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Identification and screening of air pollutant emissions from coal seam gas (CSG) activity in the Surat Basin, Queensland.

A Component of GISERA Project H.2

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Contents

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This report was supported by the Gas Industry Social and Environmental Research Alliance (GISERA). GISERA is a collaboration between CSIRO, Commonwealth and state governments and industry, established to undertake publicly-reported independent research. The purpose of GISERA is to provide quality-assured scientific research and information to communities living in gas development regions, with a focus on social and environmental topics including: groundwater and surface water, biodiversity, land management, the marine environment, and socio-economic impacts. The governance structure for GISERA is designed to provide for and protect research independence and transparency of research. Visit gisera.org.au for more information about GISERA's governance structure, projects and research findings.

We wish to acknowledge local stakeholder reference group participants for their time and providing valuable insights for the project, and Jennifer Powell, Melita Keywood and Cameron from CSIRO for providing valuable comments on this report.

Glossary

ha	hectare, unit of area equal to 10 000 m2, or approximately 2.47 acres. There are 100 hectares in one square kilometre.
µg m^{-3}	micrograms per cubic metre (1 microgram = one millionth of a gram)
ng m^{-3}	nanograms per cubic metre (1 nanogram = 1 billionth of a gram)
ppm	parts per million by volume
ppb	parts per billion by volume
l min^{-1}	litres per minute
ml min^{-1}	millilitres per minute
Bqm^{-3}	Becquerel per cubic metre, a unit of radioactivity
µm	micrometre (1 micrometre = 1 millionth of a metre)

Aldehydes & ketones	Classes of oxygenated volatile organic compounds
Ambient air	the outdoor air environment, excludes the air inside structures and buildings.
BTEX	Benzene, toluene, ethylbenzene, xylenes (a subset of VOCs)
CPP	Central processing plant. A CSG industry facility complex where Gas and produced water are processed.
Coal Seam Gas (CSG)	A type of natural gas, composed primarily of methane, extracted from coal seams
Detection limit	The lowest reliably measurable concentration of a pollutant for a particular analytical technique
Flowback	Following hydraulic fracturing, the target coal seams which have become pressurised, may be allowed to depressurise by opening a discharge valve on the wellhead, which allows the well to flowback fluid to surface.

Gas processing facility (GPF)	A facility which cleans, compresses, and dries gas
Hydraulic Fracturing (HF)	A well stimulation process that is used to increase the flow of gas and water from a gas well. HF involves the high-pressure injection of a large volume of fluids into a well to fracture targeted coal seams and open pathways for gas and fluids to flow into the well.
Hydraulic Fracturing Fluids	HF fluids, predominantly water and proppant (~ 97 - 98%) with a small amount of chemical additives, injected into wells at high pressure to fracture the coal seam.
PM_{10}	Particulate matter with an aerodynamic diameter ≤ 10 µm
$PM_{2.5}$	Particulate matter with an aerodynamic diameter ≤ 2.5 µm
Proppants	Solids, usually sand/silica, treated sand or manufactured ceramic material, added to hydraulic fracturing fluids in order to prop open the fractures in the target coal seam induced by the hydraulic fracturing treatment.
Geogenic	Of geological origin
GISERA	Gas Industry Social and Environmental Research Alliance https://gisera.csiro.au/
TSP	Total Suspended Particulates
Tracer	A gas or particle measurement used as a proxy for other atmospheric constituents not directly measured or used to indicate the likely impact of a specific pollution source.
VOCs	Volatile Organic Compounds. A wide range of organic chemical compounds which readily form vapours.

Executive Summary

The Surat Basin in Queensland has been the centre of rapid expansion in coal seam gas (CSG) development over the last 15 years and this rapid growth has raised community concerns about the potential impact of CSG industry on human health. In response to this concern a Health Study has been commissioned to investigate these impacts (Huddlestone-Holmes et al., 2020).

The site selected for the Health Study is situated in the in the Surat Basin and comprises an area of 2,150 square kilometres in the Miles, Chinchilla, Condamine region. This rural region hosts a variety of industries in addition to agricultural activities, and is home to ~ 45 000 people, the majority of whom reside in the Chinchilla area. The region is an area of intensive coal seam gas production and processing, with large scale associated infrastructure including > 2400 wells, ~4600 km of gathering pipelines, 8 Central processing plants (CPPS) and 35 flares. Sources of air emissions are present all along the process chain from well pads to central processing facilities to export pipelines. It is important to note that the Health Study location is situated within a wider region of very intensive coal seam gas development and CSG industry emissions that occur outside the boundary of the Health Study location also impact the ambient air the community is exposed to in the study region.

This report provides an appraisal of the available information on sources of air emissions from CSG activities in the defined study area. The composition of those emissions, and the pathways by which the community may be exposed to these air pollutants are described. The CSG industry is a source of potentially hazardous emissions to air of:

- nitrogen oxides (NO_x),
- carbon monoxide (CO),
- particulate matter (PM_{10} and $PM_{2.5}$)
- volatile and semi-volatile organic compounds (VOC)
- ozone (O_3)– secondary production from emissions of NO_x and VOCs
- inorganic gases - including hydrogen sulfide, radon and mercury

The information presented demonstrates that the substances listed satisfy the criteria for progression to subsequent stages of the health study framework comprising Screening and Further Assessment Stages of the Health Study Framework (Keywood et al.,2018) developed to assess the health impacts of CSG gas activities since

- these substances have known impacts on human health, as evidenced by the existence of legislated ambient air quality objectives (NEPC 2011, 2021), national emissions reporting requirements (NEPC 2008) and other national and state-based guidelines for the environmental levels of these substances.
- these substances are highly mobile and persistent enough in the environment to ensure plausible pathways of community exposure via inhalation pose a realistic hazard.

The available information on observation and modelling studies of the ambient air quality in the study region in relation to the identified substances was examined and includes extensive data collected in gas-field and community locations in the study region over the period 2012 – 2019. This data will provide key input into the **Screening and Further Assessment Stages** of the Health Study Framework (Keywood et al.,2018).

Analysis of extensive monitoring data from the study region found air quality in relation to NO_x, CO , VOCs and hydrogen sulfide were always well within relevant health-based air quality objectives (Lawson et al., 2018 a,b,c; Dunne et al., 2018, 2020; DES, 2020; DSITIA 2013; DSITI 2015, 2016). Analysis of the O_3 monitoring data from the study region found levels were occasionally close to (>80%) the NEPM air quality objectives, however, modelling studies indicated, that during these peak events, CSG-related emissions contributed 3 – 7 % to the total O_3 concentration (Noonan et al., 2019). Occasional exceedances of $PM_{2.5}$ air quality objectives were observed in monitoring data from the study region. Modelling studies indicated, that during these peak events, CSG-related emissions contributed at most 4 - 37 % to 24-hour $PM_{2.5}$ concentrations (Noonan et al., 2019) and analysis of satellite data and other trace species in the monitoring studies were used to show that high $PM_{2.5}$ events were typically associated with smoke from local and regional fires (Lawson et al., 2018 a,b,c, Dunne et al., 2020).

Airborne particulate matter as PM_{10} and TSP was the most common cause of observed exceedances of National and Queensland state air quality objectives reported in monitoring studies in the Surat Basin and in most cases were attributable to fugitive soil dust emissions from CSG industry activities including vehicle moments, construction, etc (Lawson et al., 2018 a,b,c, Dunne et al., 2020) plus contributions from smoke and other rural activities that re-entrain dust. It is a requirement of Queensland Government Environmental Authority conditions that companies do not cause environmental nuisance from dust at a sensitive place (e.g., residences, community buildings, public parks etc) unless a formally agreed alternative arrangement is in place. Environmental authorities also often include specified monitoring requirements for releases to air for the company to demonstrate they are complying with their EA requirements. More about reporting an environmental nuisance caused by dust can be found here.

Radon and mercury were both detected in analysis of CSG samples collected from wells in the study region, however only limited data exists on the ambient levels of radon and mercury for the study region. Observed ambient concentrations were always well below guidelines for households and workplaces (Tait et al., 2013, Dunne et al., 2020). Combined with more data on the composition of CSG over the lifetime of the CSG developments, the air emissions of mercury, radon, VOCs and H_2S via fugitive CSG releases could be inferred using previously determined estimates of fugitive methane emissions from the CSG industry in the region (Luhar et al., 2018, 2020).

A case-study of a real life CSG release event was used along with CSG composition data, to demonstrate the likely impact of an unintentional CSG release event on the airborne levels of contaminants such as VOCs, radon, mercury, and hydrogen sulfide that are found in CSG. The results of this analysis showed that, while the methane concentrations during this event were significantly elevated above background concentrations (~80 ppm) the low levels of these other gases in the CSG were estimated to have made only a minor contribution to ambient air pollutant concentrations, well below air quality objectives, once the CSG was diluted in ambient air.

Overall, the information summarised in this report provides a synthesis of the available information on the sources and occurrence of air pollutants associated with the CSG industry in the Health Study region and can be used to inform subsequent stages in the Health Study framework when determining priorities for exposure assessments and developing recommendations for more in-depth source analysis, monitoring and/or modelling studies.

1 Introduction

The Surat Basin in Queensland has been the centre of rapid expansion in coal seam gas (CSG) development over the last 15 years and this rapid growth has raised community concerns about the potential impact of CSG industry on human health. In response to this concern a Health Study has been commissioned to investigate these impacts (Huddlestone-Holmes et al., 2020).

1.1 Health study design **Framework**

A health study design **Framework** to assess the health impacts of CSG gas activities was developed and reported in 2018 as part of GISERA Project H.1 (Keywood et al., 2018). The Framework based on health impact assessment, proceeds via 5 stages:

1. A **scoping** and planning stage defines the overall project structure and strategies for involving stakeholders, communicating findings, and meeting all ethics requirements. A major aim of this stage is to establish processes and governance that will support the legitimacy and quality of the research. The research objectives and project team are established in this stage.

2. The **identification** stage establishes the potential sources of chemical and physical hazards (chemicals in air, water, and soil, plus noise and light) and other stressors, such as social stressors, and the pathways by which the community may be exposed to the hazards. This is done by developing a site-specific conceptual model of hazard and risk identification. At the end of this stage a decision is made about whether a chemical or physical hazard poses a health risk and whether further screening and assessment is required.

3. The **screening** stage involves the collection of all existing data (physical, chemical, social and health) and establishes the quality of existing data sets. Gaps in data are identified and new data may be collected if required to understand key exposure and health factors for the study location.

4. The **further assessment** stage involves in-depth exposure and risk assessments, as well as health outcome assessments. This stage addresses any gaps for relevant chemical and physical stressors. A health needs assessment approach would be used to further investigate and mitigate social stressors.

5. The final **recommendations** stage integrates findings, draws conclusions, and makes recommendations including any need for ongoing monitoring.

The report presented here is part of a program of work in the Health Impact Assessment - GISERA Project H.2 'Potential Health Impacts of CSG' (https://gisera.csiro.au/project/potential-health-impacts-from-csg/) which aims to identify potential chemical and physical hazards and exposure pathways in a defined CSG development area, and assess the quality and completeness of existing data. This report contributes information for Stage 2 and Stage 3 of the Framework. Potentially hazardous factors will be prioritised for further in-depth assessment as part of the project and progressed through Stages 4 and 5 of the Framework.

This report provides an appraisal of potential sources of chemical factors emitted to air from CSG activities in the defined study area, and the pathways by which the community may be exposed to these air pollutants are described. A summary of the available information on the occurrence of air pollutants in the Surat Basin is provided, and levels of pollutants are compared with relevant state, national and international air quality objectives. This information will contribute to the identification and screening stage of the Health Study.

1.2 Air Emissions Appraisal Methodology

The appraisal methodology proceeded as follows:

- **Identify** potential **sources** of emissions to air from CSG activities in the study region (Sections 2)
- **Identify** and describe plausible **pathways** by which the community may be exposed to air emissions from CSG activities in the study region (Section 3)
- **Identify** available source composition data and information to identify potential **hazardous** air pollutants present in CSG industry emissions. (Section 4)
- **Screen** and summarise available information on the occurrence of identified pollutants in ambient air in the study region (Sections 5 and 6).

1.3 Study Site

A detailed description has been developed for the study area in a separate companion report with some relevant details summarised here. The reader is directed to Huddlestone-Holmes (2021) for further detail. The site selected in the Surat Basin for this study is centred on the area of earliest coal seam gas development and comprises an area of 2,150 km^2 in the Miles, Chinchilla, Condamine region. This rural region hosts a variety of industries in addition to agricultural activities, and is home to ~ 45 000 people, the majority of whom reside in the Chinchilla area. The region is an area of significant coal seam gas production and processing, with large scale associated infrastructure including > 2400 wells, ~4600 km of gathering pipelines (water + gas), 8 Central processing plants (CPPs) and 35 flares. The key components of a typical CSG development in Queensland are shown in Figure 1, and sources of air emissions are present all along the production & processing chain from well pads to central processing facilities to export pipelines. It is important to note that the defined Health Study area is situated within a wider region of intensive coal seam gas development that also may influence air quality across the region.

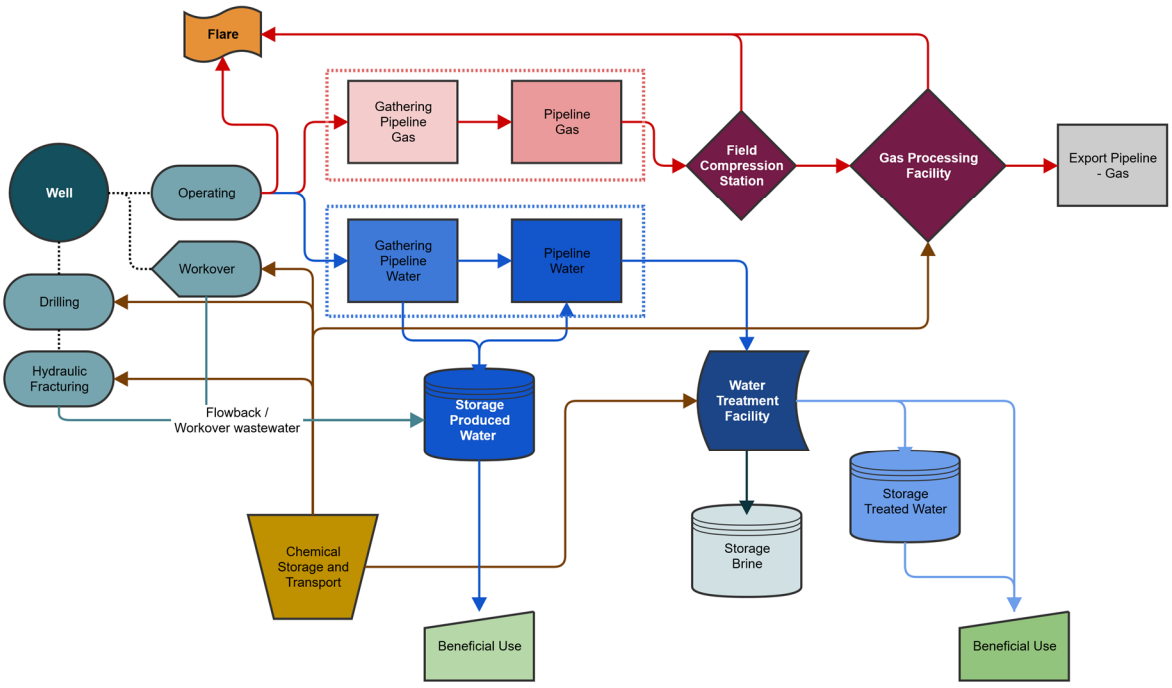


Figure 1 : Key components of a typical CSG development in Queensland (note that less than 10% of CSG wells in the Surat Basin have been hydraulically fractured).

1.4 Limitations and Assumptions

The information presented here is not designed to assess actual human exposure to chemical or physical factors. The purpose of this report is to identify potential CSG industry air emissions that have a plausible pathway to community exposure via inhalation and to provide a synthesis on the available information on the occurrence of air pollutants in ambient air for the study region.

Potential exposure via deposition of air pollutants to surface materials then ingestion via food web was not assessed here. Potential emissions from breakdown products of drilling and hydraulic fracturing fluids, or emissions to air of geogenic contaminants from produced water were not assessed here.

The information provided in this report is intended for use inform the next stage of research which will prioritise factors that have plausible pathway for potential impact on human health. This allows for the most cost-effective and targeted use of research resources by ruling out factors of no concern to focus on fewer factors with a plausible pathway for potential impact on human health.

This report has utilised industry data that was collected in a variety of ways and in many cases was not designed for health study purposes. The industry data reported here reflects the data that was available or that was able to be obtained in a suitable format within the timeframe of the study. Differences between datasets and data collection and reporting techniques presented further challenges.

The selected location of the Health Study is an area of intensive coal seam gas production and processing, with large scale CSG infrastructure and associated air emissions occurring within the

study domain. However, it is important to note that the Health Study location is situated within a wider region of very intensive coal seam gas development and CSG industry emissions that occur outside the boundary of the Health Study location also impact the ambient air quality the community is exposed to within the study domain.

The data on air pollutant concentrations in the study region were compared with current relevant air quality guidelines which are subject to change as new information on health impacts of air pollutants becomes available, and the data in this report may be revisited as new health guidelines are developed.

2 Identification - CSG industry emissions

Here we provide a summary of the available information on the sources and nature of the emissions to air from the CSG industry in the study region. This information includes regulatory reporting data, emissions inventories developed for air quality modelling studies and environmental impact statements, as well as data from emission monitoring at CSG infrastructure in the study region.

2.1 National Pollutant Inventory

Air pollutant monitoring and reporting activities are typically undertaken via national and state regulatory authorities, and legislated health-based objectives. National, state and territory governments have agreed to the National Environment Protection Measures (NEPM) legislation, which are designed to protect human health and the environment. Under the National Environment Protection (National Pollutant Inventory) Measure (2008) Australian industries are required to report any emissions for 93 substances, identified due to their known effects on human health and the environment if they exceed defined thresholds. Data are made publicly available via the NPI website (http://www.npi.gov.au/about-npi).

Two CSG companies, APLNG and QGC, operate 6 CSG facilities in the health study area that report substance emissions data to the NPI, and these are listed in Table 1.

Table 1 CSG Facilities in the health study region that report their annual emissions to the National Pollutants Inventory (NPI).

Facility Name	Annual NPI Reports for this facility
APLNG Pty Ltd, Origin LNG Pipelines (Miles)	2014/15 – 2019/20
APLNG Pty Ltd, Condabri	2011/12 – 2019/20
APLNG Pty Ltd, Talinga	2001/02 – 2019/20
QGC Pty Ltd, Bellevue CPP	2013/14 – 2019/20
QGC Pty Ltd, Windibri CPP	2007/08 – 2019/20
QGC Pty Ltd, Kenya CPP	2009/10 – 2019/20

The NPI reported emissions data from CSG facilities typically includes wells, field compressor stations and central processing plants. While a given address/coordinate is associated with each reporting facility the actual emissions are spread amongst that infrastructure. To provide an indication of the nature and scale of the NPI reported emissions, the total air emissions reported for 2019/20 for the 6 CSG facilities in Health Study region are presented in Figure 2.

As shown in Figure 2, the largest emissions were for oxides of nitrogen, CO , particulate matter, total volatile organic substances, and formaldehyde. Total VOCs (TVOC) are reported due to their role as precursors to photochemical smog (see Section 2.5) and are included as a group in NPI reporting to capture the potential combined effect of compounds to smog formation that may not otherwise have been captured due to individual VOCs not meeting reporting thresholds. As such TVOCs are defined as "any organic compound that participates in atmospheric photochemical reactions" (NPI 2009). Specifically excluded are CO , methane, acrylamide, hexachlorobenzene, biphenyl, chlorophenols, n-dibutyl phthalate, ethylene glycol, di-(2-ethylhexyl) phthalate (DEHP), 4,4-methylene bis 2,4 aniline (MOCA), Methylenebis, Phenol; and toluene-2,4-diisocyanate.

