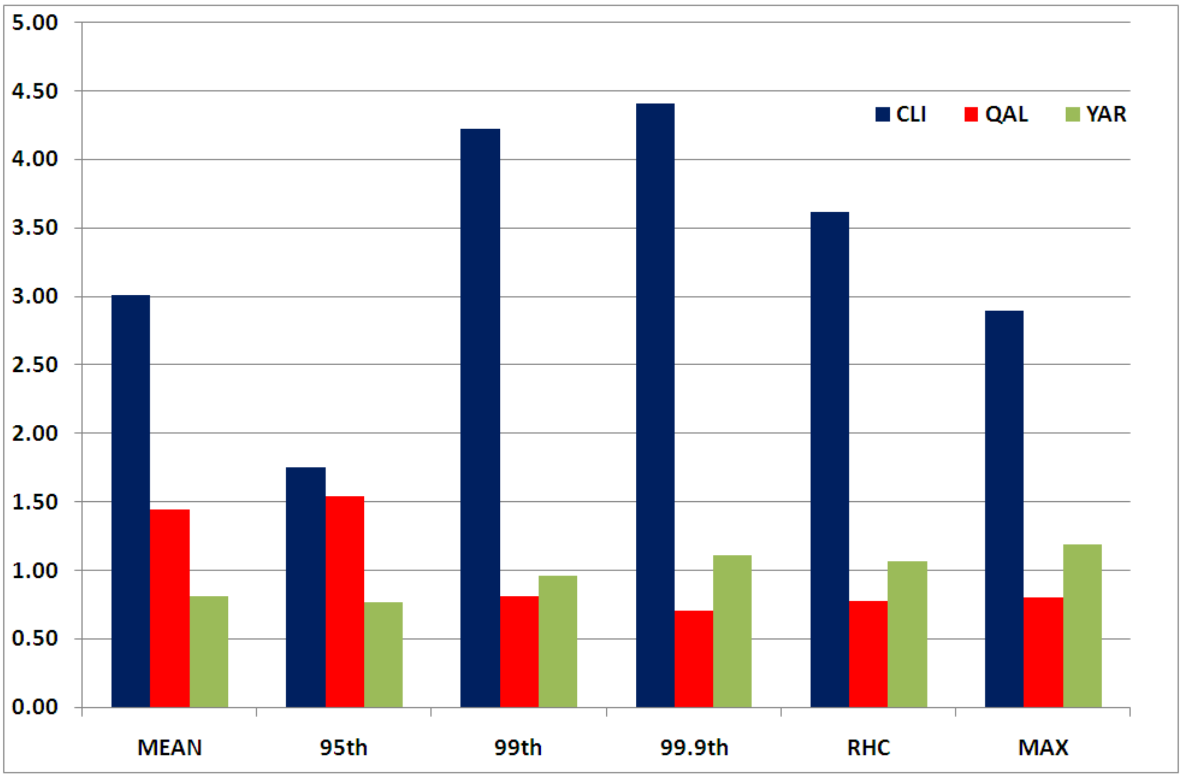

Figure B4 Sulfur dioxide top end distribution difference (modelled – observed)			
Location: CLI, QAL and YAR	**Period:** April 2006 to March 2007	**Data source:** CALPUFF	**Units:** µg/m³
Type: Histogram		**Prepared by:** Andrew Wiebe	**Date:** January 2009