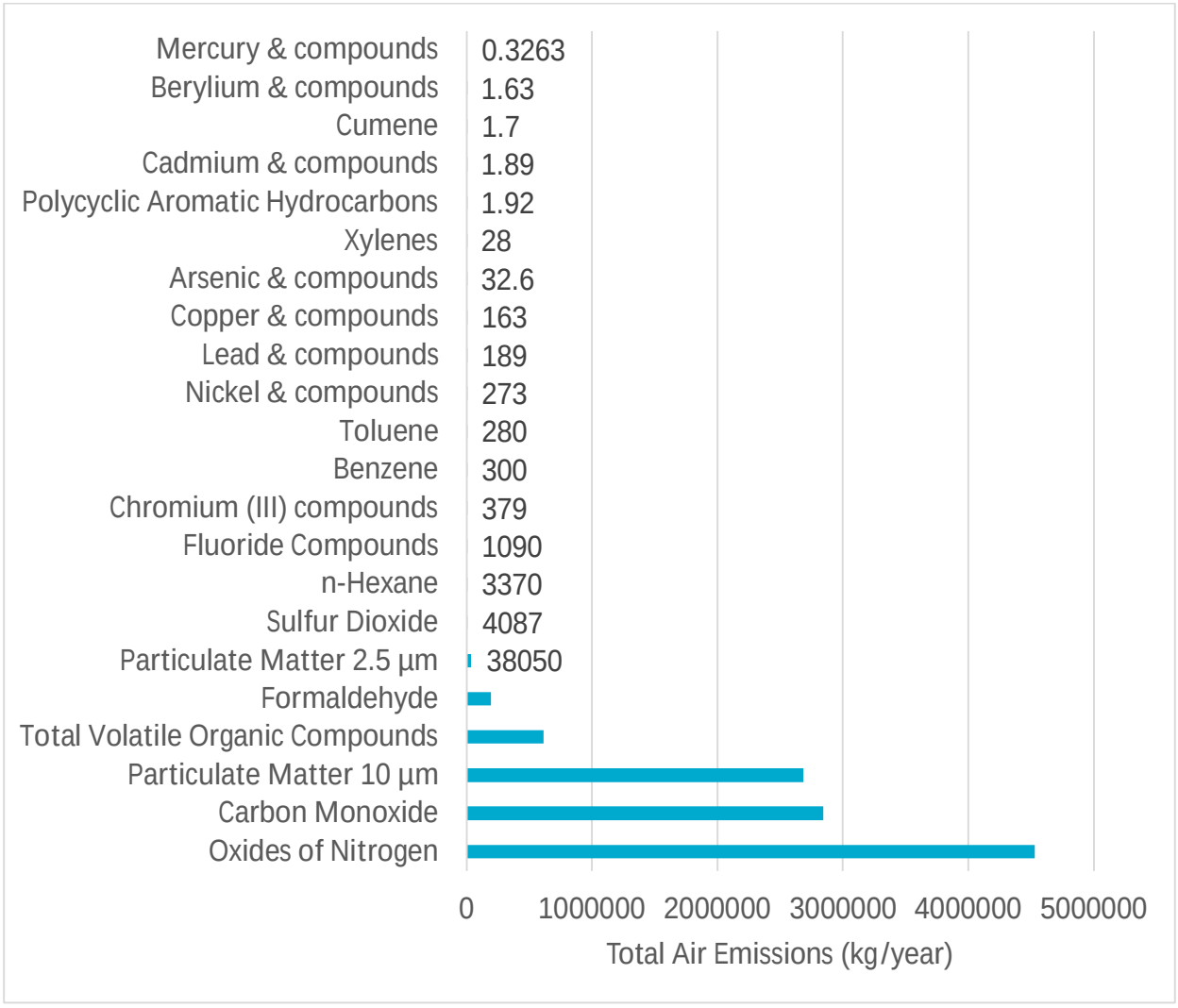


Figure 2 : Total annual air emissions for the year 2019/20 reported to the NPI from 6 CSG facilities in the health study region. Note: For the purpose of NPI reporting, Total VOC are defined as any chemical compound based on carbon chains or rings with a vapour pressure greater than 0.01 kPa at 293.15 K (i.e., 20°C), that participate in atmospheric photochemical reactions (Source: http://www.npi.gov.au/resource/total-volatile-organic-compounds).

The CSG facility emissions reported to the NPI change over the lifetime of CSG development in the region (Figure 3), as the industry has expanded and shifted from construction into operational phase. Note, changes in reported emissions can also be due to updated emission calculation

techniques, first time reporting of a substance, or changes in facility environmental performance / pollution control.

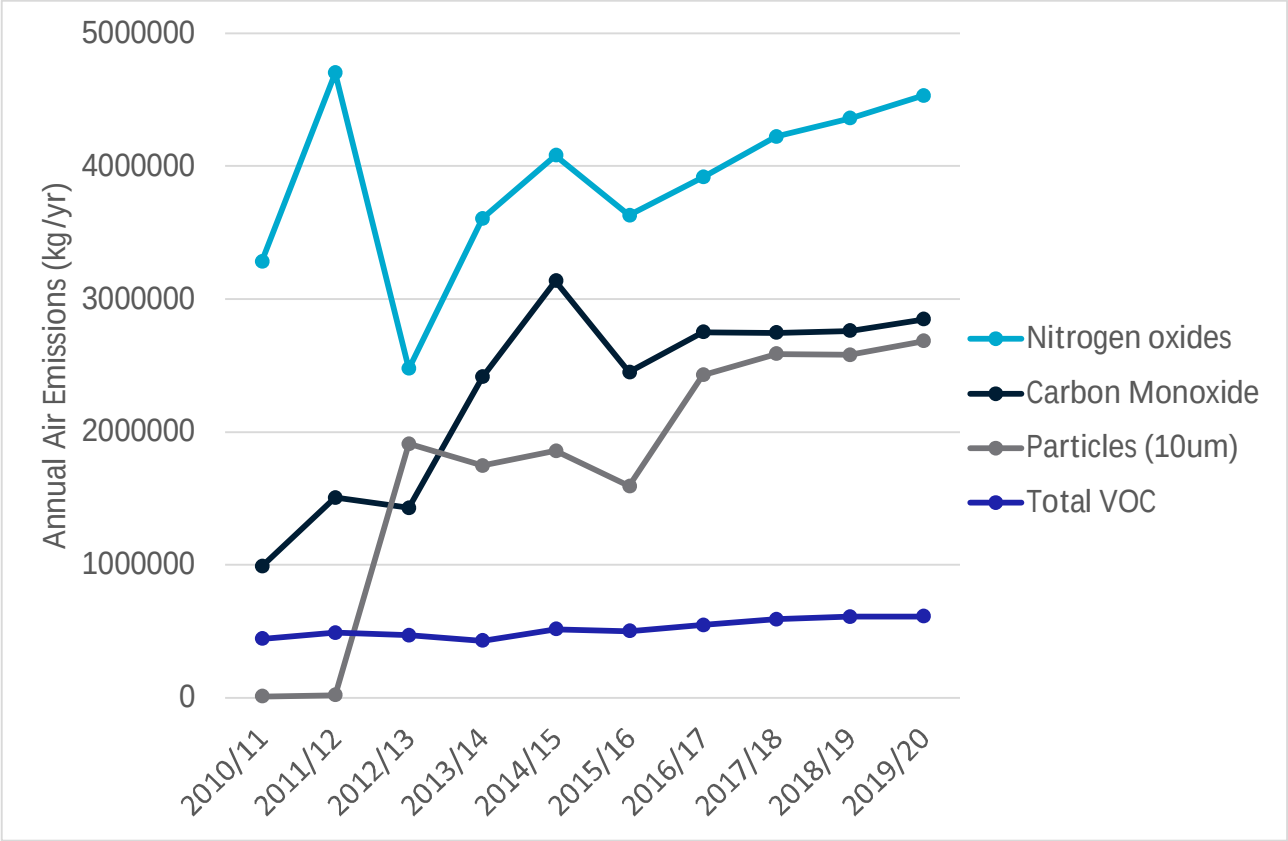


Figure 3: Total annual NPI reported emissions of four key air pollutants from the 6 CSG facilities in the study region. Source: npi.gov.au

2.2 Air quality modelling emission inventories

Detailed air emissions inventories were developed for the year September 2015 - August 2016 as part of a previous GISERA study *Modelling Ambient Air Quality in the Surat Basin, Queensland* (Noonan et al., 2019) which modelled the impact of CSG industry emissions on air quality for an area that encompasses the Health Study Region.

These CSG-related emissions were categorised as Production or Processing emissions and the inventory provides more detailed information on the sources of emissions. Production emissions related to the activities required to extract CSG from the ground and transport gas and water to processing facilities and included emissions from:

- Well pad microturbines / gas engines
- Well pad flares
- Well leaks & pneumatic valve releases
- High point vents
- Mobile Engines
- Wheel Generated Dust

Sources of air emissions associated with processing raw CSG to produce saleable natural gas include activities such as cleaning and drying of gas, compressing raw CSG at compressor stations, centralised processing plants and water treatment plants. Processing emissions included:

- Stack/gas consumption emissions
- CPP Flares
- Diesel consumption

Stack/gas consumption emissions include emissions from gas fired engines at CPPs used to drive gas compressors and generate electrical power and used in gas fired boilers that regenerate the tri-ethylene glycol used in the gas dehydration units.

For the CSG facilities in the modelling study domain, the emission rates were reported for CO , NO_x, sulfur dioxide (SO_2), particles ($PM_{2.5}$, PM_{10}, TSP), total volatile organic compounds (TVOC) and selected VOCs (Xylenes, Ethylbenzene, Toluene, Formaldehyde, Ethane, propane). The magnitude of CSG industry emissions from production and processing sources calculated for the modelling study period (Sept 2015 – Aug 2016) are shown in Figure 4 and Figure 5.

The emissions inventory developed for Noonan et al., (2019) estimates the largest air emissions are associated with combustion in both the production and processing phases and are dominated by emissions of NO_x, CO and VOCs. For further details on emissions inventory development methods the reader is directed to Noonan et al., (2019) here. The modelled impacts of the CSG industry on the levels of airborne pollutants in the Surat Basin will be discussed further in Sections 5 and 6).

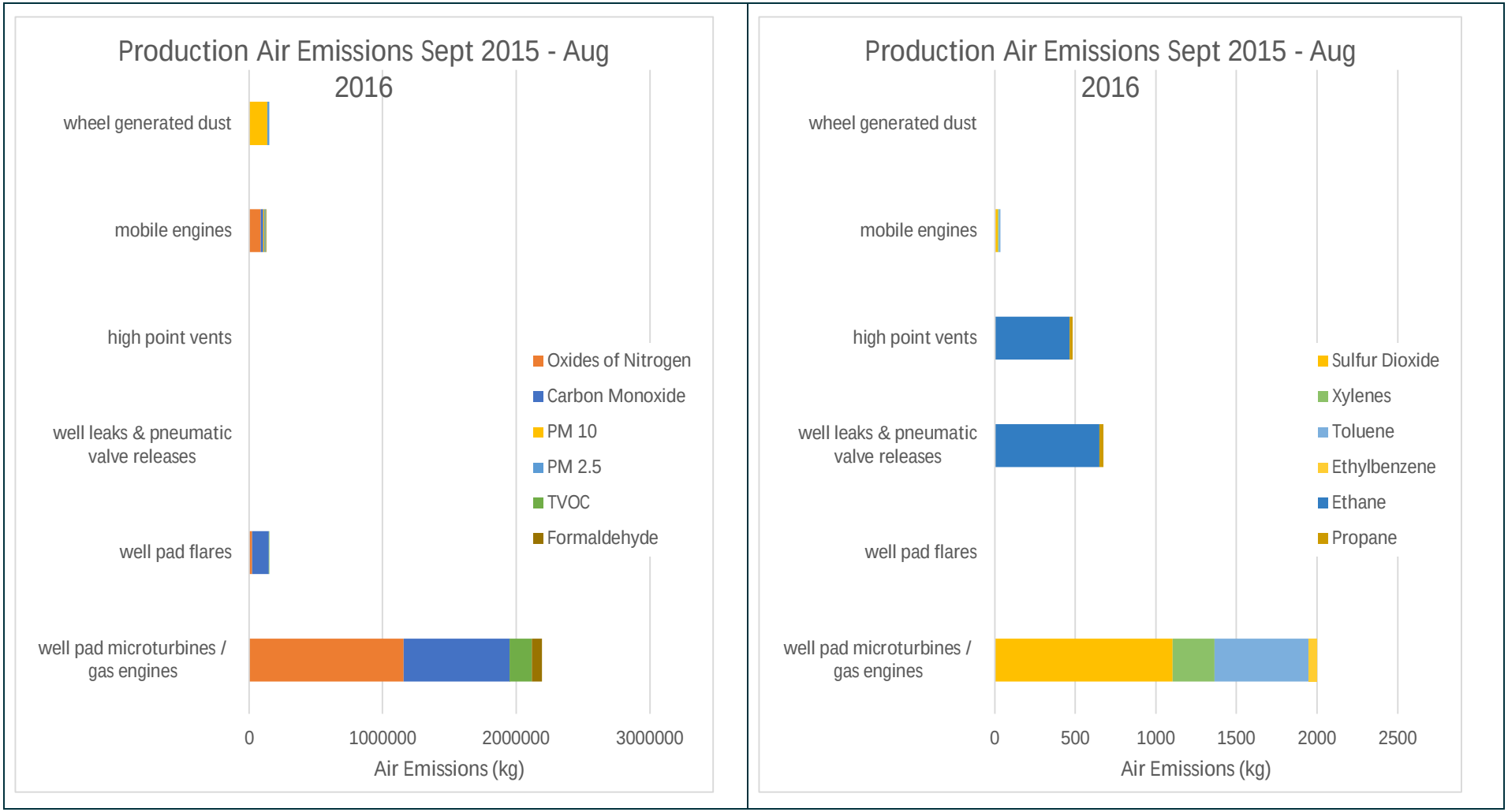


Figure 4: CSG Industry Production air emissions for 12 substances released from CSG facilities reported for the period Sept 2015 – Aug 2016 calculated for the GISERA study *Modelling Ambient Air Quality in the Surat Basin, Queensland* (Noonan et al., 2019).

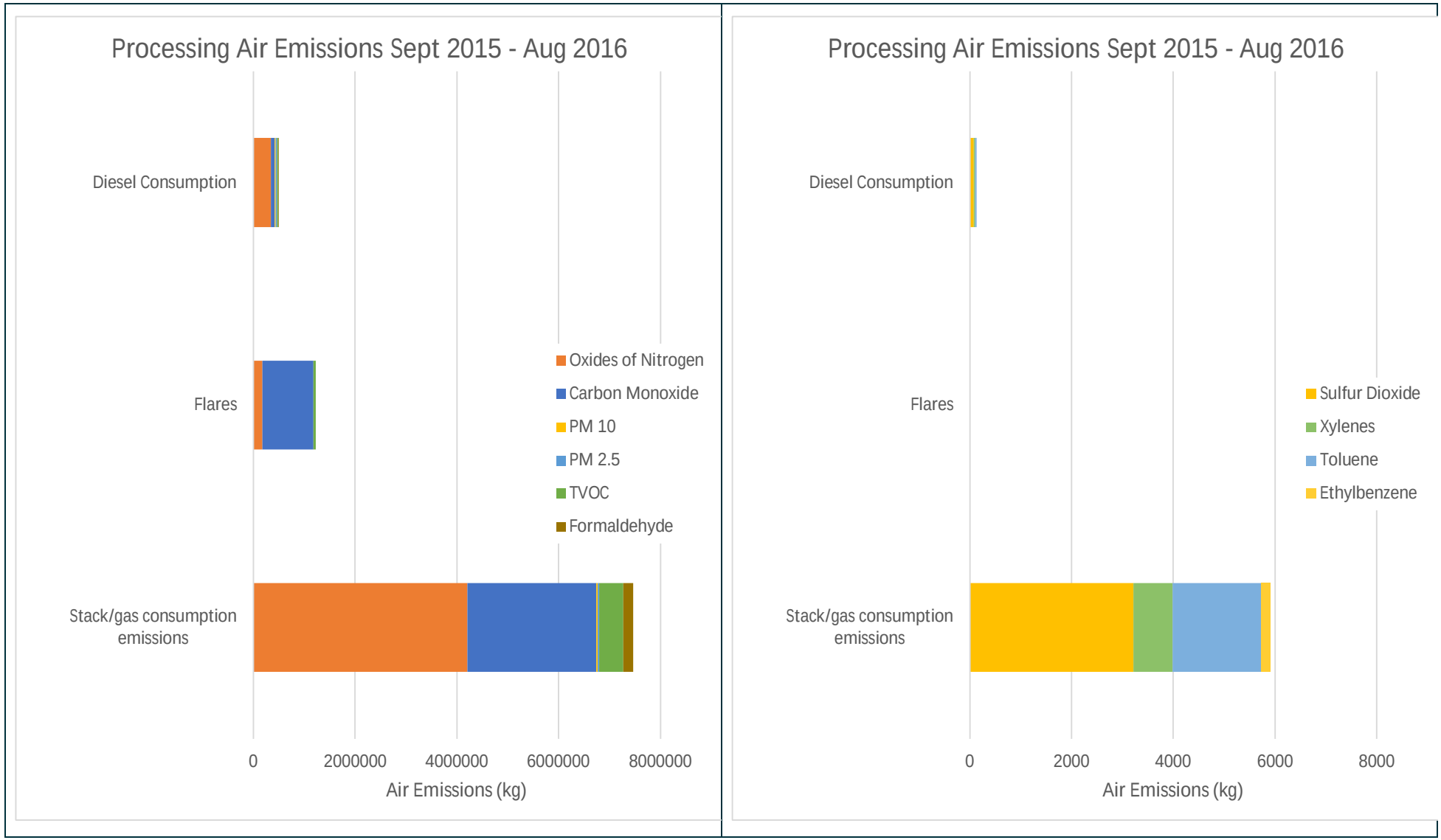


Figure 5: CSG Industry Processing air emissions for 10 substances released from CSG facilities reported for the period Sept 2015 – Aug 2016 calculated for the GISERA study *Modelling Ambient Air Quality in the Surat Basin, Queensland* (Noonan et al., 2019).

2.3 Environmental Impact Statements for CSG Developments

Environmental Impact Statements (EIS) for CSG developments provide information on the anticipated composition and magnitude of air emissions for the proposed facilities. An EIS is required as part of the application process for mining projects in Queensland. The EIS is a tool to assess the environment in the area of the project prior to development, the potential environmental, economic, and social impacts of the project, and proposed mitigation processes to reduce or offset the potential impacts. The EIS related to developments in the health study region are:

- QGC-BGI Group Surat Basin, Qld – https://www.shell.com.au/about-us/projects-and-locations/qgc/environment/environment-management-assessment.html
- APLNG Surat and Bowen Basin, Qld - https://www.aplng.com.au/content/origin-aplng/en/index/about-us/compliance/eis.html

Air Quality impacts were explicitly considered as part of the EIS process for both the APLNG and QGC proposed developments in the study region. The EIS air quality impact assessments included information on:

- Identification of potential sources of air emissions associated with the CSG development (i.e., activities, infrastructure)
- The likely composition and quantity of air emissions from the identified CSG development sources
- The ambient air quality values of the development areas that may be impacted by the proposed CSG projects
- Atmospheric dispersion modelling of predicted air emissions to provide estimates of the impact of CSG projects on ground level ambient air quality in the development areas
- Air quality impact assessment under typical operating conditions, as well as abnormal (worst case) operating conditions.
- Cumulative impacts of air emissions from the proposed CSG projects

In line with emissions inventory data reported in previous sections, the industry EIS identified 5 key air pollutants likely to be emitted from their CSG developments, with the largest releases to air associated with combustion emissions of NO_x, as well as significant quantities of, CO, sulphur dioxide, particulate matter with an aerodynamic diameter less than ten microns (PM_{10}), and hydrocarbons (a class of VOCs).

2.4 CSG Industry Emissions Monitoring Data for Gas Processing Facilities

As part of the design of the previous GISERA study of Ambient Air Quality in the Surat Basin (Lawson et al., 2017), data from emissions monitoring undertaken at Talinga gas processing facility were provided to CSIRO to assist in identifying target air pollutants for ambient monitoring. The

monitoring was performed using reference methods (Australian Standard, US EPA, NIOSH) undertaken by NATA certified laboratories engaged by APLNG/Origin Energy and CSIRO was supplied with the original consultant reports for these measurements.

At the time these monitoring data were collected in 2014-15 the Talinga GPF operated a series of gas-powered engines and screw compressors. It should be noted that several of the GPFs in the study area are powered by electricity rather than gas and so will have significantly lower emissions than the gas-powered Talinga engines and compressors.

Data were reported for oxides of nitrogen, CO, and a suite of VOC species including several aldehydes. The composition of emissions differed between engines types, but the largest concentrations detected in exhaust emissions were reported for NO_x (107 - 10805 mg /m^3), CO (149 - 4862 mg/m^3) and methane (445 - 513 mg m^3). More than 50 VOC species were reported to be present in one or more combustion emissions samples examined, with the largest emissions generally reported for aldehydes (formaldehyde, acrolein), aliphatic hydrocarbons (including ethane, ethene, propane, propene, butane, butene) and the aromatic hydrocarbons (including benzene, toluene and xylenes). A full list of the species measured, and the range of values reported is provided in Table A.1 in the Appendices to this report. The original monitoring reports are available publicly at: https://gisera.csiro.au/project/ambient-air-quality-in-the-surat-basin/.

2.5 Secondary atmospheric pollutants

As described in the previous section, airborne particles are emitted directly from CSG industry sources (e.g., gas combustion, diesel exhaust, dust). However, secondary particles can also be formed in the atmosphere from reactions of gas phase precursors such as ammonia, NO_x, SO_2 and VOCs. These secondary aerosol particles almost wholly occur in the fine particle size fraction measured as particles with diameters < 2.5 µm ($PM_{2.5}$).

Likewise, ground level O_3 is not directly emitted to the atmosphere but rather is formed through photochemical reactions between other pollutants in the atmosphere mainly VOCs and NO_x, with additional contributions from methane reaction products. Elevated O_3 concentrations have been associated with emissions from oil and gas developments in studies from multiple US states (Schnell et al, 2009, Martin et al, 2011, Gilman et al, 2013, Edwards et al, 2014, Ahmad & John 2015).

The secondary formation of fine particles and O_3 are the processes responsible for the formation of photochemical smog, prevalent in cities with large emissions of gaseous precursors and less prevalent in rural/regional areas. However, as discussed in previous sections, the CSG industry emits large quantities of NO_x and VOCs primarily from gas combustion, as well as significant quantities of methane, and is therefore a potential source of O_3 and secondary aerosol production in the study region. The available information on the ambient air levels of O_3 and PM2.5 in the study region will be discussed in Sections6and 7.

2.6 Composition of Fugitive CSG emissions

Fugitive CSG emissions result from planned or unplanned releases of coal seam gas to the atmosphere. During extraction of CSG, gas can be released at the well pad from: wellheads,

separators, control equipment; and, during well flowback, completions and workovers; and as a result of leaks. CSG is also intentionally released from gas/water gathering networks such as high point vents (HPVs) and low point drains (LPVs) and pipeline control equipment (Luhar et al., 2020, Day et al., 2017, DEEDI 2010). At processing facilities CSG can be released from control equipment, compressor venting, and gas conditioning units, and from produced water ponds (Lu et al., 2021, Luhar et al., 2020, Iverach et al., 2015, Day et al 2013).

The CSG infrastructure in the study area is targeting the Walloon coal measures. Coal Seam Gas (CSG) from the region is predominantly composed of methane (95 - 97%) with small amounts (~1 - 4%) of nitrogen (N_2), carbon dioxide (CO_2), and hydrocarbons always present. Minor to trace amounts of other organic and inorganic substances may also be present.

Information on the chemical composition of fugitive gas emissions of relevance to the study presented here are collated from three sources.

1) For the purposes of this study and previous GISERA studies APLNG/Origin Energy provided chemical composition analysis data from CSG samples collected in the study region, including:

- 133 CSG samples collected from 114 well heads from 3 well fields (Condabri, Orana, Talinga)
- 4 CSG samples collected at the inlet of 4 GPFs (Strathblane, Taloona, Talinga, Spring Gully)
- 6 CSG sales (processed) gas samples from 5 GPFs (Strathblane, Taloona, Talinga, Spring Gully, Peat)

The samples were collected between 2011 – 2016 and were undertaken by NATA certified laboratories engaged by APLNG. Data were provided in electronic format, with original analysis certificates available for a subset of 30 samples that were provided to CSIRO by the well operators Origin Energy for use in this and previous GISERA studies (e.g., Lawson et al., 2017) and are available publicly at: https://gisera.csiro.au/project/ambient-air-quality-in-the-surat-basin/.

2) QGC/Shell provided sales (processed) gas composition data as a flow weighted average for contribution of gas from all upstream fields, as measured at the Central Gas Processing Facilities using analysis methods which meet the National Greenhouse and Energy Reporting (NGER) Measurement Determination requirements for sampling and analysis of gas composition and flow. Quarterly/ monthly averaged composition data were reported for 4 chemical species- methane, CO_2, N_2, and ethane for the years 2017 - 2019. These reported substances are not considered air pollutants at typical ambient levels and so this data is of limited relevance to the study presented here.

3) Day et al., (2016) reported data from a more sensitive analysis of organic compounds present in gas collected from CSG wells in the Gloucester and Camden regions of NSW. For the purposes of the study presented here, additional trace species identified in CSG from NSW wells were added to those species identified in industry gas composition data from the Health Study region, in order to provide a more comprehensive list of substances which may be present in CSG.

The CSG composition data are summarised in Table A 2 of the Appendix to this report including the species measured and range of concentrations in CSG reported from the 3 datasets listed above. Note, non-detection of a substance does not necessarily imply the absence of the chemical in the CSG sample. Some species may have been present at concentrations at or lower than the detection limits of the analytical methods applied, and the potential for these non-detectable concentrations of a substance to pose an air pollution hazard should be considered.

Across the 3 CSG composition datasets examined here, 131 substances were analysed and the data can be summarised as follows:

- Methane comprised 96 - 98 % of the CSG with small amounts (~1 - 4%) of nitrogen, carbon dioxide always present
- VOCs that were detected in the CSG included C_2 – C_8 alkanes and cycloalkanes, and aromatic VOCs (Benzene, Toluene, Xylenes)
- No other hydrocarbon VOCs were detected above their respective limits of reporting
- No halogenated compounds were detected above their respective limits of reporting
- Poly aromatic hydrocarbons (PAHs) were not detected (detection limit 10 μgm^{-3})
- Hydrogen sulphide (H_2S) levels in CSG samples ranged from 140 - 230 $\mu g /m^3$
- Other sulphur gases (carbonyl sulphide, and carbon disulphide) were not detected above their limits of reporting.
- Radon-222 was detected in CSG samples with levels ranging from 34 - 330 Bq/m^3
- Total mercury concentrations in CSG samples ranged from 0.002 – 0.23 $\mu g /m^3$
- National and state ambient air quality objectives exist for many of the VOCs reported in CSG as well as hydrogen sulfide, mercury, and radon. The available information on the levels of some of these contaminants in ambient air in the study region will be discussed in Sections 5 and 6)

A case study of a real-life CSG release event is presented in Section 7.

2.7 Summary

CSG industry emissions of a large number of substances were identified in an examination of CSG Company Environmental Impact Assessments, annual regulatory reporting to air emissions inventories, and industry monitoring data from CSG facilities. The key substances identified in CSG industry emissions were:

- NO_x,
- CO,
- PM_{10} and $PM_{2.5}$
- VOC
- O_3 – secondary production from emissions of NO_x and VOCs

- inorganic gases - including hydrogen sulfide, radon and mercury

3 Identification-potential pathways of community exposure to CSG industry air pollutant emissions

A complete human exposure pathway includes the following elements (USEPA 1989):

- A source and release (emission) or transformation product from precursor emissions
- Movement or a transport medium away from the source (fate and transport)
- Contact with humans (exposure point)
- Exposure through ingestion, inhalation, or dermal contact (exposure route)

Unlike emissions to soil and water, the CSG industry's emissions to air represent a direct and well-recognised pathway of community exposure to potentially hazardous substances via inhalation. Deposition of air emissions onto soil and water and uptake by biota are outside of scope of this report.

As described in Section 2, CSG emissions to air are released from a variety of sources including:

- Large continuous point sources such as gas-fired engine combustion emissions at CPPs.
- Large intermittent point sources such as flares at CPPs
- Dispersed continuous point sources such as well pads engines and flares, HPVs, LPDs,
- Mobile / Transient sources such as drilling, hydraulic fracturing, workovers, completions, construction activities and vehicles.
- Accidental release of low- or high-pressure gas

The study region is an area of intensive CSG development and consequently there is a large amount of CSG infrastructure and associated air emission sources distributed right across the study region. Setbacks provide separation between the general public and large central processing facilities however, well pads, gathering lines, HPVs, LPDs, associated road infrastructure as well construction and well development activities (drilling, hydraulic fracturing, completions, workovers) are distributed across the study region and are often in proximity to places where people live and work, particularly in agricultural areas.

Table 2 provides an account of CSG industry elements in the study region as of February 2020 (Huddlestone-Holmes 2021), which demonstrates the large number of points within the study region which have the potential to act as sources of air emissions.

Table 2: CSG industry Infrastructure in the study area (as of February 2020). Source: Huddlestone-Holmes (2021).

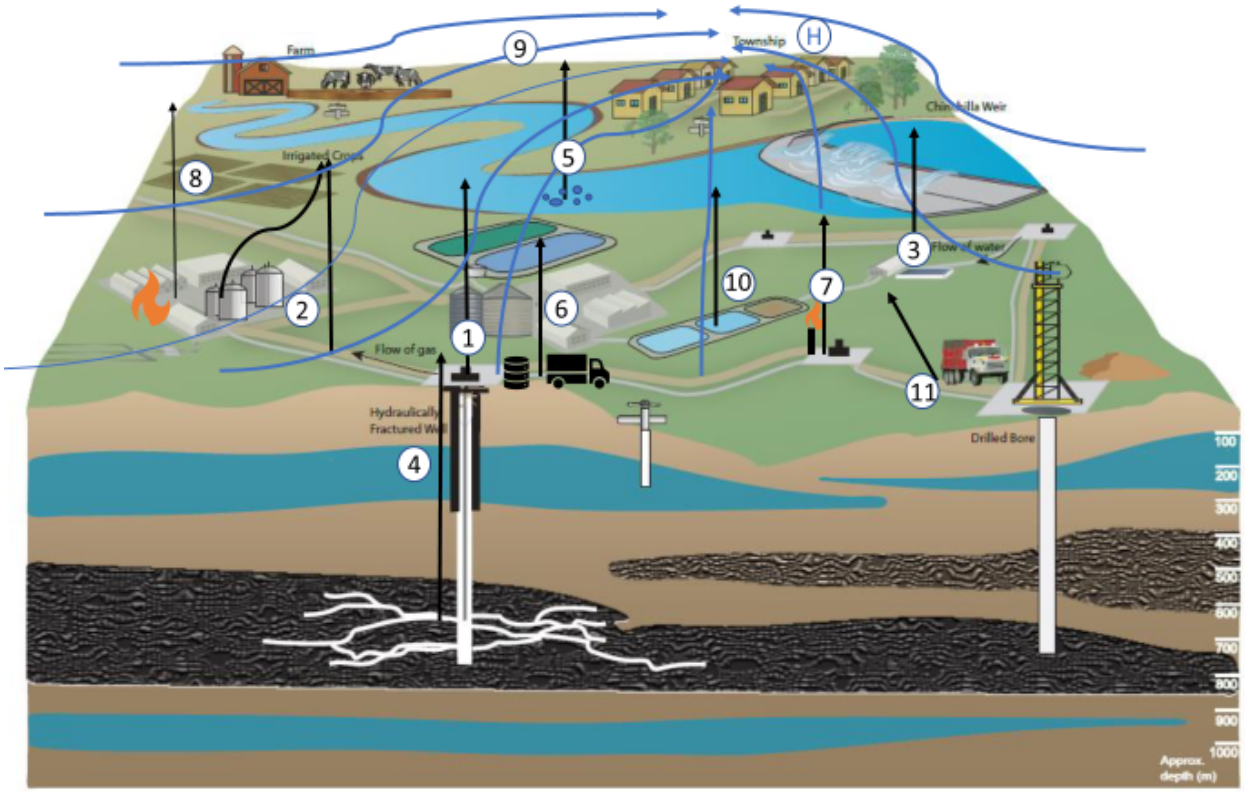
Category	APLNG infrastructure	QGC Infrastructure	TOTAL
CSG Wells	1240	1184	2424
Wells hydraulically fractured	43	31	74
Gathering pipelines (water and gas)	2,286.7 km	2,313.5 km	4600.2 km
High point vents/Low point drains	1386/823	199/323	1585 / 1146
Water ponds	47 (2.4 km^2)	24 (6.01 km^2)	71 (8.41 km^2)
Water treatment facilities	2	2	4
Field compression stations	3	12	15
Gas processing plants	5	3	8
Flares	11	24	35

The key substances identified in CSG industry emissions have atmospheric lifetimes ranging from hours, such as nitric oxide and some of the more reactive VOCs, to many weeks such as CO, mercury, and radon. Given the proximity of community receptors to CSG industry sources in the study region, these atmospheric lifetimes are certainly long enough to assume the persistence of emitted pollutants in air as they are transported from source to receptor. Ozone however is rapidly destroyed on contact with surfaces and therefore does not penetrate building envelopes, confining potential exposures predominantly to outdoor environments only. Furthermore, O_3 is produced by photochemical reactions between NOx and VOCs and due to dependence of its reactions on sunlight, concentrations are strongly diurnal with peak concentrations in the daytime.

Furthermore, the health study location sits within a larger region of intensive CSG development so that air emissions from outside of the health study region will be transported through air and contribute to cumulative air pollutant loads experienced by communities within the health study region. So overall, there are multiple pathways via air the community may be exposed to emission from the CSG industry in the health study region as shown in the conceptual site model in Figure 6

Air quality modelling studies (discussed further in 5.1.2) indicated the maximum impact of CSG-related emissions on air pollutant levels tended to be localised and occurred within a few kilometres of emission sources (for example CPPs) (Noonan et al., 2019). Overall the impact of CSG industry emissions on local and regional ambient air quality, which community members in the study region may be exposed to depends on their proximity to these variety of sources, the quantity of substances emitted in a given time, substance's atmospheric lifetime and fate, contributions from other sources of emissions (natural, domestic, other industry) and meteorology and local topography. The levels of pollutants in ambient air represents the combined sum of the processes.

In the following section we will review the available information on the levels of CSG associated air pollutants in the ambient air of the study region.



1	CSG releases from well pad infrastructure	7	Combustion emissions from well head microturbines/engines and flares
2	CSG releases from gathering network, valves, CPP and other infrastructure	8	Gas combustion emissions from power generation at CPPs and WTFs
3	CSG releases from high point vents and low point drains in gathering network	9	Secondary formation of air pollutants in the atmosphere
4	CSG releases via new connections with sub-surface strata e.g., wells	10	Emissions from produced waters/ brine ponds
5	CSG releases via existing connections with sub-surface strata e.g., seeps, legacy bores	11	Fugitive dust from movement of equipment and vehicles
6	Emissions of drilling and hydraulic fracturing fluids, breakdown products, and flowback waters during transport, storage and handling and use.	H	**Exposure Pathway** – Transport via the atmosphere and exposure of population via inhalation of gaseous and particulate air pollutants

Figure 6: Conceptual site model showing plausible pathways of community exposure to air emissions from CSG industry activities

4 Identification- potential CSG industry air pollutant hazards for further screening and assessment

The information presented in sections 4 and 5 can be considered as key inputs into the *Identification Stage* of the Health Study Framework (Figure 7). Several potentially hazardous substances emitted to air from CSG industry sources were clearly identified in the information that was contained in CSG Company EIS' completed prior to development, as well as ongoing annual air emissions inventories and industry monitoring data from CSG facilities reported in Section 2. The key substances identified in CSG industry emissions were:

- NO_x,
- CO,
- PM_{10} and $PM_{2.5}$
- VOC
- O_3 – secondary production from emissions of NO_x and VOCs
- inorganic gases - including hydrogen sulfide, radon and mercury

As outlined in Section 3 plausible pathways exist for community exposures to CSG industry air emissions from numerous source points distributed across the study region.

Due to their potential impact on human health, national and state ambient air quality objectives exist for NO_x, CO, O_3, particulate matter, and several VOCs and these legislated measures are described below, along with other relevant ambient air quality guidelines.

Based on the information presented in Sections 2 and 3, the substances listed above satisfy the criteria for progression to subsequent stages of the health study framework comprising screening and further assessment as they have known impacts on human health, as evidenced by the existence of legislated ambient air quality objectives (NEPC 2011, 2021), national emissions reporting requirements (NEPC 2008) and other national and state-based guidelines for these substances; and are highly mobile and persistent enough in the environment to ensure plausible pathways of community exposure via inhalation pose a realistic hazard.

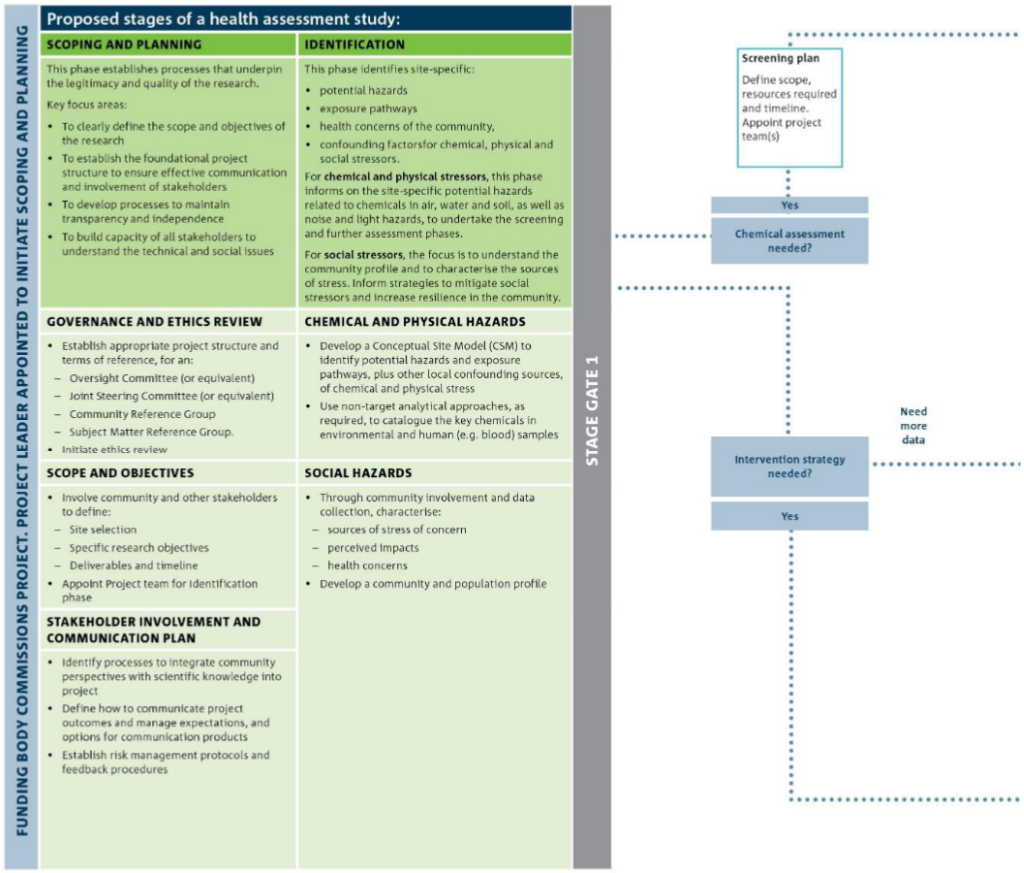


Figure 7: An overview of the Healthy Study framework, with a description of the key steps. Source: Keywood et al (2018).

4.1 Relevant Air Quality Objectives

National, state and territory governments have agreed to the National Environment Protection Measures (NEPM) legislation, which are designed to protect human health and the environment. Some States, including Queensland, also have their own environment protection policies in relation to air quality (Qld EPP 2019).

- National Environment Protection (Ambient Air Quality) Measure –2021. This recently updated measure prescribes objectives for monitoring and reporting of ambient concentrations of 7 criteria air pollutants: nitrogen dioxide (NO_2), CO, O_3, sulphur dioxide, particulate matter (PM) with diameters less than 10 µm (PM_{10}) and 2.5 µm ($PM_{2.5}$) and lead. In some cases air quality data presented in this report were compared with the 2015 version of the Ambient Air Quality NEPM in order to match the averaging periods of the data as it was reported.
- National Environment Protection (Air Toxics) Measure –2011. This measure prescribes objectives for monitoring and reporting of ambient concentrations of 5 Air Toxics: BTEX compounds (benzene, toluene, xylenes, ethylbenzene) as well as formaldehyde and polycyclic aromatic hydrocarbons (PAHs) as benzo(a)pyrene.

- Queensland Environmental Protection (Air) Policy (EPP) –2019. The EPP (2019) includes criteria pollutants and air toxics prescribed in the Ambient Air Quality and Air Toxics NEPMs (above) along with 18 other organic and inorganic pollutants as well as Total Suspended Particulates (TSP).
- Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) 2017. Radiation Protection in Existing Exposure Situations, Radiation Protection Series G-2. Provides recommended action levels for radon-222 concentration in air for households and workplaces.
- WA Dept of Health (2016) Hydrogen Sulfide and Public Health, Government of Western Australia, Dept. of Health, Accessed: 5/7/2021, Available: https://ww2.health.wa.gov.au/Articles/F_I/Hydrogen-sulfide-and-public-health

Australian federal or state ambient air quality objectives are not available for many of the VOCs that have been reported in CSG emissions and observations of ambient air reported here. In the absence of Australian objectives, international objectives that covered the range of VOCs measured in this study have been consulted, in particular:

- Texas Commission on Environmental Quality Air Monitoring Comparison Values (ACMV) and Effects Screening Levels (ESLs). The AMCV and ESL values are "chemical specific air concentrations set to protect human health and welfare". Where AMCV values were not available for a specific compound the appropriate ESL was used. For details on the difference between AMCVs and ESLs the reader is referred to TCEQ (2016a) and TCEQ (2016b).