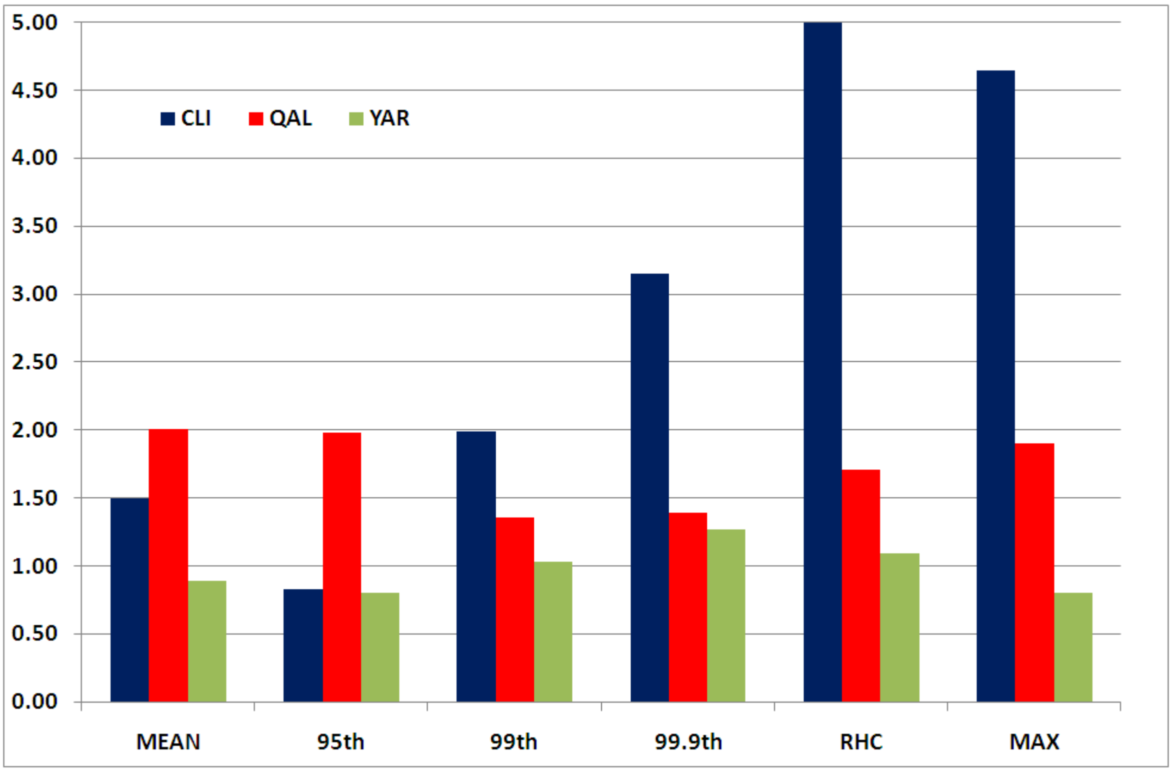

Figure B5	**Oxides of nitrogen top end distribution difference (modelled – observed)**		
Location: CLI, QAL and YAR	**Period:** April 2006 to March 2007	**Data source:** CALPUFF	**Units:** µg/m³
Type: Histogram		**Prepared by:** Andrew Wiebe	**Date:** January 2009

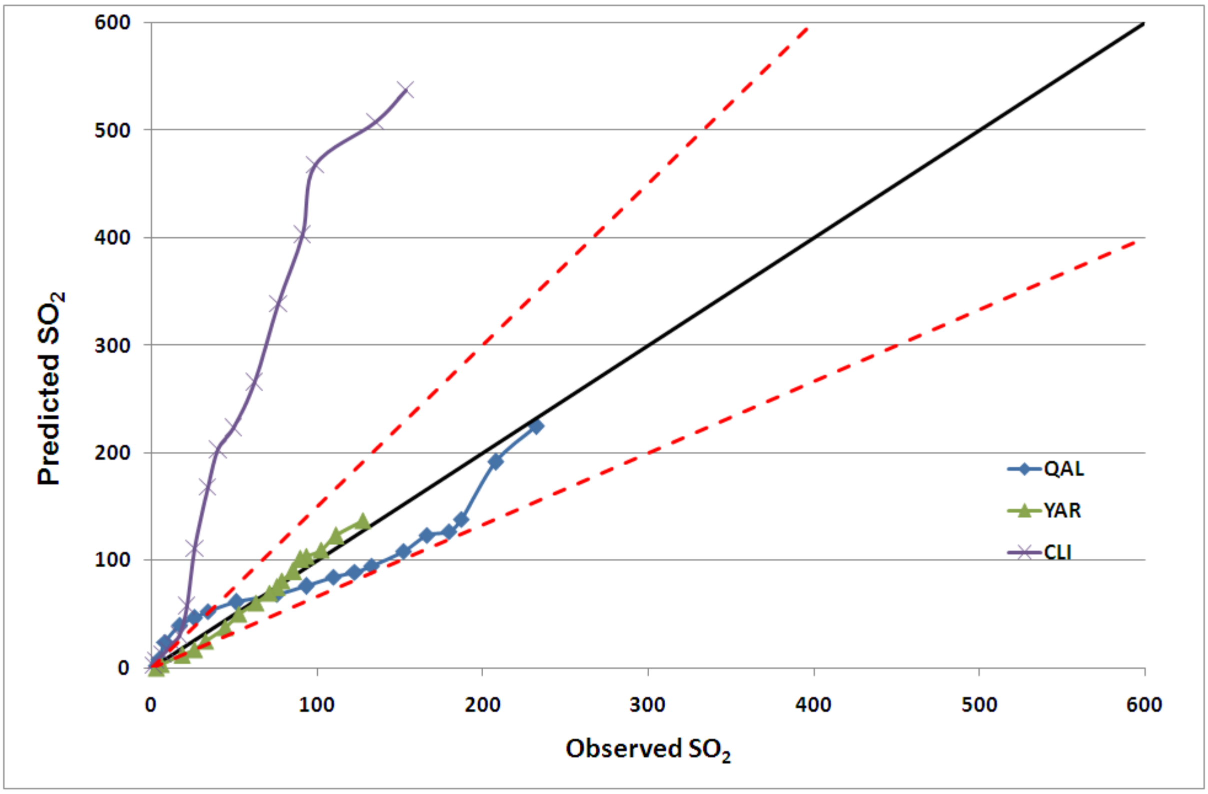

Figure B6	**Sulfur dioxide cumulative frequency distribution of observed and predicted concentrations. Black line is the 1 to 1 line; the red dashed lines indicate a factor of 2 over and under prediction**		
Location: CLI, QAL and YAR	**Period:** April 2006 to March 2007	**Data source:** Observations and CALPUFF	**Units:** µg/m^3
Type: X Y scatter plot		**Prepared by:** Andrew Wiebe	**Date:** January 2009