It is important to note that air quality guidelines are subject to change as new information on health impacts of air pollutants becomes available, and the data in this report may be revisited as new health guidelines are developed.

5 Screening - observation and modelling studies of air quality in the Surat Basin

The information presented in the previous sections of this report demonstrate that the CSG industry is a significant source of potentially hazardous air emissions in the study region and there are direct pathways of community exposure via inhalation of CSG industry associated air pollutants form a large number of sources across the study region. This section provides a summary available observation and modelling studies of ambient air quality collected in gas-field and community locations in the study region which can provide input into the **Screening and Further Assessment Stages** of the Health Study Framework (Keywood et al., 2018).

Assessment of the potential health impacts of reported air pollutant levels was performed by comparing measured pollutant concentrations against the relevant ambient air objective for protection of human health. A summary of the data collected across all of these studies is provided in Section 6 alongside their relevant air quality objectives.

5.1 GISERA Studies of Ambient Air Quality in the Surat Basin

The Gas Industry Social and Environmental Research Alliance (GISERA) is a collaboration between CSIRO, Commonwealth & State Governments and industry established to undertake publicly reported independent research. The purpose of GISERA is for CSIRO to provide quality assured scientific research and information to communities living in gas development regions focusing on social and environmental topics including air quality and health. Several previous GISERA projects have provided key information related to air emissions and air quality relevant to the Health Study Area, including:

5.1.1 Ambient Air Quality Monitoring in the Surat Basin 2014 - 2018

The Surat Basin Ambient Air Quality Study was undertaken in the Condamine, Miles and Chinchilla region of Queensland from 2015 – 2018, to assess overall regional air quality and investigate the influence of CSG activities on air quality (https://gisera.csiro.au/project/ambient-air-quality-in-the-surat-basin/). Measurements were collected according to the relevant Australian Standard by NATA accredited providers and underwent independent QA/QC processing by CSIRO.

Data were collected from a network of 5 air quality monitoring stations (Figure 8) that measured the NEPM (Ambient Air) pollutants - NO_x, CO, SO_2, O_3, particulate matter, as well as methane and meteorological variables.

The stations were located as follows:

- 3 stations located in gas field sites (Hopeland, Miles Airport and Condamine). These sites were selected to be situated in an area expected to experience the largest impact of CSG emissions, based on preliminary dispersion modelling by Day et al., (2015). The stations

were between 1 and 5 km from gas processing facilities, between 100 – 450 m from operating CSG wells and had 15 - 25 wells within a 2 km radius.

- 2 regional sites (Tara Region and Burncluith). Located 10-20 km away from major potential CSG-related emission sources.

Figure 8: An Air Quality Monitoring Station

Air quality data for each monitoring station in the Health Study Region are available for the following periods shown in Table 3:

Table 3 air quality monitoring periods at 6 sites across the Surat Basin

Air Quality Monitoring Site	Reporting period
Hopeland	January 2015 – present
Miles Airport	July 2015 – present
Condamine	March 2016 – June 2017
Burncluith	June 2016 – July 2018
Tara	June 2016 – September 2019
Upper Humbug	September 2019 – present

In addition to the air quality monitoring sites described above, a network of 10 monitoring sites were established to collect two-weekly integrated passive sampling measurements for > 50 individual VOCs, aldehydes and hydrogen sulphide (H_2S). These monitoring sites were also located in gas field (Miles Airport, Miles/Condabri, Hopeland, Nangram/Monreagh, Greenswamp, Rockwood/Talinga) and regional areas (Tara region, Burncluith) as well as in the Chinchilla township (Lawson et al., 2017).

Reporting

A summary of the air quality monitoring program is provided in Lawson et al., (2018c) available on the GISERA website here with details of the study design and interim data assessments provided in earlier reports (Lawson et al., 2017, 2018 a,b). Note data for VOCs, aldehydes and hydrogen sulfide from the passive sampling network were provided for the period 2014 – 2016 in Lawson et al., (2018). Data for the period 2016 – 2017 were provided in Dunne et al. (2018) available here.

Summary of Findings

This is the most extensive air quality monitoring study ever undertaken for this region spanning 10 monitoring sites across the region and collecting ~4 years of continuous monitoring data on NEPM Ambient Air Pollutants and Air Toxics as well as a large suite of other VOCs.

The levels of air pollutants were compared with relevant air quality objectives described previously in Section 4.1. Summary data from this study are presented in Section 6, Table 4 to Table 7 alongside data from other studies and relevant ambient air quality objectives.

Overall, air quality in relation to the gaseous air pollutants emitted by CSG activities (NO_2, CO, SO_2, O_3, VOCs and H_2S) were well within relevant air quality objectives for most of the study period. Analysis of the PM data collected in this study indicated CSG activities were likely to have contributed to infrequent, high levels of coarse particulate matter (PM_{10} and TSP) most likely dust, which were also associated with other activities and sources typical of rural areas (farming, road-dust, windblown soil) and which exceeded NEPM and Qld EPP Air Quality objectives on a number of occasions. CSG activities were not found to contribute to infrequent fine particle ($PM_{2.5}$) events in the region, which were mainly the result of smoke from vegetation fires.

Ongoing Air Quality Monitoring

While the air quality monitoring network was initially established by CSIRO's GISERA as part of the Surat Basin Air Quality study, since August 2016 the data has been streamed to the Queensland Department of Environment and Science (DES) website under South West Queensland region available here.

5.1.2 Modelling Air Quality in the Surat Basin

Modelling of Ambient Air Quality in the Surat Basin was undertaken as part of the GISERA Ambient Air Quality in the Surat Basin Project and details of the emissions inventory used, the modelling approach and model outputs are reported in Noonan et al., (2019) here. This study utilised an air quality model to examine the impact of CSG industry emissions on air quality in the Surat Basin for a 12-month period September 2015 to August 2016 and examined the spatial variability of NO_x, CO, O_3, particulate matter (PM), as well as the VOCs: formaldehyde, benzene, toluene, xylenes; across the Surat Basin modelling domain (Figure 9). The chemical transport component models interactive emission, transport, chemical transformation and wet and dry deposition of a mixed gas and aerosol system, including secondary particle and O_3 formation.

Summary of findings

- Concentrations of NO_2, CO, O_3, $PM_{2.5}$ and VOCs produced by the model showed reasonable agreement with observation data reported from the ambient air quality monitoring network described in Section 5.1.1 above.
- Modelled ambient concentrations were in general well below air quality objectives. There were some modelled exceedances of the 24-hour average $PM_{2.5}$ objective and some modelled near exceedances (>80 % of air quality objective) for 1-hour NO_2 and 4-hour O_3 concentrations (NEPC (2016), QLD EPP (2008)).
- Smoke from vegetation fires resulted in the largest modelled air quality impacts over the region, particularly for $PM_{2.5}$, CO and O_3.
- When CSG-related emissions contributed to an exceedance of the 24-hour air quality objective for $PM_{2.5}$, CSG industry emissions contributed at most 4 - 37 % to 24-hour $PM_{2.5}$ concentrations.
- When CSG-related emissions contributed to values of $PM_{2.5}$, O_3 and NO_2 which were >80 % of the relative air quality objective (NEPC 2016, and Qld EPP 2008), CSG-related emissions contributed 6 – 92 %, 3 – 7 % and 99 % to the total concentration respectively.
- The modelled concentrations of the air toxics benzene, toluene, xylenes, and formaldehyde were very low and well below air quality objectives (NEPC, 2011), Texas AMCV (2016a). The modelled contribution of CSG-related emissions to ambient concentrations of these air toxics was very low to negligible.

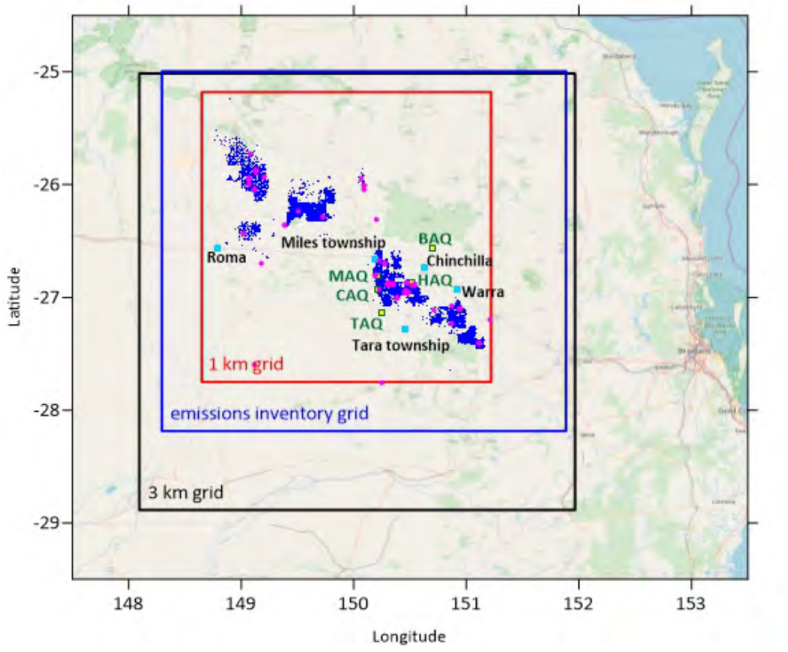


Figure 9: The emissions inventory grid as well as nested 3 and 1 km modelling grids. Locations of the modelled CSG-related emission sources are also shown blue = well areas, high point vent areas, other area sources, pink = stacks, flares, other point sources. Source: Noonan et al (2019). BAQ, MAQ, CAQ, TAQ, HAQ refer to the air quality monitoring locations in Burncluith, Miles, Condamine, Tara and Hopeland respectively.

- The maximum impact of the modelled CSG-related emissions on air pollutant levels tended to be localised and occurred within a few kilometres of emission sources (for example CPPs) particularly for NO_2 and $PM_{2.5}$.
- For O_3 the maximum impact of CSG-related emissions was generally to decrease the O_3 concentration near combustion sources (due to reaction of O_3 with NO_x). CSG-related emissions sometimes contributed to higher O_3 concentrations downwind from CSG-related emission source.
- Combustion of gas and/or diesel in CSG infrastructure/sources was the likely major source of CSG-related emissions of $PM_{2.5}$, CO, NO_2, and precursors leading to O_3, rather than fugitive emissions of CSG itself.
- The modelling system used in this study is not able to capture localised coarse particle (PM_{10}, TSP) exceedances such as dust events associated with CSG activities, cattle farming and other agricultural activities as reported in Lawson et al. (2018) at Gas field sites likely (Lawson et al., 2018c).
- The modelling indicates air quality data from the gas field monitoring sites (Lawson et al., 2018c) were well-located to experience CSG-related air pollution impacts. These sites are likely to provide a 'worst case' regional impact from CSG-related emissions for the period 2015 - 2016.

5.1.3 Measurements of Air Quality at Hydraulic Fracturing Sites in the Surat Basin

Measurements of air quality were undertaken at well development sites in the Miles-Condamine region in 2016-17 and Roma-Yuleba region in 2017 as part of the GISERA Study of Air, Soil and Water Impacts of Hydraulic Fracturing (Phase 1 & 2) and the data were provided in the following reports:

- Dunne et al., (2018) "Measurements of VOCs by passive Radiello sampling at a hydraulic fracturing site in the Surat Basin, Queensland". Available: https://gisera.csiro.au/wp-content/uploads/2018/07/Water-11-Milestone-6-report.pdf.
- Dunne et al., (2020) "Measurements of air quality at a hydraulic fracturing site in the Surat Basin, Queensland" Available: https://gisera.csiro.au/wp-content/uploads/2020/04/Water-12-Milestone-3-report_final.pdf.

Dunne et al., (2018) reported the ambient concentrations of a range of VOCs, aldehydes and hydrogen sulphide measured by passive sampling methods at 7 locations in well development sites within Miles – Condamine region where 18 CSG wells underwent hydraulic fracturing treatments in late 2016 and mid-2017. This represents nearly a quarter of the 74 wells reported to have undergone hydraulic fracturing in the study region up to Feb 2020. Levels of all substances reported were well below national, state, and relevant international annual ambient air quality objectives, and were similar to those measured at other regional and gas field locations in the Surat Basin not known to be directly undergoing hydraulic fracturing treatment. Occasional peaks in the 14-day average concentrations of toluene, xylenes, ethylbenzene and formaldehyde, and some other VOCs were associated with well development activities but were still below air quality

objectives. Observed peaks in benzene concentrations were attributed to smoke from regional fires.

Figure 10: A hydraulic fracturing spread in the Roma-Yuleba region of the Surat Basin

In a later report, Dunne et al., (2020) described the results of more comprehensive ambient air monitoring study undertaken in the vicinity of well development activities (drilling, hydraulic fracturing, well completions) in Roma-Yuleba region of the Surat Basin from July – December 2017 (Figure 10). The study measured NO_x, CO, SO_2, O_3, particulate matter, methane, VOCs, hydrogen sulfide as well a number of other potential CSG related air pollutants not previously studied extensively in this region (radon, mercury, PAHs). Summary data from this study are presented in Section 6, Table 4 to Table 7 alongside data from other studies and relevant ambient air quality objectives.

Impacts on air quality associated with well development were short term (hours to days) and were transient within gas development regions as drilling, hydraulic fracturing and well development operations moved from well site to well site.

Small increases above background in NO_2, CO, $PM_{2.5}$, formaldehyde, BTEX and PAHs were attributed to emissions from diesel powered vehicles and equipment on site during well development, which were still well within relevant ambient air quality objectives.

No evidence of significant emissions to air from drilling and hydraulic fracturing additives was observed at these well sites.

Occasional high airborne dust events associated with the movement of vehicles and equipment on unsealed roads which exceeded ambient air quality objectives were reported. These are examined in more detail below.

5.1.4 Sources of PM_{10}

Given high levels of PM were the most common cause of exceedances of the NEPM air quality objectives their sources are examined in more detail here. A unique aspect of the hydraulic fracturing air quality study described above was the sampling and analysis of ninety-three 12-hour PM_{10} samples collected before and during drilling and hydraulic fracturing. The chemical composition data for the PM_{10} samples were statistically analysed using positive matrix

factorisation (PMF) receptor model (Norris & Duvall, 2014). This receptor model relies on internal correlations between species in the data set to identify both the factors contributing to the samples and the amount that each factor contributed to the total PM_{10} mass collected on the filter.

Nine Factors that contributed to PM_{10} concentrations were identified. The first and largest factor was soil dust. Contributions from four other factors (ammonium sulfate, secondary nitrate, aged biomass burning, woodsmoke and sea salt), (Figure 11), were the result of regional transport (tens to hundreds of kilometres) of PM to the study site from both natural and other industrial sources, such as electricity generation in the region. PM from these factors were predominantly in the fine size fraction ($PM_{2.5}$). Contributions from two other factors (glucose and bioaerosols) 2 other factors were from natural biological sources at the study site. Combined these sources comprise the background PM in the atmosphere of the study region and well development activities on site did not significantly contribute to these factors. Only local emissions of soil dust from vehicle traffic and equipment on unsealed roads and well pads were attributable to CSG well development activities and on occasion resulted in exceedances in 24-hour PM_{10} and TSP air quality objectives.

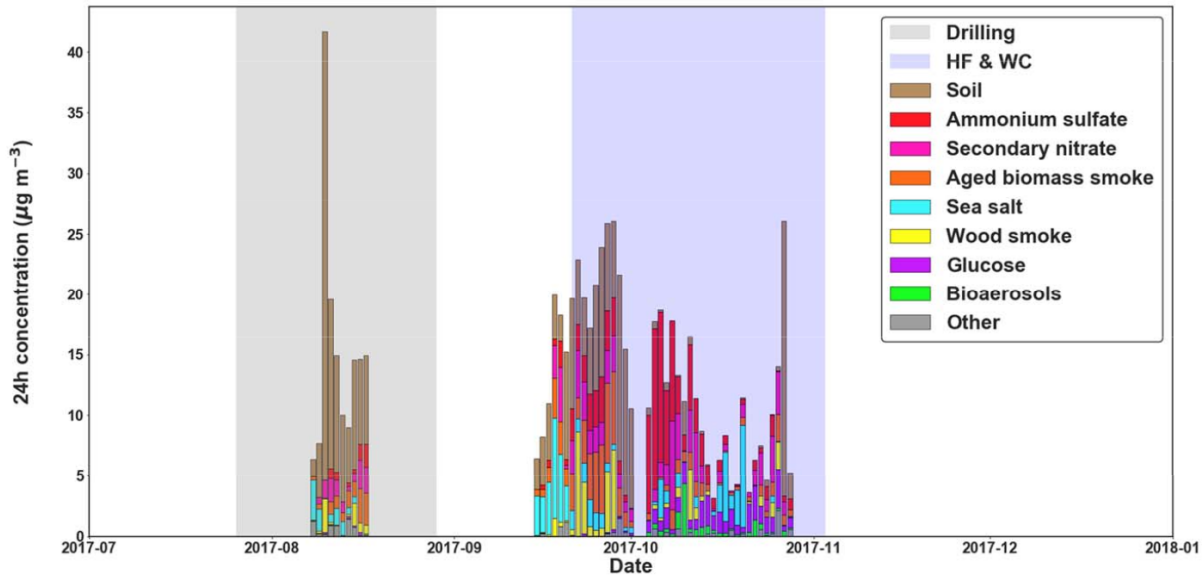


Figure 11: Time series of the contribution of each PMF Factor to PM10 at the HF Study site (µg/m³). Shaded areas represent drilling (grey) and hydraulic fracturing (HF) & Well completions (WC)periods (purple). "Other" refers to the PM10 mass not accounted for by one of the identified PMF factors

5.1.5 Airborne Silica in PM_{10}

As discussed in section **Error! Reference source not found.**, the Queensland Alliance for Environmental Health Sciences (QAEHS), University of Queensland (UQ) have undertaken a site-specific appraisal of potential hazards posed by chemical and physical factors associated CSG industry activities in the health study region including drilling and hydraulic fracturing additives and geogenic contaminants in produced water. As part of this appraisal process crystalline respirable silica has been identified as a contaminant of potential concern requiring further

research. Crystalline silica (a form of silicon dioxide SiO_2) is used during drilling and hydraulic fracturing (**Error! Reference source not found.**) and is present in produced water and the major human exposure pathway for silica exposure is via inhalation of dusts. The mandatory limit for airborne workplace concentrations of silica dust in Australia is 50 µg/m^3 (particles with diameter < 16 µm, PM_{16}) averaged over an eight-hour day (with exception of Tasmania - 100 µg/m^3), although the Cancer Council are urging a reduction in this limit to 20 µg/m^3 (Cancer Council 2021, Available: https://www.cancer.org.au/cancer-information/causes-and-prevention/workplace-cancer/silica-dust).

Limited information on the potential occurrence of airborne silica is available for the study region. Using the data from the analysis of PM_{10} samples collected at the hydraulic fracturing site described above revealed:

- silica was the one of the major components measured in the analysis of the PM_{10} samples.
- Assuming all silica was present as silicon dioxide (SiO_2), an average 24-hour concentration of 2.86 µg/m^3 of SiO_2 can be estimated from the ~3 months of samples during drilling and hydraulic fracturing at the study site with a maximum 24 hour concentration of 22.03 µg/m^3. Note, this estimate of SiO_2 includes both crystalline and non-crystalline forms. This is significantly lower than the workplace Australian standard discussed above .
- The concentrations of SiO_2 were highly correlated (R^2 > 0.96) with known soil markers aluminium and titanium oxides, and their ratios to Si were typical of soil dust (Lide 1997).

It can be concluded that while SiO_2 was present in PM_{10} during drilling and hydraulic fracturing in the 2017 study, the observed concentrations were primarily attributable to soil dust emissions, rather than crystalline silica used as an additive in drilling and hydraulic fracturing fluids.

5.2 Government Studies

In addition to ongoing air quality monitoring data reported through Queensland Department of Environment and Science (DES), several short-term studies of air quality have been undertaken by

the Queensland Government in the health study region. Results from these studies are discussed below.

1) DSITIA (2013) *Wieambilla Estates Odour Investigation Results: July-December 2012*. Report prepared by Environmental Monitoring and Assessment Sciences, Science Delivery Division, Department of Science, Information Technology, Innovation and the Arts (DSITIA) for the Department of Environment and Heritage Protection (DEHP).

In 2012, the former Queensland Department of Science, Information Technology, Innovation and the Arts (DSITIA) undertook a VOC sampling program in the Wieambilla Estates in response to community concerns about the impacts of CSG industry air emissions on air quality:

Short-term (1 min) vacuum canister grab sampling was conducted between July – December 2012 at four residences in Wieambilla Estates. Community members collected air samples outside their residences when they perceived odour was present in the environment. Vacuum canister samples were also collected at a forested site as well as several sites associated with coal seam gas fields, although the location and nature of these sites is not well described. They were: 2 high point vents (HPVs) samples, a sample collected at an unknown location labelled TO1743, and a third location named 'Rhyme Pond'. Three-weekly integrated passive samples of VOCs were also collected at the 4 residences as well as a site in the township of Chinchilla.

Overall, only 14 samples were collected as part of this study, which measured for > 100 VOC species. All detected compounds occurred at levels well below their relevant ambient air quality objectives. Data from these investigations are presented Table 6 alongside data from other studies and their relevant air quality objectives. Samples collected at HPVs, Rhyme pond and TO1743 are reported collectively as 'Gas-fields data in Table 6

2) In 2015, the former Queensland Department of Science, Information, Technology and Innovation (DSITI) undertook a 2-stage investigation in the Hopelands /Chinchilla region measuring the levels of VOCs including some species listed in the Air Toxics NEPM, and Qld EPP (Air) :

- 'Air Quality Investigation Hopeland Chinchilla March 2015' (DSITI 2015)
- 'Air Quality Investigation Hopeland Chinchilla December 2015' (DSITI 2016)

These investigations occurred in response to detection of high levels of gases including CO, and hydrogen sulfide in the subsoil in the Hopeland area which were associated with the Linc Energy underground coal gasification (UCG) project. The air monitoring investigations were undertaken in March and December 2015 at 6 residential dwellings in the Hopeland area and within the grounds of three local schools in Hopeland and Chinchilla. Data were collected on levels of CO, hydrogen sulfide, 127 VOCs including phenolic compounds, using a variety of methods from handheld detectors for CO and TVOC, and samples collected vacuum canisters and with radiello passive samplers followed by analyses in the laboratory for individual VOC species, hydrogen sulfide and phenolic compounds.

The levels of CO, hydrogen sulfide, VOCs and phenolic compounds measured in the air in the community were all below relevant health-based air quality objectives. Data from these investigations are presented in Table 6 alongside data from other studies and their relevant air quality objectives.

5.3 Studies of Radon in the Surat Basin

Radon is a radioactive noble gas and is a product of the decay of Uranium 238. Radon is present in almost all rocks and sediments and consequently, natural emissions from soils are the largest source of radon to the atmosphere. Radon was detected in the analyses of CSG reported in Section 2.6. and therefore, fugitive CSG emissions represent a potential pathway to exposing the community to elevated levels of radon.

Due to its potential impact on human health the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) have developed Radiation Recommendations for Limiting Exposure to Ionizing Radiation (ARPANSA 2002) (Guidance note [NOHSC:3022(1995)]) with recommended action levels for radon-222 in air of 200 Becquerel per cubic metre (Bq/m^{-3}) for households and 1000 Bq/m^{-3} for workplaces.

In 2012, a ~3-day study was undertaken in a CSG field in Tara region (Tait et al., 2013), ambient radon levels were measured at 4 sites within a gas field, and at a reference site (> 3 km from wells). This study reported a maximum (24-hour averaged) radon concentration of ~30 Bq/m^{-3} with typical 24-hour average levels of ~5 – 8 Bq/m^{-3} measured at gas field sites, which are well below the ARPANSA recommended action levels for workplaces and households. A positive association between average and maximum radon concentrations and the number of wells within 3 km was reported.

Monitoring of ambient radon concentrations was undertaken for several months (8 Aug – 25 Nov 2017) at a hydraulic fracturing site in the Surat Basin (See Section 5.1.3; Dunne et al., 2020). As a reference, radon monitoring was also conducted at regional site > 10 km from large CSG industry sources. The average (max) radon concentration at the HF study site and reference site were 4.4 (10.0) and 9.2 (34.2) Bq/m^{-3}respectively, also well below the ARPANSA recommended action levels for workplaces and households.

Reports from radiological surveys of CSG infrastructure were reviewed as part of the GISERA Ambient Air Quality Study (Lawson et al., 2017). The reported radiological survey measurements in count rate and dose rate recorded for Talinga GPF, WTF and wells were comparable with the natural background measurements. Analysis of process waters and sludge identified activity concentrations consistent with levels encountered in the natural environment. The full radiological survey reports are available here.

In Section 7 a case study of a real-life CSG release event is presented which includes an estimate of radon concentrations associated with an accidental CSG release.

6 Screening -summary of available data on the occurrence of key CSG industry air pollutants in ambient air of the health study region

In this section the information presented in the preceding sections on the sources, emissions (Section 2) and occurrence of key CSG industry gas pollutants (Section 5) are summarised and compared with relevant ambient air quality objectives.

6.1 Nitrogen Oxides and Carbon Monoxide (NO_x and CO)

The largest reported air emissions from the CSG industry in the study region are combustion emissions of NO_x and CO with releases in the order of 100 000s kilograms per year for each (See Section 2.1). These substances are released directly to air from small stationary point sources dispersed throughout the study region in the form of well pad microturbines/engines and well pad flares, as well as from larger stationary point sources in the form of stack /gas combustion emissions and flares at central processing facilities. In addition, there are mobile combustion emissions from diesel powered equipment and vehicles. Air quality modelling indicated the maximum impact of CSG-related emissions on air pollutant levels tended to be localised and occurred within a few kilometres of emission sources (for example CPPs) (Noonan et al., 2019).

Due to their potential impact on human health and the environment both CO and oxides of nitrogen (as NO_2) are listed in the National Environment Protection Measures for Ambient Air (NEPC, 2021). NO_2 and CO have been continuously monitored at several sites across the health study region from 2015 onwards (See Section 5.1.1). Monitoring data are summarised in Table 4 alongside their NEPM ambient air quality objectives. Analysis of the monitoring data found air quality in relation to these gaseous air pollutants was always well within relevant air quality objectives (Lawson et al., 2018 a,b,c, Dunne et al., 2020, DES 2020).

6.2 Sulfur dioxide (SO_2)

Sulfur dioxide (SO_2) emissions on the order of 10 000s of kgs/ per year are reported from CSG industry combustion sources in the study region. However, these emissions are dwarfed by the large regional emissions of SO_2 from electricity generation facilities that are on the order of 40 million kg/year which impact the study region (Noonan et al., 2019). As such SO_2 has not been a priority for monitoring in studies of CSG industry impacts on air quality. Data from a single monitoring study in 2017 are shown in Table 4, with values well below NEPM ambient air quality objectives (Dunne et al., 2020).

6.3 Ozone (O_3)

Ground level O_3 is not directly emitted to the atmosphere but rather is formed through photochemical reactions between other pollutants in the atmosphere mainly VOCs and NO_x. As discussed in Section 2, the CSG industry emits large quantities of NO_x and VOCs primarily from gas combustion and is therefore a potentially significant source of O_3 in the study region.

Due to its significant potential impact on human health and the environment O_3 is listed in the National Environment Protection Measures for Ambient Air (NEPC, 2021). O_3 has been continuously monitored at several sites across the health study region from 2015 onwards (See 5.1and Lawson et al., 2018 a,b,c, Dunne et al., 2020, DES, 2020). Monitoring data are summarised in Table 4 alongside the NEPM ambient air quality objectives. Analysis of the monitoring data from the study region found air quality in relation to O_3 was occasionally close to (>80%) the NEPM air quality objectives (Lawson et al., 2018 a,b,c, Dunne et al., 2020, DES 2020). However, modelling studies indicated, that during these peak events, CSG-related emissions contributed 3 – 7 % to the total O_3 concentration (Noonan et al., 2019).

Table 4: Summary ambient air quality monitoring data from the Surat Basin 2015 – 2018 for NO_x, CO, SO_2 and O_3 which are NPI reported substances emitted from CSG industry production and processing (Section 2.1) in the study region. Data were collected at gas-field air quality (AQ) monitoring sites: Miles (MAQ), Hopeland (HAQ), Condamine (CAQ), Upper-Humbug (UHAQ); and North and South AQ monitoring stations at a Hydraulic fracturing site.

Reference		**GISERA Ambient Air Quality Monitoring Study[1]**			**GISERA Hydraulic Fracturing Study[2]**	**Qld DES reported data [3]**		**Ambient Air Quality Objectives**	
Sites		**MAQ, HAQ**	**MAQ, HAQ, CAQ**	**MAQ, HAQ, CAQ**	**NAQ, SAQ**	**MAQ, HAQ**	**MAQ, HAQ, UHAQ**	**Value**	**Averaging period**
Year		2015	2016	2017	2017	2018	2019		
NO_x as NO_2 (ppb)	**Max 1 h**	15	23	22	18	49	37	80 ppb[a]	1 h [a]
	1 h Avg (range)	2 - 4	2 - 3	1 - 4	1 - 2	-	-		
	Annual avg	2	2	2	-	1 - 2	1 - 2	15 ppb[a]	Annual [a]
CO (ppm)	**Max 8 h**	0.9	1.2	1.2	0.6	0.9	4.2	9 ppb[a]	8 h[a]
	8 h Avg (range)	0.1 – 0.3	0.1 – 0.5	0.1 – 0.5	0.1	<0.1 – 0.1	0.2 – 0.3		
O_3 (ppb)	**Max 1h**	61	67	70	62	64	79	100 ppb[a]	1 h [a]
	1h Avg (range)	20 - 33	19 - 36	22 - 33	25 - 35	13 - 24	25 - 33		
	Max 4h	59	65	69	59	62	76	80 ppb[b,c]	8 h [b,c]
	4h (range)	20 - 32	19 - 35	23 - 30	25 - 35	13 - 24	24 - 33		
SO_2 (ppb)	**Max 1 h**	-	-	-	4	-	-	100 ppb[a]	1 h[a]
	Max 24 h	-	-	-	2	-	-	20 ppb[a]	24 h[a]

[a] NEPM (Ambient Air Quality) 2021 [b] NEPM (Ambient Air Quality) 2015 [c] Qld EPP (Air) 2008; [1] Lawson et al., (2018 a,b) see Section 7.2.1, [3] Qld DES (2018,2019) see Section 7.2.1 [2] Dunne et al., (2020), see Section 7.2.3

6.4 Airborne Particulate Matter (PM_{10} and $PM_{2.5}$)

The CSG industry reports large emissions of particulate matter on the order of millions of kg/year for PM_{10}, and ~40 000 kg/year for $PM_{2.5}$ (See Section 2.1) and are released directly to air from combustion sources (well pad engines, CPP gas powered engines, and flares) as well as in the form of wheel generated dust. Air quality modelling indicated the maximum impact of CSG-related emissions on $PM_{2.5}$ levels tended to be localised and occurred within a few kilometres of combustion emission sources (for example CPPs) (Noonan et al., 2019). Sources of dust emissions, measured as PM_{10}, associated with the CSG industry include wheel generated dust, construction activities and tend to be localised, short term and transient (Lawson et al., 2018 a,b,c; Dunne et al.,2020).

Due to their potential significant impact on human health and the environment both $PM_{2.5}$ and PM_{10} are listed in the National Environment Protection Measures for Ambient Air (NEPC, 2021). In addition to equivalent objectives for PM_{10} and $PM_{2.5}$ the Qld EPP also sets air quality objectives for total suspended particulates (TSP). It is also a requirement of Queensland Government Environmental Authority conditions that companies do not cause environmental nuisance from dust at a sensitive place (e.g., residences, community buildings, public parks etc) unless a formally agreed alternative arrangement is in place (Qld Gov 2018). Environmental authorities also often include specified monitoring requirements for releases to air in order for the company to demonstrate they are complying with their EA requirements. More about reporting an environmental nuisance caused by dust can be found here.

TSP, PM_{10} and $PM_{2.5}$ and have been continuously monitored at several sites across the health study region from 2015 onwards (See Section 5.1). Monitoring data are summarised in Table 5 alongside their NEPM ambient air quality objectives.

Airborne particulate matter as PM_{10} was the most common cause of observed exceedances of air quality objectives reported in monitoring studies in the Surat Basin and in most cases were attributable to fugitive soil dust emissions from CSG industry activities including vehicle moments, construction, etc (Lawson et al., 2018 a,b,c, Dunne et al., 2020) plus re-entrainment of dust from other rural activities such as vehicle and stock movement. There were also occasional exceedances of $PM_{2.5}$ air quality objectives observed in monitoring data from the study region. Modelling studies indicated, that during these peak events, CSG-related emissions contributed at most 4 - 37 % to 24-hour $PM_{2.5}$ concentrations (Noonan et al., 2019) and analysis of satellite data and other trace species in the monitoring studies were used to show that high $PM_{2.5}$ events were typically associated with smoke from local and regional fires (Lawson et al., 2018 a,b,c, Dunne et al., 2020). PM_{10} is comprised of $PM_{2.5}$ thus elevated $PM_{2.5}$ from smoke events also contributes to elevated PM_{10}.

Table 5: Summary data for ambient levels of particulate matter, which are NPI reported substances emitted from CSG industry production and processing (Section 2.1) in the study region. Data are for Particulate matter with diameters < 10 µm (PM10), < 2.5 µm (PM2.5) and Total Suspended Particulates (TSP, < 18 µm)). Data are from gas-field air quality (AQ) monitoring sites: Miles (MAQ), Hopeland (HAQ), Condamine (CAQ), Upper-Humbug (UHAQ); and North and South AQ monitoring stations at a Hydraulic fracturing site.

Reference		**GISERA Ambient Air Quality Monitoring Study[1]**			**GISERA Hydraulic Fracturing Study[2]**	**Qld DES reported data [3]**		**Ambient Air Quality Objectives**	
Sites		**MAQ, HAQ**	**MAQ, HAQ, CAQ**	**MAQ, HAQ, CAQ**	**NAQ, SAQ**	**MAQ, HAQ**	**MAQ, HAQ, UHAQ**	**Value**	**Averaging period**
Year		2015	2016	2017	2017	2018	2019		
PM_{10} ($\mu g/m^3$)	**Max 24 h**	67	59	54	69	231	556	50 $\mu g/m^3$ [a]	24 h[a,b,c]
	24 h Avg (range)	8 – 17	4 – 19	6 – 19	7 - 23	11 - 16	21 – 36		
$PM_{2.5}$ ($\mu g/m^3$)	**Max 24 h**	30	56	24	23	57	83	25 $\mu g/m^3$ [a]	24 h[a,b,c]
	24 h Avg (range)	4 – 9	2 – 8	3 – 7	3 – 9	4 – 6	7 – 15		
TSP ($\mu g/m^3$)	**Max 24 h**	121	94	84	130	-	-	60 $\mu g/m^3$	24 h[c]
	24 h Avg (range)	12 – 28	5 – 33	9 – 33	11 – 39	-	-		

[a] NEPM (Ambient Air Quality) 2021 [b] NEPM (Ambient Air Quality) 2015 [c] Qld EPP (Air) 2008; [1] Lawson et al., (2018 a,b), [2] Dunne et al., (2020), [3] Qld DES (2018,2019)

6.5 Volatile Organic Compounds (VOCs)

The CSG industry in the study region reports large emissions of total VOCs on the order of > 500 000 kg/year to the NPI each year as well as several individual VOC species including formaldehyde (~200 000 kg/year), n-hexane, benzene, toluene, xylenes and cumene (< 5000 kg/year) that are emitted above the NPI reporting threshold (See Section 2.1).

A large number of VOCs are emitted from a range of CSG industry sources including combustion emissions from well-pad microturbines/engines, gas engines at CPPs, and flares, as well as in fugitive CSG emissions from wells, gathering networks (HPVs, LPDs), and CPPS. For instance, more than 50 VOC species were detected in samples of emissions from gas-powered engines and compressors during monitoring at a CPP in the study region in 2014 - 15 (Section 2.4), and ~25 VOCs were detected in analysis of > 130 CSG samples collected from wellheads and CPPs in the study region (Section 2.6).

Due to their potential significant impact on human health, several VOCs are listed in the National Environment Protection Measures for Air Toxics NEPM (NEPC, 2011) including several of those reported in CSG industry emissions namely formaldehyde and BTEX. There are no national air quality objectives for TVOC; reporting is required due to their role as precursors to photochemical smog.

Over the period 2012 - 17, 6 monitoring studies were undertaken across a number of sites in the Surat Basin including gas-field sites (< 500 m gas infrastructure), hydraulic fracturing sites and residential/community sites (DSITIA 2013, DSITI 2015, 2016, Lawson et al., 2018 a,b,c, Dunne et al., 2018, Dunne et al., 2020). Many hundreds of samples were collected, and data have been reported for over 120 VOC species (See Section 5). Overall, all VOCs measured were within their relevant air quality objectives in all of the ambient air monitoring studies examined for this report.

Monitoring data for formaldehyde, and BTEX compounds are summarised in Table 6 alongside their NEPM Air Toxics (NEPC, 2011) ambient air quality objective. Table 7 provides a summary of the information available on the detection or non-detection of each VOC in the available source composition and/or ambient air data, as well as data for PAHs, and several inorganic substances that have been examined in this study.

Table 6: Summary of available ambient data from the study region for VOCs that were reported to the NPI as air emissions from CSG facilities in the health study region (Section 5), alongside their relevant ambient air quality objectives.

[a] NEPM (Air Toxics) 2011, [b]Qld (EPP) Air 2019, [c] Texas AMCV,
[1] Lawson et al (2018) see Section 7.2.1; [2] Dunne et al., (2018) and [3]Dunne et al., (2020) see Section 7.2.3.; [4]DSITIA (2013) and [5]DSITI (2015) and [6]DSITI (2016) See Section 7.3.

Substance	Reported CSG Industry Sources	GISERA Ambient Air Quality Study and Hydraulic Fracturing Study	Qld Government Studies (DSITIA, DSITI)	Ambient Air Quality Objectives	
		Reported conc, site type/name, year/s [REF] (ppb)	Reported conc, site type/name, year/s [REF] (ppb)	Value	Averaging period
Benzene	Production & Processing (Sect. 5.2) Fugitive CSG (Section 5.3)	24 h integrated samples: Avg 0.02 ± 0.01, Hopeland, 2015[1] Avg range 0.02 – 0.03, Max 0.09, HF site, 2017[3]	Samples ≤ 24 h: <1.0 Gas-fields, 2012[4] <0.5, Wieambilla residential, 2012[4] <0.5, Hopeland, Chinchilla residential 2015[5]	180 ppb [c]	Short-term[c]
		~ 2 – 3 week integrated samples: Avg 0.02, Max 0.08, Gas-fields, 2014-16[1] Range 0.01 – 0.09, Gas-fields, 2016-17[2] Range 0.01 – 0.09, HF sites, 2016-17[2] Avg 0.06, Max 0.20, Chinchilla, 2014 - 16[1] Range 0.02 - 0.28, Chinchilla, 2014 – 16[2]	~ 2 – 3 week integrated samples: Range <0.2 – 0.6, Wieambilla residential, 2012[4] <0.2, Chinchilla, 2012[4] Range 0.03 – 0.09, Hopeland, Chinchilla residential 2015[5] Range 0.03 – 0.07, Hopeland, Chinchilla residential 2015[6]	3 ppb [a,b]	Annual [a,b]
Toluene	Production & Processing (Sect. 5.2) Fugitive CSG (Section 5.3)	24 h integrated samples: Avg 0.2 ± 0.1, Hopeland, 2015 [1] Avg range 0.01 – 0.02, Max 0.06, HF sites, 2017[3]	Samples ≤ 24 h: <1.0 Gas-fields, 2012[4] Range <0.5 – 1.5 Wieambilla residential, 2012[4]	1000 ppb [a,b]	24 h[a,b]

Substance	Reported CSG Industry Sources	GISERA Ambient Air Quality Study and Hydraulic Fracturing Study	Qld Government Studies (DSITIA, DSITI)	Ambient Air Quality Objectives	
		Reported conc, site type/name, year/s [REF] **(ppb)**	**Reported conc, site type/name, year/s** [REF] **(ppb)**	**Value**	**Averaging period**
			0.5 – 14, Hopeland, Chinchilla residential 2015[5]		
		~ 2 – 3 week integrated samples: Avg 0.02, Max 0.04, Gas-fields, 2014 – 16[1] Range 0.01 – 0.04, Gas-fields, 2016-17[2] Range 0.01 - 0.18, HF sites, 2016-17[2] Avg 0.15, Max 0.39, Chinchilla 2014 – 16[1] Range 0.03 - 0.42, Chinchilla, 2016-17[2]	~ 2 – 3 week integrated samples: Range <0.2 – 7, Wieambilla residential, 2012[4] 0.5, Chinchilla, 2012[4] Range 0.08 – 0.78, Hopeland, Chinchilla residential 2015[5] Range 0.02 – 0.27, Hopeland, Chinchilla residential 2015[6]	100 ppb [a,b]	Annual [a,b]
Xylenes	Production & Processing (Sect. 5.2) Fugitive CSG (Section 5.3)	24 h integrated samples: <0.01 , Hopeland, 2015 [1] Avg range 0.01 – 0.02, Max 0.04, HF sites, 2017[3]	Samples ≤ 24 h: <1.0 Gas-fields, 2012[4] <0.5 Wieambilla residential, 2012[4] ≤0.5 Hopeland, Chinchilla residential 2015[5]	250 ppb[a,b]	24 h[a,b]
		~ 2 – 3 week integrated samples: Avg 0.03, Max 0.08, Gas-fields 2014 – 16[1] Range 0.02 – 0.08, Gas-fields, 2016 – 17[2] Range 0.02 - 0.11, HF sites, 2016 - 17[2] Avg 0.08, Max 0.22, Chinchilla 2014 – 16[1] Range 0.03 – 0.29, Chinchilla 2016 – 17[2]	~ 2 – 3 week integrated samples: Range <0.2 – 1.8, Wieambilla residential, 2012[4] 0.8, Chinchilla, 2012[4] Range 0.03 – 0.80, Hopeland, Chinchilla residential 2015[5]	200 ppb[a,b]	Annual [a,b]

Substance	Reported CSG Industry Sources	GISERA Ambient Air Quality Study and Hydraulic Fracturing Study	Qld Government Studies (DSITIA, DSITI)	Ambient Air Quality Objectives	
		Reported conc, site type/name, year/s [REF] (ppb)	**Reported conc, site type/name, year/s [REF] (ppb)**	**Value**	**Averaging period**
			Range 0.03 – 0.16, Hopeland, Chinchilla residential 2015[6]		
Formaldehyde	Production & Processing (Sect. 5.2)	24 h integrated samples: Avg 0.5 ± 0.1, Hopeland, 2015 [1] Avg range 1.0 – 2.7, Max 4.9, HF site, 2017[3]	Not measured	40 ppb[a,b]	24 h[a,b]
		~ 2 – 3 week integrated samples: Avg 0.7, Max 1.9, Gas-fields, 2014-16[1] Range 0.5 – 1.7, Gas-fields, 2016 -17[2] Range 0.3 – 2.1, HF sites, 2016 -17[2] Avg 0.7, Max 1.0, Chinchilla, 2014 - 16[1] Range 0.5 – 1.8, Chinchilla, 2016 -17[2]	Not measured	8.9 ppb[c]	Long-term [c]

Table 7: Summary of available source composition and ambient air data for VOCs, PAHs, and some inorganic substances that have been examined in this study. Substances in bold have been detected in ambient air in the study region. Open circles represent substances that have been analysed for but not detected above the analytical reporting threshold, and closed circles represent substances detected above the analytical reporting threshold.