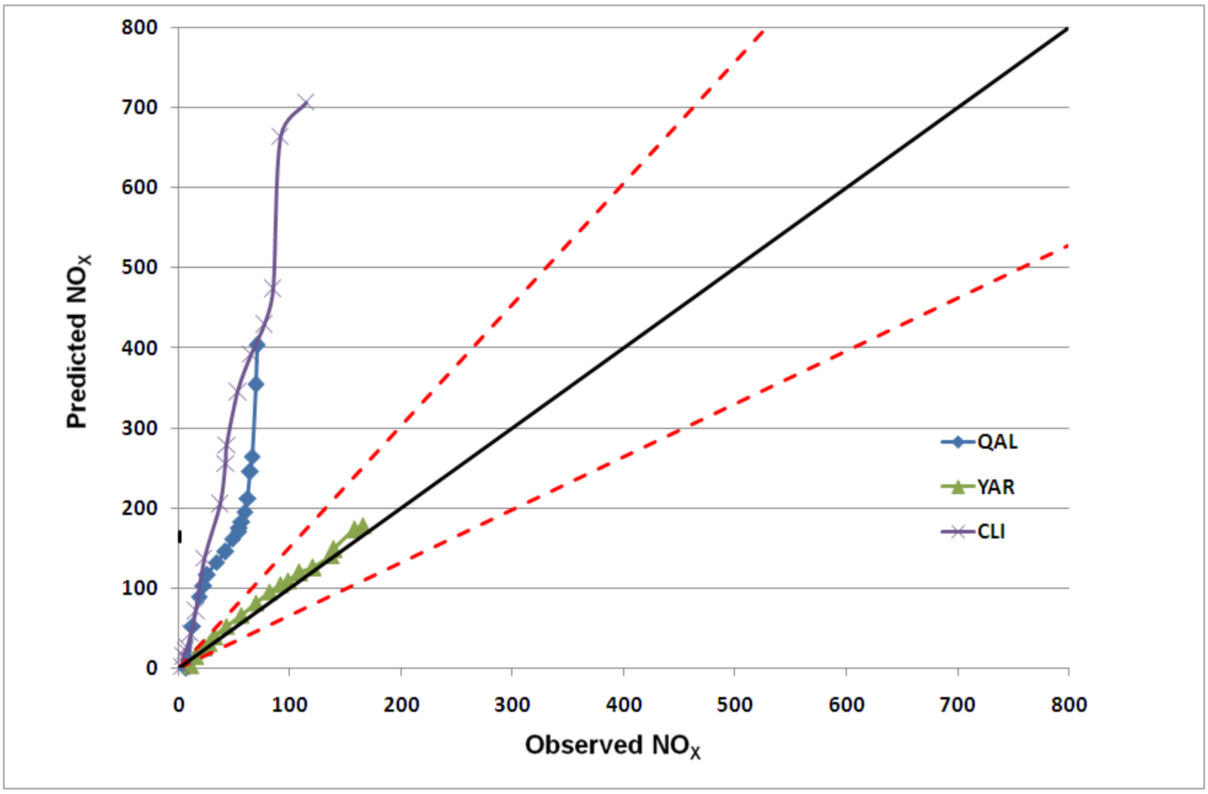

Figure B7 **Oxides of nitrogen cumulative frequency distribution of observed and predicted concentrations. Black line is the 1 to 1 line; the red dashed lines indicate a factor of 2 over and under prediction**

Location: CLI, QAL and YAR	**Period:** April 2006 to March 2007	**Data source:** Observations and CALPUFF	**Units:** µg/m^3
Type: X Y scatter plot		**Prepared by:** Andrew Wiebe	**Date:** January 2009

Appendix C

Assessment of minor air pollutants for 100% load case

Contents

Tables

Figures

Assessment of minor air pollutants for 100% load case

This Appendix presents the results of the air quality impact assessment for PM_{10}, $PM_{2.5}$, CO, ozone, odour and all identified hydrocarbons for the Arrow LNG Plant during routine and non-routine operating conditions. Nitrogen dioxide and sulfur dioxide have been idenified as the most critical pollutants in terms of impacts to air quality and have been included in the main air quality report.

C1 Routine Operations

C1.1 Carbon Monoxide

The assessment of the maximum 8-hour average ground-level concentrations of CO has been made for the 100th percentile value. The predicted maximum 8-hour average ground-level concentrations of CO for the Arrow LNG Plant in isolaton and with background at sensitive receptor areas are presented in Table C1. A contour plot presenting the 8-hour average ground-level concentrations of CO for the Arrow LNG Plant in isolaton is presented in 0.

Table C1 Predicted maximum 8-hour average ground-level concentrations of carbon monoxide for the Arrow LNG Plant during routine operations at 100% load (in µg/m³)

Sensitive receptor area	Arrow LNG Plant in isolation	Arrow LNG Plant with background
Gladstone	132.0	487.6
Tannum Sands	24.3	121.4
Targinie	242.0	861.6
Yarwun	48.4	203.4
Fishermans Landing	89.7	343.8
South End	120.0	446.8
Island receptors	97.0	368.7
Construction camps	237.2	276.0
Maximum % of air quality objective	2.2%	7.8%
Air quality objective	11,000	

Table note:
Cumulative includes scaling of predicted incremental ground-level concentrations by 3.4 to account for other LNG facilities plus the addition of ambient background levels representative of receptor location. Construction camps include incremental plus ambient background levels only.

The results indicate that the predicted maximum cumulative 8-hour average concentrations of CO from Arrow LNG at sensitive receptors are very low and well below the Air EPP objectives. The contour plot indicates maximum concentrations are predicted to occur on site.

C1.2 Particulate Matter as PM_{10} and $PM_{2.5}$

The assessment of ground-level concentrations of PM_{10} and $PM_{2.5}$ has been made for the 100th percentile value. The predicted maximum 24-hour average ground-level concentrations of PM_{10} for the Arrow LNG Plant in isolaton and with background at sensitive receptor areas are presented in Table C2. The predicted maximum 24-hour and annual average ground-level concentrations of $PM_{2.5}$ at sensitive receptors are presented in Table C3.