		Identified CSG-Industry Sources		Available ambient air sampling data:					
	Substance	**CSG Combustion emissions**	**Fugitive CSG emissions**	**GISERA ambient air quality study 2015-18 Lawson et al (2018 a,b,c)**	**GISERA HF study – Phase 1 2016-17 Dunne et al (2018)**	**GISERA HF study – Phase 2 2017 Dunne et al (2020)**	**Wieambilla Odour Investigation 2012 DSITIA (2013)**	**Hopeland, Chinchilla air monitoring study Mar 2015 DSITI (2015)**	**Hopeland, Chinchilla air monitoring study Dec 2015 DSITI (2016)**
1	**Acetaldehyde**	●		●	●				
2	**Acetone**						●	●	
3	Acetylene		○						
4	**Acrolein**	●					●	●	
5	Acrylonitrile		○						
6	Allyl chloride							○	
7	**Benzene**	●	●	●	●	●	●	●	●

		Identified CSG-Industry Sources		Available ambient air sampling data:					
	Substance	**CSG Combustion emissions**	**Fugitive CSG emissions**	**GISERA ambient air quality study 2015-18 Lawson et al (2018 a,b,c)**	**GISERA HF study – Phase 1 2016-17 Dunne et al (2018)**	**GISERA HF study – Phase 2 2017 Dunne et al (2020)**	**Wieambilla Odour Investigation 2012 DSITIA (2013)**	**Hopeland, Chinchilla air monitoring study Mar 2015 DSITI (2015)**	**Hopeland, Chinchilla air monitoring study Dec 2015 DSITI (2016)**
8	**Benzaldehyde**			●	○	○			
9	Benzyl chloride	○						○	
10	Bromobenzene		○						
11	Bromochloromethane		○	○	○	○		○	○
12	Bromodichloromethane	○	○				○	○	
13	Bromoform	○	○					○	
14	Bromomethane	○					○	○	
15	1,3-Butadiene						○	○	
16	**Butane**	●	●				○	●	
17	**Butanaldehyde**			●	●				
18	**Butanol**			●	○	○		●	○

		Identified CSG-Industry Sources		Available ambient air sampling data:					
	Substance	**CSG Combustion emissions**	**Fugitive CSG emissions**	**GISERA ambient air quality study 2015-18 Lawson et al (2018 a,b,c)**	**GISERA HF study – Phase 1 2016-17 Dunne et al (2018)**	**GISERA HF study – Phase 2 2017 Dunne et al (2020)**	**Wieambilla Odour Investigation 2012 DSITIA (2013)**	**Hopeland, Chinchilla air monitoring study Mar 2015 DSITI (2015)**	**Hopeland, Chinchilla air monitoring study Dec 2015 DSITI (2016)**
19	1-Butene	●	○				○	○	
20	cis-2-Butene	●	○				○	○	
21	trans-2-Butene	●	○				○	○	
22	**2-Butoxyethanol**			●	○	○		○	○
23	**Butyl acetate**			○	○			●	○
24	n-Butylbenzene	○							
25	Sec-Butylbenzene	○							
26	Tert-Butylbenzene	○							
27	**Carbon tetrachloride**	○	○	●	●		○	●	●
28	**Chloromethane**	○					●	●	
29	Chloroethane	○						○	

		Identified CSG-Industry Sources		Available ambient air sampling data:					
	Substance	**CSG Combustion emissions**	**Fugitive CSG emissions**	**GISERA ambient air quality study 2015-18 Lawson et al (2018 a,b,c)**	**GISERA HF study – Phase 1 2016-17 Dunne et al (2018)**	**GISERA HF study – Phase 2 2017 Dunne et al (2020)**	**Wieambilla Odour Investigation 2012 DSITIA (2013)**	**Hopeland, Chinchilla air monitoring study Mar 2015 DSITI (2015)**	**Hopeland, Chinchilla air monitoring study Dec 2015 DSITI (2016)**
30	Chloroethene						○		
31	Chlorobenzene	○		○	○	○	○	○	○
32	2-Chlorotoluene		○						
33	4-Chlorotoluene		○						
34	Cresol							○	
35	Cumene	●	○	○	○	○	○	○	○
36	**Cyclohexane**	●	●	●	●	○	●	●	●
37	**Cyclohexanone**			●	○	○		○	●
38	Cyclopentane	○	●				○	○	
39	Cyclopropane							○	
40	**Decane**	●	○	●	●		○	●	●

		Identified CSG-Industry Sources		Available ambient air sampling data:					
	Substance	**CSG Combustion emissions**	**Fugitive CSG emissions**	**GISERA ambient air quality study 2015-18 Lawson et al (2018 a,b,c)**	**GISERA HF study – Phase 1 2016-17 Dunne et al (2018)**	**GISERA HF study – Phase 2 2017 Dunne et al (2020)**	**Wieambilla Odour Investigation 2012 DSITIA (2013)**	**Hopeland, Chinchilla air monitoring study Mar 2015 DSITI (2015)**	**Hopeland, Chinchilla air monitoring study Dec 2015 DSITI (2016)**
41	Dibromomethane		○						
42	1,2-Dibromoethane	○	○				○	○	
43	Dibromochloromethane	○	○				○	○	
44	1,2-Dibromo-2-chloropropane		○						
45	Dichloromethane	●							
46	1,1-Dichloroethane		○					○	
47	1,2-Dichloroethane	○	○	○	○	○	○	○	○
48	1,1-Dichloroethylene	○	○				○	○	
49	cis-1,2-Dichloroethylene	○	○				○	○	
50	trans-1,2-Dichloroethylene	○					○	○	
51	1,2-Dichloropropane	○	○	○	○	○	○	○	○

		Identified CSG-Industry Sources		Available ambient air sampling data:					
	Substance	**CSG Combustion emissions**	**Fugitive CSG emissions**	**GISERA ambient air quality study 2015-18 Lawson et al (2018 a,b,c)**	**GISERA HF study – Phase 1 2016-17 Dunne et al (2018)**	**GISERA HF study – Phase 2 2017 Dunne et al (2020)**	**Wieambilla Odour Investigation 2012 DSITIA (2013)**	**Hopeland, Chinchilla air monitoring study Mar 2015 DSITI (2015)**	**Hopeland, Chinchilla air monitoring study Dec 2015 DSITI (2016)**
52	1,3-Dichloropropane		○						
53	2,2-Dichloropropane		○						
54	1,1-Dichloropropene		○						
55	cis-1,3-Dichloropropene	○	○				○	○	
56	trans-1,3-Dichloropropene	○	○				○	○	
57	1,2-Dichlorobenzene	○	○				○	○	
58	1,3-Dichlorobenzene	○	○				○	○	
59	**1,4-Dichlorobenzene**	○	○	○	○	○	○	●	●
60	**Dichlorodifluoromethane**	○					●	○	
61	Dichlorotetrafluoroethane	○						○	
62	1,2-dichloro-1,1,2,2-tetrafluoro- Ethane						○		

		Identified CSG-Industry Sources		Available ambient air sampling data:					
	Substance	**CSG Combustion emissions**	**Fugitive CSG emissions**	**GISERA ambient air quality study 2015-18 Lawson et al (2018 a,b,c)**	**GISERA HF study – Phase 1 2016-17 Dunne et al (2018)**	**GISERA HF study – Phase 2 2017 Dunne et al (2020)**	**Wieambilla Odour Investigation 2012 DSITIA (2013)**	**Hopeland, Chinchilla air monitoring study Mar 2015 DSITI (2015)**	**Hopeland, Chinchilla air monitoring study Dec 2015 DSITI (2016)**
63	1,3-Diethylbenzene		○					○	
64	1,4-Diethylbenzene	○	○				○	○	
65	2,2-Dimethylbutane	○	●				○	○	
66	2,3-Dimethylbutane	○					○	○	
67	2,3-Dimethylpentane	●	●				○	○	
68	2,4-Dimethylpentane	○	○				○	○	
69	Dimethyl heptane							○	
70	2,6-Dimethyl-4-heptanone		○						
71	Dimethylphenol							○	
72	1,4-Dioxane	○					○	○	
73	**Dodecane**	●	○				○	●	●

		Identified CSG-Industry Sources		Available ambient air sampling data:					
	Substance	**CSG Combustion emissions**	**Fugitive CSG emissions**	**GISERA ambient air quality study 2015-18 Lawson et al (2018 a,b,c)**	**GISERA HF study – Phase 1 2016-17 Dunne et al (2018)**	**GISERA HF study – Phase 2 2017 Dunne et al (2020)**	**Wieambilla Odour Investigation 2012 DSITIA (2013)**	**Hopeland, Chinchilla air monitoring study Mar 2015 DSITI (2015)**	**Hopeland, Chinchilla air monitoring study Dec 2015 DSITI (2016)**
74	Ethane	●	●						
75	**Ethanol**						●	●	
76	**Ethyl acetate**	○		●	●		●	●	●
77	**Ethylbenzene**	●	○		●	●	●	●	●
78	Ethyl chloride						○		
79	Ethylene	●	○						
80	2-Ethylhexanol			○	○	○		○	○
81	Ethyl tert-butyl ether			○	○	○		○	○
82	2-Ethyltoluene	●	○				○	○	
83	3-Ethyltoluene	●	○				○	○	
84	4-Ethyltoluene	●	○				○	○	

		Identified CSG-Industry Sources		Available ambient air sampling data:					
	Substance	**CSG Combustion emissions**	**Fugitive CSG emissions**	**GISERA ambient air quality study 2015-18 Lawson et al (2018 a,b,c)**	**GISERA HF study – Phase 1 2016-17 Dunne et al (2018)**	**GISERA HF study – Phase 2 2017 Dunne et al (2020)**	**Wieambilla Odour Investigation 2012 DSITIA (2013)**	**Hopeland, Chinchilla air monitoring study Mar 2015 DSITI (2015)**	**Hopeland, Chinchilla air monitoring study Dec 2015 DSITI (2016)**
85	Formaldehyde	●		●	●	●			
86	Glutaraldehyde			○	○				
87	Glyoxal								
88	**Heptane**	●	●	●	○	○	●	●	○
89	Hexachlorobutadiene	○	○				○	○	
90	**Hexane**	●	●	●	●		●	○	●
91	**Hexanaldehyde**			●	●				
92	2-Hexanone	●					○		
93	1-Hexene	●	○				○	○	
94	**Isobutane**	●	●				○	●	
95	**Isobutanol**			○	○	○		●	○

		Identified CSG-Industry Sources		Available ambient air sampling data:					
	Substance	**CSG Combustion emissions**	**Fugitive CSG emissions**	**GISERA ambient air quality study 2015-18 Lawson et al (2018 a,b,c)**	**GISERA HF study – Phase 1 2016-17 Dunne et al (2018)**	**GISERA HF study – Phase 2 2017 Dunne et al (2020)**	**Wieambilla Odour Investigation 2012 DSITIA (2013)**	**Hopeland, Chinchilla air monitoring study Mar 2015 DSITI (2015)**	**Hopeland, Chinchilla air monitoring study Dec 2015 DSITI (2016)**
96	Isoprene							○	
97	**Isopropyl alcohol**	○					○	●	
98	p-Isopropyl toluene	○							
99	**2-Methylbutane**	●	●				●	●	
100	2-Methyl -1,3-butadiene	●	○				○		
101	1-Methoxy-2-propanol			○	○	○			○
102	1-Methoxy-2-propylacetate			○	○	○			○
103	3-Methyl-2-butanone		○						
104	**Methylene chloride**						○	●	
105	Methyl butyl ketone							○	
106	**Methylcyclohexane**	●	●	●	○	○	●	●	○

		Identified CSG-Industry Sources		Available ambient air sampling data:					
	Substance	**CSG Combustion emissions**	**Fugitive CSG emissions**	**GISERA ambient air quality study 2015-18 Lawson et al (2018 a,b,c)**	**GISERA HF study – Phase 1 2016-17 Dunne et al (2018)**	**GISERA HF study – Phase 2 2017 Dunne et al (2020)**	**Wieambilla Odour Investigation 2012 DSITIA (2013)**	**Hopeland, Chinchilla air monitoring study Mar 2015 DSITI (2015)**	**Hopeland, Chinchilla air monitoring study Dec 2015 DSITI (2016)**
107	**Methyl cyclopentane**	●	●	●	○	○	○	●	●
108	**Methyl ethyl ketone**	●	○	●	○	○	●	●	○
109	2-Methylheptane	●	○				○	○	
110	3-Methylheptane	●	○				○	○	
111	2-Methylhexane	●	●				○	○	
112	3-Methylhexane	●	●				○	○	
113	**Methyl isobutyl ketone**	○		○	●	○		○	○
114	**2-Methylpentane**	●	●	●	●	○	○	○	●
115	**3-Methylpentane**	●	●	●	●	○	●	●	●
116	4-Methyl-2-pentanone		○						
117	Methyl methacrylate	○		○	○	○	○	○	○

		Identified CSG-Industry Sources		Available ambient air sampling data:					
	Substance	**CSG Combustion emissions**	**Fugitive CSG emissions**	**GISERA ambient air quality study 2015-18 Lawson et al (2018 a,b,c)**	**GISERA HF study – Phase 1 2016-17 Dunne et al (2018)**	**GISERA HF study – Phase 2 2017 Dunne et al (2020)**	**Wieambilla Odour Investigation 2012 DSITIA (2013)**	**Hopeland, Chinchilla air monitoring study Mar 2015 DSITI (2015)**	**Hopeland, Chinchilla air monitoring study Dec 2015 DSITI (2016)**
118	Methyl tert-butyl ether	○		○	○	○	○	○	○
119	**Naphthalene**			○	○	○	●	●	○
120	**Nonane**	●	○	●	○	○	○	●	○
121	**Octane**	●	●	●	○	○	○	○	○
122	**Pentane**	●	●				●	●	
123	**Pentanaldehyde**			●	●	○			
124	1-Pentene	●	○				○	○	
125	cis-2-Pentene	●	○				○	○	
126	trans-2-Pentene	●	○				○	○	
127	**Phenol**							●	
128	α-Pinene							○	

		Identified CSG-Industry Sources		Available ambient air sampling data:					
	Substance	**CSG Combustion emissions**	**Fugitive CSG emissions**	**GISERA ambient air quality study 2015-18 Lawson et al (2018 a,b,c)**	**GISERA HF study – Phase 1 2016-17 Dunne et al (2018)**	**GISERA HF study – Phase 2 2017 Dunne et al (2020)**	**Wieambilla Odour Investigation 2012 DSITIA (2013)**	**Hopeland, Chinchilla air monitoring study Mar 2015 DSITI (2015)**	**Hopeland, Chinchilla air monitoring study Dec 2015 DSITI (2016)**
129	β-Pinene							○	
130	**Propane**	●	●				○		
131	**Propanaldehyde**			●	●				
132	**Propene**	●	○				●		
134	**2-Propenenitrile**							●	
135	**Propylbenzene**	●	○	○	○	○	○	●	○
136	Propylene glycol methyl ether							○	
137	Propylene glycol methyl ether acetate							○	
138	**Styrene**	●	○	○	○	●	○	●	○
139	1,1,1,2-Tetrachloroethane		○						
140	1,1,2,2-Tetrachloroethane	○					○	○	

		Identified CSG-Industry Sources		Available ambient air sampling data:					
	Substance	**CSG Combustion emissions**	**Fugitive CSG emissions**	**GISERA ambient air quality study 2015-18 Lawson et al (2018 a,b,c)**	**GISERA HF study – Phase 1 2016-17 Dunne et al (2018)**	**GISERA HF study – Phase 2 2017 Dunne et al (2020)**	**Wieambilla Odour Investigation 2012 DSITIA (2013)**	**Hopeland, Chinchilla air monitoring study Mar 2015 DSITI (2015)**	**Hopeland, Chinchilla air monitoring study Dec 2015 DSITI (2016)**
141	**Tetrachloroethylene**	○	○	○	●	○	●	○	○
142	Tetradecanes		○						
143	Tetrahydrofuran	●					○	○	
144	**Toluene**	●	●	●	●	●	●	●	●
145	Tribromomethane						○		○
146	Tridecanes	○							
147	1,1,1-Trichloroethane	○	○	○	○	○	○	○	○
148	1,1,2-Trichloroethane	○	○				○	○	
149	Trichloroethylene	○	○	○	○	○	○	○	○
150	**Trichlorofluoromethane**	○					○	●	
151	**Trichloromethane**	○	○	●	●	○	○	●	

		Identified CSG-Industry Sources		Available ambient air sampling data:					
	Substance	**CSG Combustion emissions**	**Fugitive CSG emissions**	**GISERA ambient air quality study 2015-18 Lawson et al (2018 a,b,c)**	**GISERA HF study – Phase 1 2016-17 Dunne et al (2018)**	**GISERA HF study – Phase 2 2017 Dunne et al (2020)**	**Wieambilla Odour Investigation 2012 DSITIA (2013)**	**Hopeland, Chinchilla air monitoring study Mar 2015 DSITI (2015)**	**Hopeland, Chinchilla air monitoring study Dec 2015 DSITI (2016)**
152	1,2,3-Trichlorobenzene		○						
153	1,2,4-Trichlorobenzene	○	○				○	○	
154	1,2,3- Trichloropropane		○						
155	1,1,2-trichloro-1,2,2-trifluoro- Ethane	○						○	
156	1,2,3-Trimethylbenzene	●	○				○	○	
157	**1,2,4-Trimethylbenzene**	●	○	●	○	○	●	●	●
158	1,3,5-Trimethylbenzene	●	○				○	○	
159	2,2,4-Trimethylpentane	○	●	●	○	○	○	○	
160	2,3,4-Trimethylpentane	●	●				○	○	○
161	**Undecane**	●	○	●	●		○	●	●
162	**Vinyl acetate**	○					●	●	

		Identified CSG-Industry Sources		Available ambient air sampling data:					
	Substance	**CSG Combustion emissions**	**Fugitive CSG emissions**	**GISERA ambient air quality study 2015-18 Lawson et al (2018 a,b,c)**	**GISERA HF study – Phase 1 2016-17 Dunne et al (2018)**	**GISERA HF study – Phase 2 2017 Dunne et al (2020)**	**Wieambilla Odour Investigation 2012 DSITIA (2013)**	**Hopeland, Chinchilla air monitoring study Mar 2015 DSITI (2015)**	**Hopeland, Chinchilla air monitoring study Dec 2015 DSITI (2016)**
163	Vinyl bromide							○	
164	Vinyl chloride	○						○	
165	**Xylenes**	●	●	●	●	●	●	●	●
166	Acenaphthene		○						
167	Acenaphthylene		○						
168	Anthracene		○						
169	**Benz(a) anthracene**		○			●			
170	Benzo(a)pyrene		○						
171	**Benzo(e)pyrene**					●			
172	**Benzo(b,j,k)fluoranthene**		○			●			

		Identified CSG-Industry Sources		Available ambient air sampling data:					
	Substance	**CSG Combustion emissions**	**Fugitive CSG emissions**	**GISERA ambient air quality study 2015-18 Lawson et al (2018 a,b,c)**	**GISERA HF study – Phase 1 2016-17 Dunne et al (2018)**	**GISERA HF study – Phase 2 2017 Dunne et al (2020)**	**Wieambilla Odour Investigation 2012 DSITIA (2013)**	**Hopeland, Chinchilla air monitoring study Mar 2015 DSITI (2015)**	**Hopeland, Chinchilla air monitoring study Dec 2015 DSITI (2016)**
173	**Benzo(g,h,i)perlyene**		○			●			
174	**Chrysene**		○			●			
175	**Dibenz(a,h)anthracene**		○			●			
176	Fluoranthene		○						
177	**Fluorene**		○			●			
178	**Indeno(1,2,3-c-d)pyrene**		○			●			
179	Phenanthrene		○						
180	**Pyrene**		○			●			
181	Hydrogen sulfide		●	○	○	○		○	
182	Carbon disulfide		○						

		Identified CSG-Industry Sources		Available ambient air sampling data:					
	Substance	**CSG Combustion emissions**	**Fugitive CSG emissions**	**GISERA ambient air quality study 2015-18 Lawson et al (2018 a,b,c)**	**GISERA HF study – Phase 1 2016-17 Dunne et al (2018)**	**GISERA HF study – Phase 2 2017 Dunne et al (2020)**	**Wieambilla Odour Investigation 2012 DSITIA (2013)**	**Hopeland, Chinchilla air monitoring study Mar 2015 DSITI (2015)**	**Hopeland, Chinchilla air monitoring study Dec 2015 DSITI (2016)**
183	Dimethyl disulfide		○						
184	**Carbon disulfide**	○	○				○	●	
185	**Mercury**		●			●			
186	**Radon-222 (see sect 7.4)**		●			●			
187	Arsenic		○			○			
188	**Manganese**					●			
189	Nickel					○			
190	Sulfate					●			
191	Carbon monoxide		○					○	

7 Case Study- Impact of a CSG release event on air quality

The Health Study region is an area of intensive CSG development and large-scale gas infrastructure, with associated air emission sources distributed across the study region. Setbacks provide separation between the general public and large central processing facilities, however well pads, gathering lines, HPVs, LPDs compressions stations and the associated road infrastructure are distributed throughout places where people live and work predominantly in agricultural areas.

Intentional releases of CSG from wells, gathering networks, HPVs, and LPDs are frequent, while unintentional releases are less frequent but do occur in the vicinity of residences and workplaces in the study region (DEEDI 2010). These unintentional releases often involve the release of large volumes of gas which may pose a hazard to local air quality. Here we present a case study of a real-life unintentional methane release event observed in the Health Study region in 2016 and provide an analysis of the likely impact of air quality at the location where the release was detected.

Ambient methane data was collected at 5 sites in the Health Study region from 2014 – 2018 as part of the GISERA Ambient Air Quality Study and GISERA Regional Methane Fluxes projects (https://gisera.csiro.au/project/methane-seepage-in-the-surat-basin/). In addition, ambient methane data from 3 monitoring sites in the Health Study region for the period 2017 – 2019 was provided by industry for the purposes of the report presented here.

The maximum methane level observed across the data sets from 2014 – 2019 was 79 ppm (5-min average) recorded in March 2016 at the Condamine air quality monitoring station (Lawson et al., 2018). This methane event is higher than the highest methane peak of 53 ppm recently reported by Lu et al., (2021) from vehicle mounted methane surveys across the study region undertaken in 2018 and 2019.

The CSG company advised that the emission source in the Condamine event was due to a failure of an auto-low point drain injection point approximately 150 m to the southwest of the Condamine ambient air station. The low point drain is designed to move water from the gas gathering line into the adjacent water gathering line. The leak occurred because the automatic low point drain remained in the open position after operation, resulting in a gas release.

Assuming the observed methane level of 79 ppm was solely attributed to the release of CSG this would represent a ~ 1/12000 dilution of pure CSG. Based on gas composition analysis data reported in Section 2.6 the maximum calculated concentration of other components in the CSG once diluted can be estimated and the results are reported in Table 8 alongside their relevant air quality objectives.

The results of this analysis show that, while the methane concentrations during this event were significantly elevated above background concentrations (background methane ≈ 1.8 ppm), the low

levels of these other gases in the CSG are estimated to have made only a minor contribution to ambient air pollutant concentrations, well below air quality objectives, once the CSG was diluted in ambient air.

During the event levels of NEPM criteria pollutants measured at the station (Table 9) were well below air quality standards and were not correlated with methane peaks.

Table 8: Estimated maximum contribution of CSG to ambient air pollutant concentrations during a CSG release event (Case Study 1) in which a methane peak of 79 ppm (5-min average) was observed at Condamine in March 2016 (Lawson et al 2018).

Compounds	**Estimated maximum contribution to ambient levels during methane event (Case Study 1)** **(79 ppm CH_4 ≈ 1/ 12000 dilution)**	**Ambient Air Quality objective** **Short-term**	**Ambient Air Quality objective** **Long-term**
Ethane	80 ppb[1] 20 ppb[2] 1740 ppb[3]	Simple Asphyxiant[7] (not hazardous at ambient levels)	Simple Asphyxiant[7] (not hazardous at ambient levels)
Propane	10 ppb[1] 265 ppb[3]	Simple Asphyxiant[7] (not hazardous at ambient levels)	Simple Asphyxiant[7] (not hazardous at ambient levels)
Iso-Butane	0.83 ppb[1] 16.2 ppb[3]	33000 ppb [4]	10000 ppb[4]
N-Butane	0.83 ppb[1] 20.9 ppb[3]	92000 ppb[4]	10000 ppb[4]
Iso-Pentane	0.83 ppb[1] 2.42 ppb[3]	68000 ppb[4]	8100 ppb[4]
N-Pentane	0.83 ppb[1] 2.00 ppb[3]	68000 ppb[4]	8100 ppb[4]
Cyclopentane	0.06 ppb[3]	5900 ppb[4]	590 ppb[4]
2,2- Dimethylbutane	0.02 ppb[3]	5400 ppb[4]	190 ppb[4]
2,3- Dimethylbutane	0.03 ppb[3]	5400 ppb[4]	190 ppb[4]
2-Methylpentane	0.14 ppb[3]	5400 ppb[4]	190 ppb[4]
3-Methylpentane	<< 0.01 ppb[1] 0.06 ppb[3]	5400 ppb[4]	190 ppb[4]
N-hexane	< 0.08 ppb[1] 0.14 ppb[3]	5400 ppb[4]	190 ppb[4]

Compounds	Estimated maximum contribution to ambient levels during methane event (Case Study 1) (79 ppm CH_4 ≈ 1/ 12000 dilution)	Ambient Air Quality objective Short-term	Ambient Air Quality objective Long-term
Cyclohexane	< 0.08 ppb[1] 0.14 ppb[3]	1000ppb[4]	100 ppb[4]
2-Methylhexane	0.01 ppb[3]	8300 ppb[4]	2200 ppb[4]
3-Methylhexane	0.01 ppb[3]	8300 ppb[4]	2200 ppb[4]
2,3-Dimethylpentane	< 0.01 ppb[3]	8300 ppb[4]	2200 ppb[4]
N-Heptane	< 0.08 ppb[1] 0.02 ppb[3]	8300 ppb[4]	2200 ppb[4]
Iso-Octane	<< 0.01 ppb[3]	4100 ppb[4]	380 ppb[4]
N-Octane	< 0.08 ppb[1] << 0.01 ppb[3]	4100 ppb[4]	380 ppb[4]
Methylcyclohexane	< 0.08 ppb[1] 0.09 ppb[3]	4000 pbb[4]	400 ppb[4]
Benzene	≤ 0.08 ppb[1] 0.05 ppb[3]	180 ppb[4]	1.4 ppb[4] 3 ppb[5,6]
Toluene	≤ 0.08 ppb[1] 0.02 ppb[3]	4000 ppb[4] 1000 ppb[5,6]	1100 ppb[4] 100 ppb[5,6]
m- / p- Xylenes	≤ 0.08 ppb[1] ≤ 0.01 ppb[3]	1700 ppb[4] 250 ppb[5,6]	140 ppb[4] 200 ppb[5,6]
Hydrogen Sulfide	≤ 0.01 ppb[1]	118 ppb[6]	14 ppb[7]
Mercury & compounds	<< 0.01 µg/m3 [1]	-	1.1 µg /m3[9]
Radon-222	0.03 Bq/m3 [1]	200 Bq/m3[8]	-

[1] Based on gas composition data provided by Company 1; [2] Based on gas composition data provided by Company 2; [3]Based on gas composition data reported in Day et al (2016).

[4] Ambient Air Quality Objective based on Texas AMCVs/ESLs; [5] Ambient Air Quality Objective based on NEPM (Air Toxics) 2011; [6] Ambient Air Quality Objective based on Qld EPP (Air) 2008; [7] Ambient Air Quality Objective based on WA Dept of Health (2009) recommended levels (90 day exposure); [8] Ambient air quality objective based on ARPANSA (2002) Guidance note on recommended action levels for radon-222 concentration in air for households and workplaces.

Table 9: Levels of NEPM criteria ambient air pollutants during a CSG release event (Case Study 1) in which a methane peak of 79 ppm (5-min average) was observed at Condamine in March 2016 (Lawson et al 2018a).

Criteria pollutant	Event	Air quality Objective	Averaging period
PM_{10}	9.3 µg/m3	50 µg/m3	24-hour
$PM_{2.5}$	2.8 µg/m3	25 µg/m3	24-hour
CO	0.10 ppm	9.0 ppm	8-hour
O_3	0.04 ppm 0.03 ppm	0.10 ppm 0.08 ppm	1-hour 4-hour
NO_2	0.01 ppm	0.12 ppm	1-hour

8 Summary

CSG production has rapidly expanded in the Surat Basin in Queensland in the last 20 years and this rapid growth has raised community concerns about the potential impact of CSG industry emission on the air quality in the region.

This report provides an appraisal of the available information on sources of air emissions from CSG activities in the defined study area, the composition of those emissions, and the pathways by which the community may be exposed to these air pollutants are described. The CSG industry is a source of potentially hazardous emissions to air of:

- NO_x,
- CO,
- particulate matter (PM_{10} and $PM_{2.5}$)
- VOC
- O_3 – secondary production from emissions of NO_x and VOCs
- inorganic gases - including hydrogen sulfide, radon and mercury

Based on the information examined in Sections 3 and 4, the substances listed above satisfy the criteria for progression to subsequent stages of the health study framework comprising screening and further assessment, as they have known impacts on human health, as evidenced by the existence of legislated ambient air quality objectives (e.g. NEPC 2011, 2021, Qld EPP 2019), national emissions reporting requirements (NEPC 2008) and other national and state-based guidelines for these substances; and are highly mobile and persistent enough in the environment to ensure plausible pathways of community exposure via inhalation pose a realistic hazard.

Sections 5 and 6 examined the available information from observation and modelling studies of the ambient air quality in the study region in relation to the identified substances. The data examined was collected in gas-field and community locations in the study region over the period 2012 – 2019 and provide key input into the **Screening and Further Assessment** Stages of the Health Study Framework (Keywood et al., 2018).

Analysis of monitoring data from the study region found air quality in relation to NO_x and CO was always within relevant health-based air quality objectives (Lawson et al., 2018 a,b,c, Dunne et al., 2020, DES 2020). Modelling studies indicate that when CSG-related emissions contributed to modelled values of NO_2 which were >80 % of the relative air quality objective (NEPC 2016), CSG-related emissions contributed up to 99 % to the total concentration.

Analysis of the O_3 monitoring data from the study region found levels were occasionally close to (>80%) the NEPM air quality objectives (Lawson et al., 2018 a,b,c, Dunne et al., 2020, DES, 2020), however, modelling studies indicated, that during these peak events, CSG-related emissions contributed only 3 – 7 % to the total O_3 concentration (Noonan et al., 2019).

There were occasional exceedances of $PM_{2.5}$ air quality objectives observed in monitoring data from the study region. Modelling studies indicated, that during these peak events, CSG-related emissions contributed at most 4 - 37 % to 24-hour $PM_{2.5}$ concentrations (Noonan et al., 2019) and analysis of satellite data and other trace species in the monitoring studies were used to show that high $PM_{2.5}$ events were typically associated with smoke from local and regional fires (Lawson et al., 2018 a,b,c, Dunne et al., 2020).

Airborne particulate matter as TSP and PM_{10} was the most common cause of observed exceedances of air state and national quality objectives reported in monitoring studies in the Surat Basin and in most cases were attributable to fugitive soil dust emissions from CSG industry activities including vehicle moments, construction, etc (Lawson et al., 2018 a,b,c, Dunne et al., 2020) and other rural activities such as smoke from fires, vehicle, machinery and stock movement. It is a requirement of Queensland Government Environmental Authority conditions that companies do not cause environmental nuisance from dust at a sensitive place (e.g., residences, community buildings, public parks etc) unless a formally agreed alternative arrangement is in place (Qld Gov 2018). Environmental authorities also often include specified monitoring requirements for releases to air in order for the company to demonstrate they are complying with their EA requirements. More about reporting an environmental nuisance caused by dust can be found here.

Data on respirable silica levels in these studies are not available however an estimate of respirable silica based on the silica concentrations measured in PM_{10} during the hydraulic fracturing study (Dunne et al., 2020) suggest that concentrations in that study would have been below workplace Australian standard for respirable silica. However, the estimated maximum concentrations were similar to the standard level being proposed by the Australian Cancer Council (20 $\mu g/m^3$).

The air quality monitoring network initially established by CSIRO's GISERA as part of the Surat Basin Air Quality study continues to monitor concentrations of key NEPM criteria pollutants. Data are streamed to the Queensland Department of Environment and Science (DES) website under South West Queensland region and available data is live-reported here.

A large number of VOCs are emitted from CSG industry sources including combustion emissions, fugitive CSG emissions as well as drilling and hydraulic fracturing additives. Due to their potential significant impact on human health, several VOCs are listed in the National Environment Protection Measures for Air Toxics (NEPC, 2011) including several of those reported in CSG industry emissions namely formaldehyde, benzene, toluene, and xylenes (BTEX).

Data from 6 VOC monitoring studies undertaken between 2012 – 2018 across a number of sites in the Surat Basin including gas-field sites, hydraulic fracturing sites and residential/community sites (DSITIA 2013, DSITI 2015, 2016, Lawson et al 2018 a,b,c, Dunne et al., 2018, Dunne et al., 2020) consistently reported levels of all VOCs that were within their relevant air quality objectives in all of the ambient air monitoring studies examined for this report.

Radon and mercury were both detected in analysis of CSG samples collected from wells in the study region, however the limited data that exists on the ambient levels of radon and mercury for the study region were well below guidelines for households and workplaces at all times (Tait et al., 2013, Dunne et al., 2020). Combined with more data on the composition of CSG over the lifetime of the CSG developments, the air emissions of mercury, radon, VOCs and H_2S via fugitive CSG

releases could be assessed further using previously determined estimates of fugitive methane emissions from the CSG industry in the region (Luhar et al., 2018, 2020).

A case-study of a real life CSG release event was used along with CSG composition data from Section 4.3, to demonstrate the likely impact of such an unintentional CSG release event on the airborne levels of contaminants such as VOCs, radon, mercury and hydrogen sulfide during such an event. The results of this analysis showed that, while the methane concentrations during this event were significantly elevated above background concentrations (~80 ppm) the low levels of these other gases in the CSG were estimated to have made only a minor contribution to ambient air pollutant concentrations, well below air quality objectives, once the CSG was diluted in ambient air.

Overall, the information summarised in this report can be used to inform subsequent stages in the Health Study framework when determining priorities for exposure assessments related to air-pollutants and when developing recommendations for more in-depth studies.

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10 Appendices

Table A 1: Emissions concentrations data from gas -fired screw compressors, reciprocating compressors and gas-powered generators collected at the Talinga GPF in 2014 and 2015 (Source: Lawson et al 2017, Appendices A.1.3).

Substance	Units	Reciprocating compressors	Screw Compressors	Power generators
Nitrogen oxides	mg/m^3	107 – 243 128 - 283	2263 – 7376 371 - 6750	4897 – 6534 7967 - 10805
Carbon Monoxide	mg/m^3	426 – 523 451 – 523	178 – 4862 149 – 3250	732 – 1052 491 – 521
Methane	mg/m^3		445 – 513	
Ethane	mg/m^3		1.9 – 5.1	
Ethene	mg/m^3		1.7 – 34.9	
Propane	mg/m^3	< 0.9	< 0.04 – 0.16 < 0.9 $\mu g/m^3$	
Propene	mg/m^3	409 – 518 470 $\mu g/m^3$	0.04 – 2.48 106 -1280 $\mu g/m^3$ 110 – 1600 $\mu g/m^3$	
I-Butane	mg/m^3	 < 1.2 $\mu g/m^3$	0.52 – 1.61 < 1.2 $\mu g/m^3$	
N-Butane		< 1.2 $\mu g/m^3$	≤ 0.08 mg/m^3 < 1.2 $\mu g/m^3$	
Butene	mg/m^3		0.35 – 0.98	
1-Butene	$\mu g/m^3$	238 - 381	39.4 – 151.0	
trans-2-Butene	$\mu g/m^3$	24.1 – 29.4	< 1.1 – 12.6	
cis-2-butene	$\mu g/m^3$	15.8 – 19.7	< 1.1 – 6.9	
Iso-Pentane	$\mu g/m^3$	< 1.5	< 1.5 – 5.7	
N-Pentane	$\mu g/m^3$	3.2 – 8.6	< 1.5 – 21.2	
1-Pentene	$\mu g/m^3$	92.6 - 114	6.6 – 44.7	
trans-2-Pentene	$\mu g/m^3$	11.8 – 18.6	< 1.4 – 5.4	

Substance	Units	Reciprocating compressors	Screw Compressors	Power generators
cis-2-Pentene	µg/m^3	5.2 – 7.4	< 1.4 – 2.9	
2-methyl-1,3-butadiene	µg/m^3	< 1.3 – 12.5	< 1.3	
2,2-Dimethylbutane	µg/m^3	< 1.8	< 1.8	
2,3-Dimethylbutane	µg/m^3	< 1.8	< 1.8	
2-Methylpentane	µg/m^3	< 1.8	< 1.8 – 19.4	
3-Methylpentane	µg/m^3	< 1.8 – 2.8	< 1.8 – 9.2	
Cyclopentane	µg/m^3	< 1.4	< 1.4	
N-Hexane	µg/m^3	< 1.8 – 4.2 < 0.7	< 1.8 – 16.6 < 10	
1-Hexene	µg/m^3	83.2 - 109	7.2 – 33.8	
2,3-Dimethylpentane	µg/m^3	< 2.0	< 2.0 – 3.3	
2,4-Dimethylpentane	µg/m^3	< 2.0	< 2.0	
Methyl cyclopentane	µg/m^3	< 1.7	< 1.7 – 7.6	
2-Methylhexane	µg/m^3	< 2.0	< 2.0 – 13.1	
3-Methylhexane	µg/m^3	3.3 – 8.2	< 2.0 – 15.2	
Cyclohexane	µg/m^3	< 1.7 < 0.7	< 1.7 – 16.2	
N-Heptane	µg/m^3	< 2.0 – 2.4 < 0.9	< 2.0 – 14.7 < 20	
Methylcyclohexane	µg/m^3	< 2.0	< 2.0 – 9.2	
2-Methylheptane	µg/m^3	< 2.3 – 2.8	< 2.3 – 41.1	
3-Methylheptane	µg/m^3	< 2.3	< 2.3 – 21.5	
Iso-Octane	µg/m^3	< 2.3	< 2.3 – 92.0	
N-Octane	µg/m^3	< 2.3	< 2.3 – 10.7	
N-Nonane	µg/m^3	< 2.6	< 2.6 – 5.8	
N-Decane	µg/m^3	< 2.9	< 2.9 – 5.2	