Table C2 Predicted maximum 24-hour average ground-level concentrations of PM_{10} for the Arrow LNG Plant (in µg/m³)

Sensitive receptor area	Arrow LNG Plant in isolation	Arrow LNG Plant with background
Gladstone	1.6	24.9
Tannum Sands	0.3	18.5
Targinie	3.8	36.8
Yarwun	1.8	25.2
Fishermans Landing	1.5	23.9
South End	1.3	28.5
Island receptors	2.7	33.1
Construction camps	4.6	28.6
Maximum % of air quality objective	9.1%	73.6%
Air quality objective	50	

Table note:
Cumulative includes scaling of predicted incremental ground-level concentrations by 3.4 to account for other LNG facilities plus the addition of ambient background levels representative of receptor location. Construction camps include incremental plus ambient background levels only.

Table C3 Predicted maximum 24-hour and annual average ground-level concentrations of $PM_{2.5}$ for the Arrow LNG Plant (in µg/m³)

Sensitive receptor area	24-hour		Annual	
	Arrow LNG Plant in isolation	Arrow LNG Plant with background	Arrow LNG Plant in isolation	Arrow LNG Plant with background
Gladstone	1.3	10.4	0.1	5.5
Tannum Sands	0.3	5.4	0.01	3.4
Targinie	3.6	16.1	0.1	4.5
Yarwun	1.6	12.4	0.1	7.0
Fishermans Landing	1.2	11.2	0.1	7.0
South End	1.1	7.6	0.03	4.1
Island receptors	2.5	12.1	0.1	4.4
Construction camps	3.5	7.2	0.9	4.9
Maximum % of air quality objective	14.6%	64.3%	11.0%	88.1%
Air Quality Objective	25		8	

Table note:
Cumulative includes scaling of predicted incremental ground-level concentrations by 3.4 to account for other LNG facilities plus the addition of ambient background levels representative of receptor location. Construction camps include incremental plus ambient background levels only.

The results indicate that the incremental ground-level concentrations of PM_{10} and $PM_{2.5}$ associated with emissions from the Arrow LNG Plant are very low and well below the Air EPP objectives. Impacts of PM_{10} and $PM_{2.5}$ are dominated by the existing industrial sources, motor vehicles and other natural sources in the region including bushfires and dust storms.

The predicted maximum 24-hour average ground-level concentrations of PM_{10} and $PM_{2.5}$ for the Arrow LNG Plant in isolation are presented in 0 and 0, respectively, while the annual average concentrations of $PM_{2.5}$ for the Arrow LNG Plant in isolation are presented in Figure C4.

The contour plot indicates maximum 24 hour average concentrations are predicted to occur close to the Arrow LNG site and on elevated terrain to the plant's north. The highest annual average concentrations of $PM_{2.5}$ are predicted to the northwest of the site due to the predominant south-easterly wind direction.

C1.3 Hydrocarbons

The predicted maximum ground-level concentrations of all hydrocarbons in all sensitive receptor areas are presented in Table C4.

The assessment indicates that predicted ground-level concentrations of hydrocarbons associated with emissions from all of the LNG facilities are predicted to be very low, with ground-level concentrations at all sensitive receptors predicted to be well below the air quality objectives. The most important substances in terms of their percentage of the air quality objectives are acrolein and formaldehyde. Acrolein was predicted to be 2.6% of the 1-hour average objective and formaldehyde was predicted to be 3.1% of the 30-minute average objective for the highest predictions over a full year.

The maximum affected sensitive receptor varies for each averaging period, with short-term (30-minute average) concentrations highest at South End, longer-term (1-hour and 24-hour average) concentrations highest at Targinie, while annual average concentrations are highest at the Construction Camps.

Table C4 Predicted maximum cumulative ground-level concentrations (in µg/m³) of hydrocarbon species for the Arrow LNG Plant during routine operations

Location	1-3 Butadiene	Acetaldehyde	Acrolein	Benzene	Ethylbenzene	Formaldehyde		Toluene			Xylenes		Dioxins and Furans
	Annual Average	Maximum 1-hour 99.9th percentile	1-hour 99.9th percentile	Annual average	Maximum 1-hour 99.9th percentile	Maximum 30-minute	Maximum 24-hour average	30 minute	Maximum 24-hour average	Annual average	Maximum 24-hour average	Annual average	Maximum 1-hour 99.9th percentile
Gladstone [1]	0.0000007	0.008	0.001	0.00002	0.006	0.3	0.03	0.05	0.006	0.0002	0.003	0.0001	6.56 E-11
Tannum Sands [1]	0.000001	0.03	0.004	0.00004	0.02	3.4	0.2	0.6	0.03	0.0004	0.02	0.0002	1.41 E-11
Targinie [1]	0.000004	0.04	0.006	0.0001	0.03	1.2	0.1	0.2	0.03	0.001	0.01	0.0006	7.75 E-11
Yarwun [1]	0.000003	0.03	0.005	0.00008	0.03	2.0	0.2	0.4	0.03	0.0008	0.02	0.0004	7.28 E-11
Fishermans Landing [1]	0.000008	0.07	0.01	0.0002	0.05	2.2	0.3	0.4	0.05	0.002	0.03	0.001	4.45 E-11
South End [1]	0.000002	0.02	0.003	0.00006	0.02	1.2	0.08	0.2	0.02	0.0007	0.007	0.0003	4.35 E-11
Island receptors [1]	0.000003	0.02	0.004	0.00008	0.02	0.7	0.1	0.1	0.02	0.0009	0.01	0.0004	8.91 E-11
Construction camps [2]	0.000009	0.02	0.003	0.0002	0.02	1.0	0.09	0.2	0.02	0.003	0.008	0.001	6.35 E-11
Maximum % of guideline	0.001	0.2	2.6	0.008	0.0007	3.1	0.6	0.06	0.001	0.002	0.002	0.0005	4.5
Air quality objective	*2.4*	*42* [3]	*0.42* [3]	*10*	*8000* [3]	*110*	*54*	*1100*	*4100*	*410*	*1200*	*950*	*2.0 E-06* [3]

Table note:
[1] Cumulative ground-level concentrations, with scaling of predicted incremental ground-level concentrations by 3.4 to account for other LNG facilities.
[2] Ground-level concentrations at construction camps are incremental.
[3] DECCW impact assessment criteria is compared against the 99.9th percentile concentration.
No ambient background levels assessed.

C1.4 Ozone

The assessment of photochemical smog impacts has been conducted assuming 100% conversion of NO_2 to ozone. This is an extremely conservative assumption. Measurements of ozone in Gladstone indicate that ozone levels are generally very low, with only a few hours per year observed at concentrations slightly above the natural background.

The predicted highest contribution (99.9^{th} 1-hour average) of Arrow LNG to ambient concentrations of NO_2 at a distance of greater than ten kilometres from the site is 54 $\mu g/m^3$. Consequently, the predicted maximum incremental increase of ozone at this location is estimated to be 54 $\mu g/m^3$. Ozone is a secondary air pollutant that transforms via several photochemically catalysed reactions of NO_X and other volatile organic compounds over time during plume transport, with concentrations peaking approximately 10-15 km downwind.

Adding the maximum contribution due to the Arrow LNG facility at a distance greater than 10 kilometres from the facility to the maximum ozone concentration recorded at the Targinie monitoring station of 120 $\mu g/m^3$ results in a maximum ozone concentration of 174 $\mu g/m^3$, which is approximately 83% of the ambient air quality objective of 210 $\mu g/m^3$ for the 1-hour average.

The highly conservative approach to the assessment of potential ozone impacts has incorporated the observed highest (99.9^{th}) 1-hour average concentration in the region with a maximum in-plume concentration based on all NO_2 being photochemically oxidised to ozone. This approach has yielded a predicted ozone impact that is less than the ambient air quality objective and consequently does not require any further investigation using a more advanced chemical transformation model.

C1.5 Odour

The predicted 99.5^{th} percentile 1-hour average ground-level odour concentrations, for identified pollutants from the Arrow LNG Plant in isolation are presented in Table C5. Predicted concentrations of odorous compounds have been converted to odour units using their published odour threshold values. A conservative approach has been adopted to calculate their combined odour concentration by summing the odour concentrations of each compound at each sensitive receptor for comparison with the DERM odour guideline.

The findings indicate that the maximum odour impact for all compounds combined due to emissions from the Arrow LNG Plant is predicted to be 44% of the DERM odour guideline at the nearest sensitive receptor, the construction camps. The maximum odour impact at all other receptors due to emissions from the plant is predicted to be low and well below the DERM odour guideline.

Table C5 Predicted 99.5th percentile 1-hour average ground-level odour concentrations for identified odorous pollutants

Location	Acetaldehyde		Nitrogen dioxide		Formaldehyde		Toluene		Benzene		Sulfur dioxide		Total
	µg/m³	ou	µg/m³	ou	µg/m³	ou	µg/m³	ou	µg/m³	ou	µg/m³	ou	ou
Gladstone	0.005	0.000015	21.9	0.06	0.09	0.00008	0.02	0.0000028	0.002	0.00000026	31.8	0.0054	0.07
Tannum Sands	0.001	0.000003	4.0	0.01	0.02	0.00002	0.00	0.0000006	0.0003	0.00000006	5.1	0.0009	0.01
Targinie	0.01	0.000031	29.3	0.08	0.18	0.00017	0.03	0.0000057	0.003	0.00000053	41.1	0.007	0.09
Yarwun	0.003	0.000008	25.6	0.07	0.05	0.00004	0.01	0.0000015	0.0008	0.00000014	36.3	0.0062	0.08
Fishermans Landing	0.004	0.000013	19.4	0.05	0.08	0.00007	0.01	0.0000024	0.001	0.00000022	27.5	0.0047	0.06
South End	0.002	0.000006	10.7	0.03	0.04	0.00003	0.01	0.0000012	0.0006	0.00000011	13.7	0.0023	0.03
Island receptors	0.01	0.000015	39.9	0.11	0.09	0.00009	0.02	0.0000029	0.002	0.00000026	58.0	0.0098	0.12
Construction camps	0.01	0.000034	76.8	0.22	0.20	0.00019	0.04	0.0000063	0.003	0.00000058	112.0	0.019	0.24
Odour threshold[1]	*339*	-	*355*	-	*1,072*	-	*5,888*	-	*12,023*	-	*1,862*	-	-

Table note:
Odour threshold in micrograms per cubic metre is equivalent to one odour unit
Odour threshold source (Devos, M. et al, 1990. Standardised Human Olfactory Thresholds, Oxford University Press)
DERM odour guideline 0.5 ou for 1-hour average, 99.5th percentile

C2 Non-routine Operations

This section summarises the results for the non-routine flare operations at the Arrow LNG Plant. This scenario comprises emissions from the routine operations plus the operation of the cold dry flare under the worst case plant upset or emergency conditions where a LNG train is depressurised with feed gas disposed of through combustion at the flare. This assessment scenario is a highly conservative worst case flaring scenario due to the very low probability of occurrence. In addition to this, the gas turbine emissions during routine operations of the LNG train being depressurised, have also been included, which is an unrealistic scenario as the gas turbines will not operate while a train is being depressurised.

As this is a short-term operating scenario annual averages have not been assessed. It should also be noted that particulate emissions are not expected from the flares.