Substance	Units	Reciprocating compressors	Screw Compressors	Power generators
N-Undecane	µg/m^3	< 3.2	< 3.2 – 4.5	
N-Dodecane	µg/m^3	< 3.5 – 8.4	< 3.5 – 4.2	
Benzene	µg/m^3	54.6 – 65.1 73	91.6 – 1410 86 – 1360	
Toluene	µg/m^3	30 – 57 39	32 – 433 26 – 360	
Ethylbenzene	µg/m^3	3.9 – 7.8 4.9	2.6 – 18.2	
m-, p- Xylene	µg/m^3	8.2 – 31.7 11	9.1 – 159 5.1 – 95	
o-Xylene	µg/m^3	3.5 – 10.4 3.8	3.0 – 46.9 1.7 - 36	
Styrene	µg/m^3	< 2.1 – 5.5 < 6	< 2.1 – 2.6 < 20	
Isopropyl benzene	µg/m^3	< 2.4	< 2.4 – 11.8	
n-Propylbenzene	µg/m^3	≤ 2.4	< 2.4 – 6.9	
2- Ethyl toluene	µg/m^3	< 2.4 – 6.4	< 2.4 – 18.2	
3- Ethyl toluene	µg/m^3	≤ 2.4	< 2.4 – 5.4	
4- Ethyl toluene	µg/m^3	< 2.5 – 3.0 < 1	< 2.5 – 9.4 < 20	
1,3,5-Trimethylbenzene	µg/m^3	< 2.4 – 2.9	< 2.4 – 2.9 < 20	
1,2,4-Trimethylbenzene	µg/m^3	< 2.4 – 13.3 < 1	< 2.4 – 23.6 < 2 – 62	
1,2,3- Trimethylbenzene	µg/m^3	< 2.4 – 3.4 3.8	< 2.4 – 4.4	
1,4-Diethylbenzene	µg/m^3	< 2.7	< 2.7	
1,3-Diethylbenzene	µg/m^3	< 2.7 – 4.9	< 2.7 – 6.0	

Substance	Units	Reciprocating compressors	Screw Compressors	Power generators
Naphthalene	µg/m^3	6.8 – 11.5 < 7	11.5 – 69.7 < 70	
Dichlorodifluoromethane	µg/m^3	< 1	< 20	
Chloromethane	µg/m^3	< 1	< 20	
1,2-Dichlorotetrafluoroethane	µg/m^3	< 1	< 30	
Vinyl chloride	µg/m^3	< 0.5	< 10	
1,3-Butadiene	µg/m^3	12	< 8	
Bromomethane	µg/m^3	< 6	< 100	
Chloroethane	µg/m^3	< 0.5	< 10	
Acetone	µg/m^3	130	41 – 120	
Ethanol	µg/m^3	48	< 20 – 85	
2- Propanol	µg/m^3	< 0.5	< 9	
Trichlorofluoromethane	µg/m^3	< 1	< 20	
1,1-Dichloroethene	µg/m^3	< 0.8	< 20	
Dichloromethane	µg/m^3	< 2	< 2 – 56	
1,1,2-Trichloro-1,2,2 trifluoroethane	µg/m^3	< 2	< 30	
Carbon disulfide	µg/m^3	4.4	18 – 45	
trans-1,2-Dichloroethene	µg/m^3	< 0.8	< 20	
1,1-Dichloroethane	µg/m^3	< 0.8	< 20	
Methyl-tert-butyl ether (MTBE)	µg/m^3	< 0.8	< 10	
Vinyl acetate	µg/m^3	< 0.7	< 10	
2-Butanone (MEK)	µg/m^3	43	12 – 27	
cis-1,2-Dichloroethene	µg/m^3	< 0.8	< 20	
Chloroform	µg/m^3	< 1	< 20	

Substance	Units	Reciprocating compressors	Screw Compressors	Power generators
Ethyl Acetate	µg/m^3	< 0.8	< 10	
Tetrahydrofuran	µg/m^3	6.6	< 10	
1,2-Dichloroethane	µg/m^3	< 0.8	< 20	
1,1,1-Trichloroethane	µg/m^3	< 1	< 20	
Carbon tetrachloride	µg/m^3	< 1	< 20	
1,2-Dichloropropane	µg/m^3	< 1	< 20	
Bromodichloromethane	µg/m^3	< 1	< 30	
Trichloroethene	µg/m^3	< 1	< 20	
1,4-Dioxane	µg/m^3	< 0.8	< 10	
Methyl methacrylate	µg/m^3	< 0.9	< 20	
cis-1,3-Dichloropropene	µg/m^3	< 1	< 20	
4-Methyl-2-pentanone (MIBK)	µg/m^3	1.4	< 20	
trans-1,3-Dichloropropene	µg/m^3	< 1	< 20	
1,1,2-Trichloroethane	µg/m^3	< 1	< 20	
2-Hexanone (MBK)		9.5	< 20	
Dibromochloromethane		< 2	< 30	
1,2-Dibromoethane		< 2	< 30	
Tetrachloroethylene		< 1	< 30	
Chlorobenzene		< 1	< 20	
Bromoform		< 2	< 40	
1,1,2,2-Tetrachloroethane		< 1	< 30	
Benzyl Chloride		< 1	< 20	
1,2-Dichlorobenzene		< 1	< 20	
1,3-Dichlorobenzene		< 1	< 20	

Substance	Units	Reciprocating compressors	Screw Compressors	Power generators
1,4-Dichlorobenzene		< 1	< 20	
1,2,4-Trichlorobenzene		< 3	< 30	
Hexachlorobutadiene		< 2		
Formaldehyde	mg/m^3	14.5 – 19.0	0.3 – 6.9	
Acetaldehyde	mg/m^3	< 0.2 – 0.4	< 0.2	
Acrolein	mg/m^3	< 0.2 – 0.4 1540 $\mu g/m^3$	< 0.2 110 - 450 $\mu g/m^3$	

Table A 2 . Summary of CSG composition data reported from analysis of gas samples collected in the health study region (Company 1 & 2) and a more sensitive analysis of CSG samples collected from gas wells in NSW (Day et al 2016). Put this table in appendix

	Substance	CAS #	Company 1 CSG Analysis[1] concentration range	Company 2 CSG Analysis[2] concentration range (N = 28)	Day et al (2016) CSG Analysis concentration range (N = 6)
1	Methane	74-82-8	96.4 - 98.5% (N=133)	98.5 - 99.1 %	NM
2	Ethane	74-84-0	58 – 930 ppm (N=133)	100 – 200 ppm	136 – 20885 ppm
3	Ethene	74-85-1	NM	NM	≤ 0.007 ppm
4	Acetylene	74-86-2	NM	NM	≤ 0.007 ppm
5	Propane	74-98-6	10 – 120 ppm (N=123)	NR	7 – 3174 ppm
6	Propene	115-07-1	NM	NM	≤ 0.007 ppm
7	I-Butane	75-28-5	2 – 10 ppm (N=51)	NR	2 – 194 ppm
8	N-Butane	106-97-8	5 – 10 ppm (N=51)	NR	1 – 251 ppm
9	1-Butene	106-98-9	NM	NM	≤ 0.007 ppm
10	cis-2-Butene	590-18-1	NM	NM	≤ 0.007 ppm
11	trans-2-Butene	624-64-6	NM	NM	≤ 0.007 ppm
12	I-Pentane	78-78-4	4 – 10 ppm (N=51)	NR	0.3 – 29 ppm
13	N-Pentane	109-66-0	4 – 10 ppm (N=51)	NR	0.1 – 24 ppm

	Substance	CAS #	Company 1 CSG Analysis[1] concentration range	Company 2 CSG Analysis[2] concentration range (N = 28)	Day et al (2016) CSG Analysis concentration range (N = 6)
14	1-Pentene	109-67-1	NM	NM	≤ 0.007 ppm
15	cis-2-Pentene	627-20-3	NM	NM	≤ 0.007 ppm
16	trans-2-Pentene	646-04-8	NM	NM	≤ 0.007 ppm
17	Isoprene	78-79-5	NM	NM	≤ 0.007 ppm
18	Cyclopentane	287-92-3	NM	NM	≤ 7 – 730 ppb
19	2,2-Dimethylbutane	75-83-2	NM	NM	≤ 7 – 190 ppb
20	2,3-Dimethylbutane	79-29-8	NM	NM	≤ 7 – 350 ppb
21	2-Methylpentane	107-83-5	NM	NM	≤ 7 – 1700 ppb
22	3-Methylpentane	96-14-0	≤ 28 ppb (N=8)	NM	≤ 7 – 760 ppb
23	n-Hexane	110-54-3	≤ 1000 ppb (N=31)	NR	≤ 7 – 1700 ppb
24	1-Hexene	592-41-6	NM	NM	≤ 7 ppb
25	Methyl cyclopentane	96-37-7	≤ 29 ppb (N=8)	NM	20 – 870 ppb
26	Cyclohexane	110-82-7	≤ 29 ppb (N=31)	NM	≤ 7 – 1700 ppb
27	2-Methylhexane	591-76-4	NM	NM	≤ 7 – 80 ppb
28	3-Methylhexane	589-34-4	NM	NM	≤ 7 – 80 ppb

	Substance	CAS #	Company 1 CSG Analysis[1] concentration range	Company 2 CSG Analysis[2] concentration range (N = 28)	Day et al (2016) CSG Analysis concentration range (N = 6)
29	2,3-Dimethylpentane	565-59-3	NM	NM	≤ 7 – 40 ppb
30	2,4-Dimethylpentane	108-08-7	NM	NM	≤ 7 ppb
31	n-Heptane	142-82-5	≤ 1000 ppb (N=31)	NR	≤ 7 – 210 ppb
32	2-Methylheptane	592-27-8	NM	NM	≤ 7 ppb
33	3-Methylheptane	589-81-1	NM	NM	≤ 7 ppb
34	Isooctane	540-84-1	NM	NM	≤ 7 – 9 ppb
35	n-Octane	111-65-9	≤ 1000 ppb (N = 31)	NR	≤ 7 – 10 ppb
36	Methylcyclohexane	108-87-2	≤ 1000 ppb (N = 31)	NM	≤ 7 – 1100 ppb
37	2,3,4-Trimethylpentane	565-75-3	NM	NM	≤ 7 ppb
38	n-Nonane	111-84-2	≤ 1000 ppb (N = 31)	NM	≤ 7 ppb
39	n-Decane	124-18-5	≤ 1000 ppb (N = 31)	NM	≤ 7 ppb
40	Undecanes	1120-21-4	≤ 1000 ppb (N = 31)	NM	≤ 7 ppb
41	Dodecanes	112-40-3	≤ 1000 ppb (N = 31)	NM	≤ 7 ppb
42	Tridecanes	629-50-5	≤ 1000 ppb (N = 31)	NM	NM
43	Tetradecanes	629-59-4	≤ 1000 ppb (N = 31)	NM	NM

	Substance	CAS #	Company 1 CSG Analysis[1] concentration range	Company 2 CSG Analysis[2] concentration range (N = 28)	Day et al (2016) CSG Analysis concentration range (N = 6)
44	Benzene	71-43-2	≤ 1000 ppb (N = 31) ≤ 31 ppb (N = 8)	NM	≤ 7 – 580 ppb
45	Toluene	108-88-3	≤ 1000 ppb (N= 31) ≤ 27 ppb (N = 8)	NM	≤ 7 – 270 ppb
46	m- + p-Xylene	179601-23-1	≤ 1000 ppb (N = 31) ≤ 46 ppb (N = 8)	NM	≤ 7 – 30 ppb
47	o- Xylene	95-47-6	≤ 23 ppb (N = 8)	NM	≤ 7 ppb
48	Ethylbenzene	100-41-4	≤ 23 ppb (N = 8)	NM	≤ 7 ppb
49	Styrene	100-42-5	≤ 24 ppb (N = 8)	NM	≤ 7 ppb
50	Isopropyl benzene	98-82-8	≤ 20 ppb (N = 8)	NM	≤ 7 ppb
51	n-Propylbenzene	103-65-1	NM	NM	≤ 7 ppb
52	m-Ethyl toluene	620-14-4	NM	NM	≤ 7 ppb
53	p-Ethyl toluene	622-96-8	NM	NM	≤ 7 ppb
54	o-Ethyl toluene	611-14-3	NM	NM	≤ 7 ppb
55	1,3,5-Trimethylbenzene	108-67-8	≤ 20 ppb (N = 8)	NM	≤ 7 ppb

	Substance	CAS #	Company 1 CSG Analysis[1] concentration range	Company 2 CSG Analysis[2] concentration range (N = 28)	Day et al (2016) CSG Analysis concentration range (N = 6)
56	1,2,4-Trimethylbenzene	95-63-6	≤ 20 ppb (N = 8)	NM	≤ 7 ppb
57	1,2,3-Trimethylbenzene	526-73-8	NM	NM	≤ 7 ppb
58	1,3-Diethylbenzene	141-93-5	NM	NM	≤ 7 ppb
59	1,4-Diethylbenzene	105-05-5	NM	NM	≤ 7 ppb
60	n-butylbenzene	104-51-8	≤ 18 ppb (N = 8)	NM	NM
61	sec-butylbenzene	135-98-8	≤ 18 ppb (N = 8)	NM	NM
62	tert-butylbenzene	98-06-6	≤ 18 ppb (N = 8)	NM	NM
63	p-isopropyl toluene	99-87-6	≤ 18 ppb (N = 8)	NM	NM
64	Carbon tetrachloride	56-23-5	≤ 100 µg /m^3 (N = 8)	NM	NM
65	Chloroform	67-66-3	≤ 100 µg /m^3 (N = 8)	NM	NM
66	1,1-dichloroethane	75-34-3	≤ 100 µg /m^3 (N = 8)	NM	NM
67	1,2-dichloroethane	107-06-2	≤ 100 µg /m^3 (N = 8)	NM	NM
68	1,1-dichloroethene	75-35-4	≤ 100 µg /m^3 (N = 8)	NM	NM
69	1,1,1-trichloroethane	71-55-6	≤ 100 µg /m^3 (N = 8)	NM	NM
70	1,1,2-trichloroethane	79-00-5	≤ 100 µg /m^3 (N = 8)	NM	NM

	Substance	CAS #	Company 1 CSG Analysis[1] concentration range	Company 2 CSG Analysis[2] concentration range (N = 28)	Day et al (2016) CSG Analysis concentration range (N = 6)
71	1,1,1,2-tetrachloroethane	630-20-6	≤ 100 µg /m^3 (N = 8)	NM	NM
72	1,1,2,2-tetrachloroethane	79-34-5	≤ 100 µg /m^3 (N = 8)	NM	NM
73	Tetrachloroethene	127-18-4	≤ 100 µg /m^3 (N = 8)	NM	NM
74	trans-1,2-dichloroethene	156-60-5	≤ 100 µg /m^3 (N = 8)	NM	NM
75	trans-1,3-dichloropropene	10061-02-6	≤ 100 µg /m^3 (N = 8)	NM	NM
76	Trichloroethene	79-01-6	≤ 100 µg /m^3 (N = 8)	NM	NM
77	1,2-dichloropropane	78-87-5	≤ 100 µg /m^3 (N = 8)	NM	NM
78	1,3-dichloropropane	142-28-9	≤ 100 µg /m^3 (N = 8)	NM	NM
79	2,2-dichloropropane	594-20-7	≤ 100 µg /m3 (N = 8)	NM	NM
80	1,1-dichloropropene	563-58-6	≤ 100 µg /m^3 (N = 8)	NM	NM
81	cis-1,2-dichloroethene	156-59-2	≤ 100 µg /m^3 (N = 8)	NM	NM
82	cis-1,3-dichloropropene	542-75-6	≤ 100 µg /m^3 (N = 8)	NM	NM
83	1,2,3-trichloropropane	96-18-4	≤ 100 µg /m^3 (N = 8)	NM	NM
84	Bromoform	75-25-2	≤ 100 µg /m^3 (N = 8)	NM	NM
85	Bromochloromethane	74-97-5	≤ 100 µg /m^3 (N = 8)	NM	NM

	Substance	CAS #	Company 1 CSG Analysis[1] concentration range	Company 2 CSG Analysis[2] concentration range (N = 28)	Day et al (2016) CSG Analysis concentration range (N = 6)
86	Bromodichloromethane	75-27-4	≤ 100 µg /m^3 (N = 8)	NM	NM
87	Dibromomethane	74-95-3	≤ 100 µg /m^3 (N = 8)	NM	NM
88	1,2-dibromoethane	106-93-4	≤ 100 µg /m^3 (N = 8)	NM	NM
89	Dibromochloromethane	124-48-1	≤ 100 µg /m^3 (N = 8)	NM	NM
90	1,2-dibromo-3-chloropropane	96-12-8	≤ 100 µg /m^3 (N = 8)	NM	NM
91	Hexachlorobutadiene	87-68-3	≤ 100 µg /m^3 (N = 8)	NM	NM
92	1,2-dichlorobenzene	95-50-1	≤ 100 µg /m^3 (N = 8)	NM	NM
93	1,3-dichlorobenzene	541-73-1	≤ 100 µg /m^3 (N = 8)	NM	NM
94	1,4-dichlorobenzene	106-46-7	≤ 100 µg /m^3 (N = 8)	NM	NM
95	1,2,3-trichlorobenzene	87-61-6	≤ 100 µg /m^3 (N = 8)	NM	NM
96	1,2,4-trichlorobenzene	120-82-1	≤ 100 µg /m^3 (N = 8)	NM	NM
97	2-chlorotoluene	95-49-8	≤ 100 µg /m^3 (N = 8)	NM	NM
98	4-chlorotoluene	06-43-4	≤ 100 µg /m^3 (N = 8)	NM	NM
99	Bromobenzene	108-86-1	≤ 100 µg /m^3 (N = 8)	NM	NM
100	Acenaphthene	83-32-9	≤ 10 µg/m^3 (N = 16)	NM	NM

	Substance	CAS #	Company 1 CSG Analysis[1] concentration range	Company 2 CSG Analysis[2] concentration range (N = 28)	Day et al (2016) CSG Analysis concentration range (N = 6)
101	Acenaphthylene	208-96-8	≤ 10 µg/m^3 (N = 16)	NM	NM
102	Anthracene	120-12-7	≤ 10 µg/m^3 (N = 16)	NM	NM
103	Benz(a)anthracene	56-55-3	≤ 10 µg/m^3 (N = 16)	NM	NM
104	Benzo(a)pyrene	50-32-8	≤ 10 µg/m^3 (N = 16)	NM	NM
105	Benzo(b,j,k)fluoranthene	205-99-2	≤ 10 µg/m^3 (N = 16)	NM	NM
106	Benzo(g,h,i)perylene	191-24-2	≤ 10 µg/m^3 (N = 16)	NM	NM
107	Chrysene	207-08-9	≤ 10 µg/m^3 (N = 16)	NM	NM
108	Dibenz(a,h)anthracene	218-01-9	≤ 10 µg/m^3 (N = 16)	NM	NM
109	Fluoranthene	53-70-3	≤ 10 µg/m^3 (N = 16)	NM	NM
110	Fluorene	206-44-0	≤ 10 µg/m^3 (N = 16)	NM	NM
111	Indeno(1,2,3-c,d)pyrene	86-73-7	≤ 10 µg/m^3 (N = 16)	NM	NM
112	Naphthalene	193-39-5	≤ 10 µg/m^3 (N = 16)	NM	NM
113	Phenanthrene	91-20-3	≤ 10 µg/m^3 (N = 16)	NM	NM
114	Pyrene	85-01-8	≤ 10 µg/m^3 (N = 16)	NM	NM
115	Methyl ethyl ketone	78-93-3	≤ 100 µg /m^3 (N = 8)	NM	NM

	Substance	CAS #	Company 1 CSG Analysis[1] concentration range	Company 2 CSG Analysis[2] concentration range (N = 28)	Day et al (2016) CSG Analysis concentration range (N = 6)
116	2,6-dimethyl-4-heptanone (DIBK)	108-83-8	≤ 100 µg /m^3 (N = 8)	NM	NM
117	3-Methyl-2-butanone (MIPK)	563-80-4	≤ 100 µg /m^3 (N = 8)	NM	NM
118	4-methyl-2-pentanone (MIBK)	108-10-1	≤ 100 µg /m^3 (N = 8)	NM	NM
119	Acrylonitrile	107-13-1	≤ 100 µg /m^3 (N = 8)	NM	NM
120	Hydrogen Sulphide	7783-06-4	140 - 230 µg /m^3 (N=71)	NM	NM
121	Carbon disulphide	75-15-0	≤ 100 ppm (N=13)	NM	NM
122	Dimethyl disulphide	624-92-0	≤ 100 µg /m^3 (N=8)	NM	NM
123	Carbonyl sulphide	463-58-1	≤ 0.1 - ≤ 5 ppm (N = 37)	NM	NM
124	Nitrogen	7727-37-9	0.6 – 3.9 % (N=133)	NM	NM
125	Oxygen	7782-44-7	≤ 0.01 – 0.12 % (N=28)	NM	NM
126	Carbon dioxide	124-38-9	0.05 – 0.57 % (N=133)	NM	NM
127	Carbon Monoxide	630-08-0	≤ 0.01 % (N=16)	NM	NM
128	Hydrogen	1333-74-0	≤ 0.01 % (N=16)	NM	NM
129	Mercury	7439-97-6	0.002 – 0.23 µg /m^3 (N=13)	NM	NM
130	Arsenic	7440-38-2	≤ 0.01 µg /m^3 (N=2)	NM	NM

	Substance	CAS #	Company 1 CSG Analysis[1] concentration range	Company 2 CSG Analysis[2] concentration range (N = 28)	Day et al (2016) CSG Analysis concentration range (N = 6)
131	Radon-222		34 – 330 Bq/m^3 (N=15)	NM	NM

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