C2.1 Carbon Monoxide

The predicted maximum 8-hour average ground-level concentrations of CO for the Arrow LNG Plant in isolation and with background at sensitive receptors are presented in Table C6.

Table C6 Predicted maximum 8-hour average ground-level concentrations (in µg/m^3) of carbon monoxide for the Arrow LNG Plant under non-routine operations at 100% load

Sensitive receptor area	Arrow LNG Plant in isolation	Arrow LNG Plant with background
Gladstone	133	491
Tannum Sands	28	134
Targinie	349	1225
Yarwun	72	282
Fishermans Landing	110	413
South End	166	603
Island receptors	97	368
Construction camps	237	276
Maximum % of air quality objective	3.2%	11.1%
Air quality objective	11,000	
Table note: Cumulative includes scaling of predicted incremental ground-level concentrations by 3.4 to account for other LNG facilities plus the addition of ambient background levels representative of receptor location. Construction camps include incremental plus ambient background levels only.		

The results indicate that the predicted maximum 8-hour average concentrations of CO from the plant at sensitive receptor areas are very low and well below the Air EPP objectives.

C2.2 Hydrocarbons

The predicted maximum incremental ground-level concentrations of all hydrocarbons at all sensitive receptor areas are presented in Table C7. The assessment indicates that predicted ground-level concentrations of hydrocarbons associated with emissions from the Arrow LNG Plant during upset conditions are predicted to be very low, with ground-level concentrations at all sensitive receptors predicted to be well below the Air EPP objectives.

Table C7 Predicted maximum incremental 1-hour average ground-level concentrations (in µg/m³) of hydrocarbon species for the Arrow LNG Plant in isolation during non-routine operations

Sensitive receptor areas	Methane	Ethane	Acetylene	Propane	Propylene
Gladstone	0.1	0.02	0.01	0.02	0.07
Tannum Sands	0.04	0.006	0.004	0.005	0.02
Targinie	5.6	0.8	0.5	0.7	2.5
Yarwun	0.06	0.009	0.006	0.008	0.03
Fishermans Landing	0.2	0.02	0.02	0.02	0.08
South End	0.03	0.004	0.002	0.003	0.01
Island receptors	0.04	0.006	0.004	0.005	0.02
Construction camps	0.06	0.009	0.006	0.008	0.03
Maximum % of guideline	n/a	0.007	0.002	0.004	0.03
Air quality objective	n/a	12,000	26,600	18,000	8,750

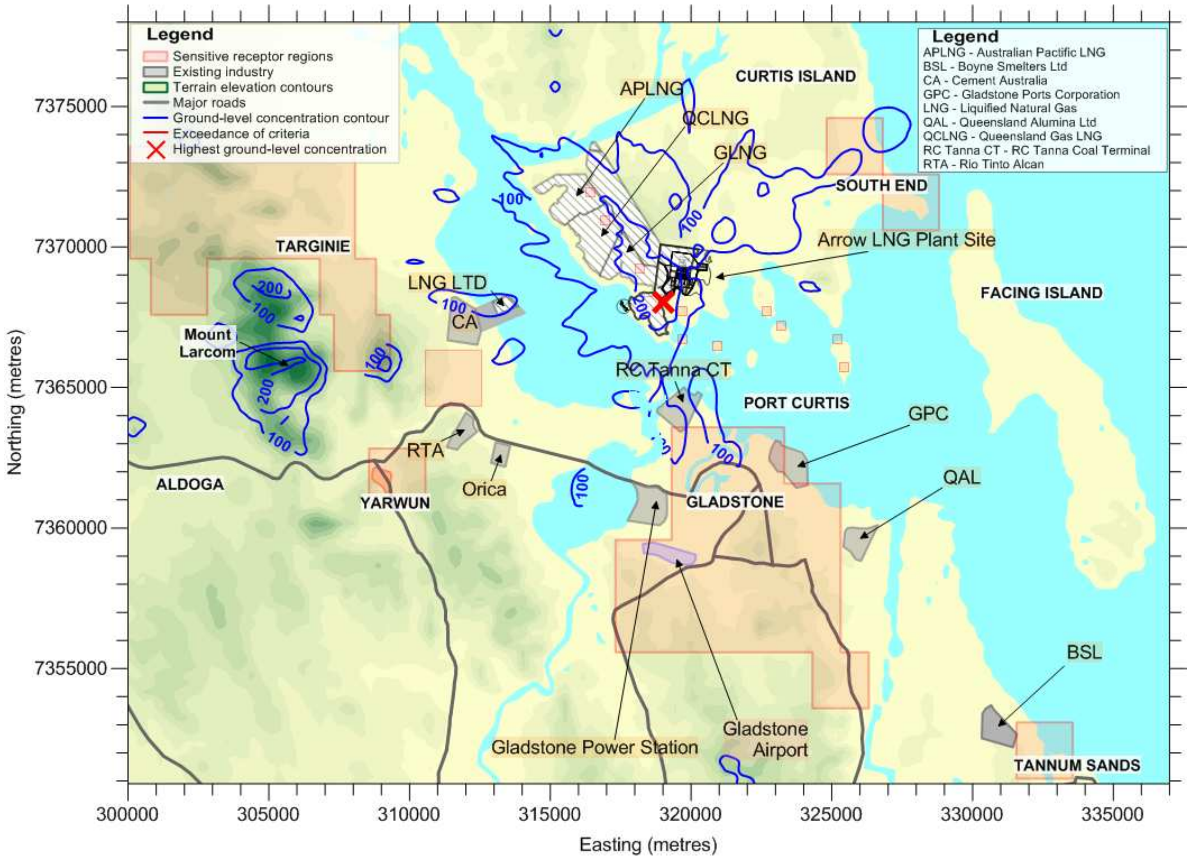

Figure C1	**Predicted maximum 8-hour average ground-level concentrations of carbon monoxide for the Arrow LNG Plant during routine operations at 100% load**

Location:	**Averaging period:**	**Data source:**	**Units:**
Arrow LNG Plant, Gladstone	8-hour	GAMSv3	µg/m³
Type: CO contour plot	**Air quality objective:** Health and wellbeing: 11,000 µg/m³	**Prepared by:** A. Vernon, S. Menzel	**Date:** June 2011

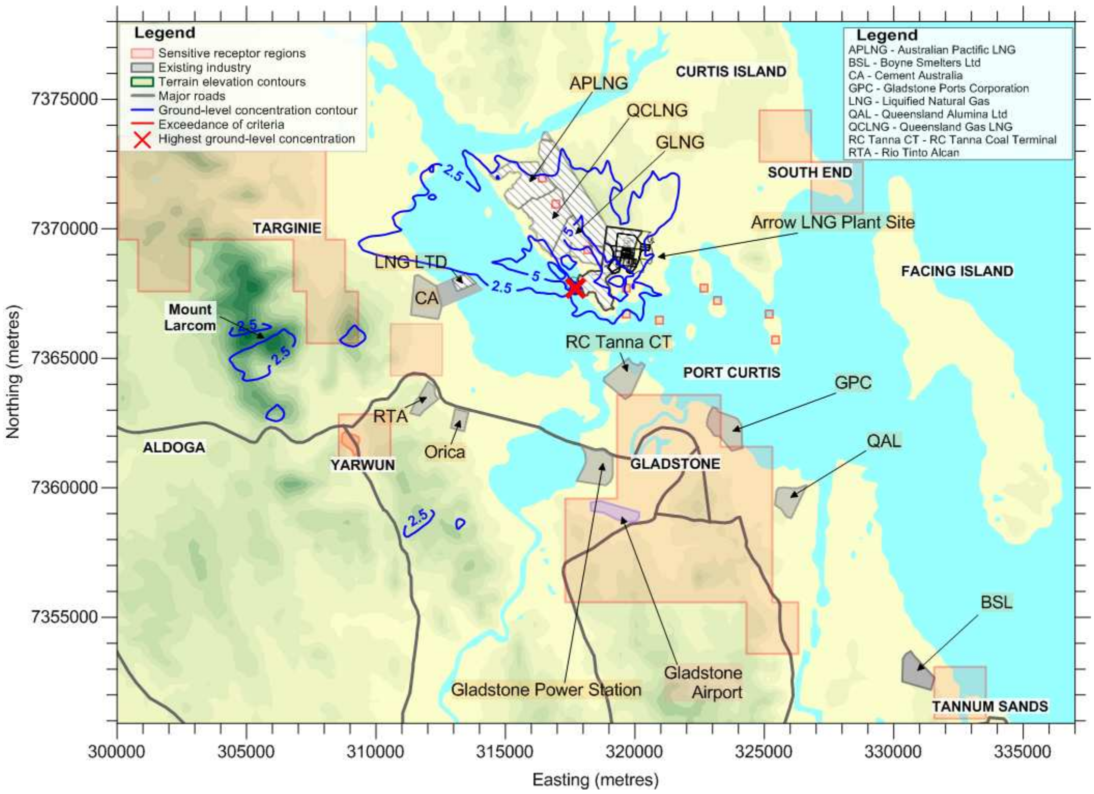

Figure C2 **Predicted maximum 24-hour average ground-level concentrations of PM_{10} for the Arrow LNG Plant during routine operations**

Location: Arrow LNG project, Gladstone	**Averaging period:** 24-hour	**Data source:** GAMSv3	**Units:** µg/m³
Type: PM_{10} maximum 24-hour average contour plot	**Air quality objective:** Health and wellbeing: 50 µg/m³	**Prepared by:** A. Vernon, S. Menzel	**Date:** June 2011

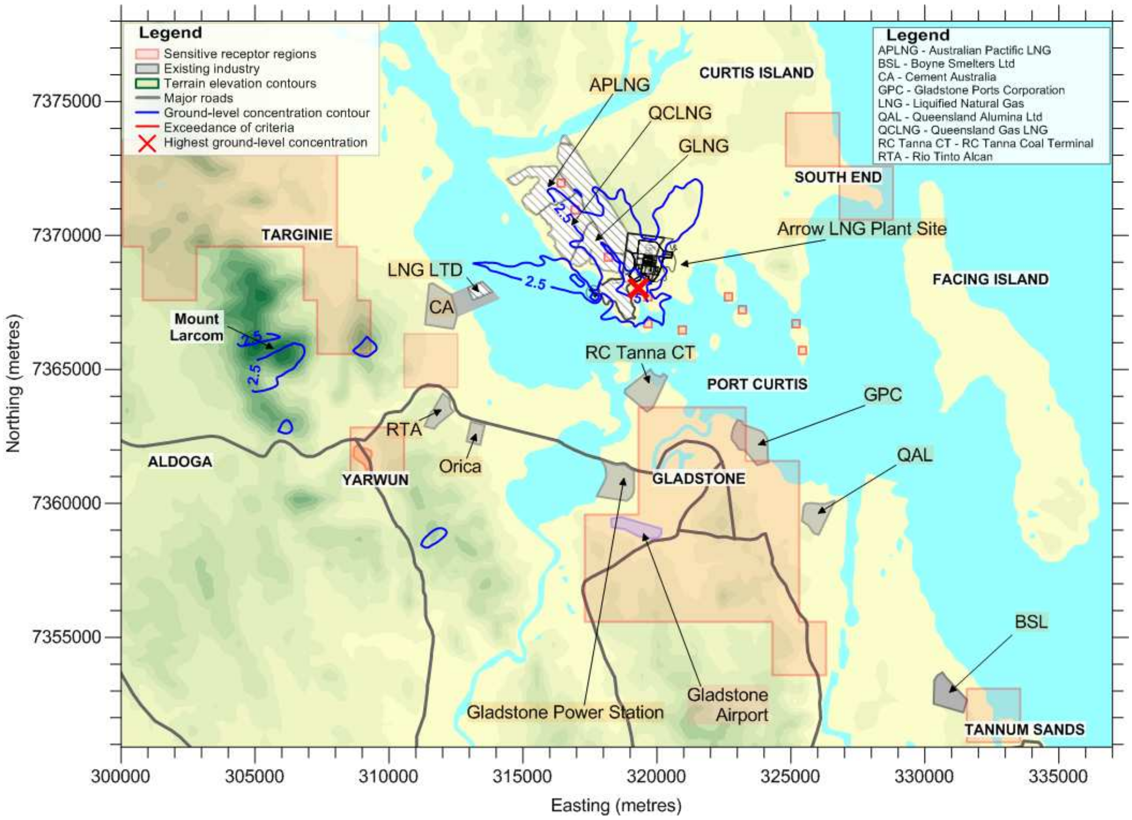

Figure C3	**Predicted maximum 24-hour average ground-level concentrations of $PM_{2.5}$ for the Arrow LNG Plant during routine operations**		
Location: Arrow LNG Plant, Gladstone	**Averaging period:** 24-hour	**Data source:** GAMSv3	**Units:** µg/m³
Type: $PM_{2.5}$ maximum 24-hour average contour plot	**Air quality objective:** Health and wellbeing: 25 µg/m³	**Prepared by:** A. Vernon, S. Menzel	**Date:** June 2011

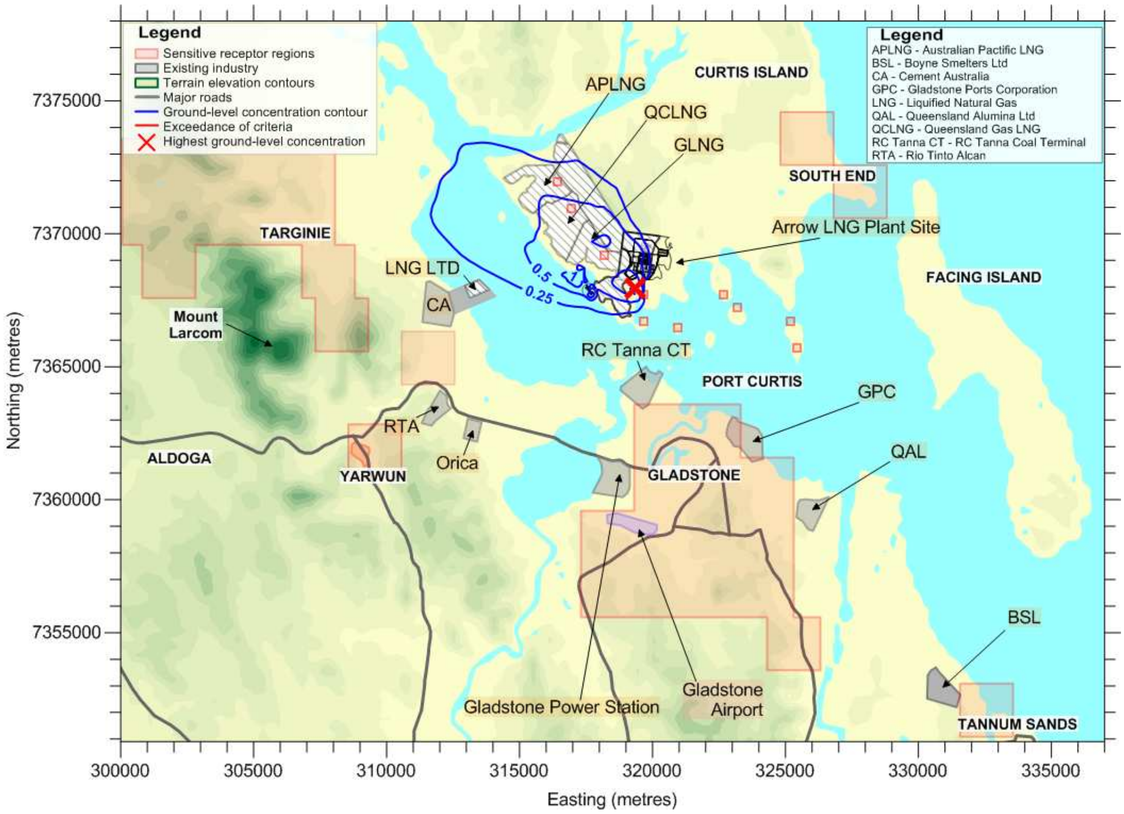

Figure C4 Predicted annual average ground-level concentrations of $PM_{2.5}$ for the Arrow LNG Plant during routine operations

Location: Arrow LNG Plant, Gladstone	**Averaging period:** Annual	**Data source:** GAMSv3	**Units:** µg/m³
Type: $PM_{2.5}$ contour plot	**Air quality objective:** Health and wellbeing: 8 µg/m³	**Prepared by:** A. Vernon, S. Menzel	**Date:** June 2011