Preliminary Field Measurements of Fugitive Methane Emissions from Coal Seam Gas Production in Australia

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Abstract

Natural gas is often regarded as a transitional fuel because of its low greenhouse gas emissions compared to coal. When comparing total greenhouse emissions from different fuels it is important to include fugitive emissions released upstream of utilisation. Some recent studies have concluded that fugitive emissions from some unconventional gas production in the United States may be much higher than previously estimated. Australia has a large coal seam gas (CSG) industry that is currently undergoing rapid expansion but the magnitude of fugitive emissions from this sector is not well understood. Here we report preliminary measurements of fugitive CH_4 emissions from CSG production facilities in Australia. In addition, the emission flux from a methane seepage site, which was apparently not associated with production infrastructure, was quantified and compared with emission rates from CSG production facilities.

Emissions from a gas compression plant were estimated to be between 13 and 58 t CH_4 y^{-1}. In general, emissions from CSG wells were low, mostly due to minor equipment leaks or venting from pneumatic equipment. However, one well had an emission rate of about 3.2 t y^{-1}, corresponding to about 0.17 % of the well's production rate. A methane seep in Queensland about 2.5 km from any CSG production activity had an emission flux from the ground of about 17 t CH_4 per year, about five times more than the highest emitting well and of the same order as the gas compression plant. The presence of seeps and other methane sources such as cattle feedlots illustrates the importance of conducting baseline monitoring ahead of gas development projects so as to properly attribute emissions, especially if top-down monitoring approaches are used.

Introduction

Natural gas is widely regarded as a 'transitional' fuel to a lower carbon economy because of its low greenhouse gas emissions compared to other fossil fuels. Direct CO_2 emissions from electricity generated with natural gas may be less than half those from subcritical coal-fired power plants. Because of its perceived greenhouse benefits and increasing worldwide demand for energy more generally, gas production has increased markedly over the past decade, especially with the development of unconventional resources such as coalbed methane (or coal seam gas as it is known in Australia), shale gas and tight gas. In Australia coal seam gas (CSG) production has undergone rapid growth in recent years and currently accounts for a considerable proportion of domestic gas consumption. Further production capacity is being developed to supply three export LNG plants currently under construction in Queensland, which are expected to be brought on line within the next few years.

Although combustion emissions from natural gas are generally lower than other fuels, it is important when comparing greenhouse intensities to consider all sources of emissions, especially fugitive releases of methane from production and processing, since methane has a much higher global warming potential than CO_2. Globally, fugitive emissions are substantial with emissions from the oil and gas industries estimated to be 1600 Mt CO_2-e per annum and about 580 Mt CO_2-e from coal mining [1]. Fugitive emissions in Australia are estimated to account for 41 Mt CO_2-e or 7.5 % of the nation's total greenhouse gas inventory [2].

The Australian CSG industry is relatively new and at present, there are very few quantitative data on the magnitude of fugitive emissions from the sector [3, 4]. The U.S. unconventional gas industry is more mature but recently, it has been suggested that fugitive emissions from unconventional gas production are much higher than previously estimated. Howarth et al. [5] reported that up to almost 8 % of the gas produced in shale gas operations is released as fugitive emissions, largely as a result of gas entrained with fluid flow-back from hydraulic fracturing operations. They further suggested that this level of fugitive emissions would eliminate any greenhouse advantage of gas over coal and may even be worse. This conclusion has been questioned, however, with other researchers arguing that current industry mitigation practices result in much lower emissions [6, 7]. A subsequent study of emissions from a tight gas field in Colorado reported emissions ranging from 1.7 to 7.7 % of production [8]. The upper estimate is consistent with Howarth et al., however, the wide range of the estimates reported illustrates the inherent level of uncertainty in current emission inventories.

In Australia there are essentially no publicly available data on the magnitude of emissions from the CSG industry. Reported estimates range from 0.1 % [9] to 4.4 % [10] of production but these are not based on measurements so are subject to high uncertainty. The higher estimate is based on U.S. shale gas data but it is not clear if this is a valid comparison since there are significant differences between CSG and shale gas production. In particular, fewer Australian CSG wells have been treated by hydraulic fracturing. Given the size of the Australian CSG industry and its likely growth, there is a need to develop a more reliable estimate of fugitive emissions from production and processing facilities.

Here we report preliminary results of a study currently underway to measure emissions at CSG production facilities within Australia. A series of measurements were made in two CSG production fields in Australia including at a number of individual well sites. In addition, we report some results for an area where methane was found to be seeping from the ground but was not obviously associated with CSG production activity.

Experimental

Measurements were made across two CSG production areas in eastern Australia (designated here as Region 1 and Region 2). Initial surveys of ambient CH_4 concentration were made using a 4WD vehicle fitted with a CH_4 analyser to measure ambient CH_4 concentrations in the vicinity of CSG operations and also in areas well away from CSG production sites to establish baseline levels. In addition to mobile surveys, more detailed measurements to determine CH_4 emission flux were made at selected well pads and in areas where there were no CSG operations. The measurement methods used at these locations are described below.

Downwind traverses
For these experiments in Region 1, the vehicle was driven up to 300 m downwind of production wells or other infrastructure. Measurements made at individual wells in Region 2, however, were made within about 15 to 50 m of each well. The concentration of CH_4 approximately 1 m above the ground was continuously measured using the CH_4 analyser while the position of the vehicle was recorded with a GPS receiver. Wind speed and direction were measured with a sonic anemometer (Climatronics Sonimometer) fitted to the roof of the vehicle.

Analyses were made using a Picarro Model 2301 Cavity Ring-down $CH_4/CO_2/H_2O$ analyser. The resolution of this instrument is < 1 ppbv and has very low drift characteristics [11] so that very small CH_4 perturbations can be reliably detected against the background concentration. The analyser was calibrated against a reference air sample containing 1.732 ppm CH_4 prepared by the CSIRO Marine and Atmospheric Research GASLAB [12], and a 10.8 ppm CH_4 in air standard gas mixture (BOC Gases, Australia).

For calculating emission rates, the horizontal width of the plume was determined by noting the region of elevated methane concentration within the plume. Because the height of the plume could not be measured directly, its vertical extent was estimated by reference to the Pasquill-Gifford curves of σ_z (i.e. the standard deviation of the distribution of CH_4 concentration in the vertical direction) as a function of downwind distance for given atmospheric turbulence conditions [13]. Since in a Gaussian distribution more than 99 % of the observations are within three standard deviations of the mean (or the maximum concentration at the centre line of the plume), the plume height was taken to be $3\sigma_z$. The concentration of CH_4, c, within the plume was assumed to decrease from the maximum measured concentration with height and across its width according to a Gaussian distribution to yield the concentration profile across the traverse plane. The average emission flux, Q, over the traverse period was estimated by integrating the concentration profile of the plume in both the horizontal (y) and vertical (z) directions and multiplying by the average wind velocity, u (Equation 1).

$$Q = u \int_{-y}^{y} \int_{0}^{z} c(y,z)\,dy\,dz \qquad \text{Equation 1}$$

Flux chamber measurements
Emissions from the ground surface were made at locations close to well pads but also in other locations away from production sites to gauge natural methane emissions. Measurements were made using a plastic cylindrical chamber 37.5 cm in diameter and 40 cm high with a total volume of about 45 L and an area of coverage of 0.11 m^2. The chamber was placed on the ground and the methane concentration within the chamber measured over several minutes. A small solar-powered fan inside the chamber ensured that the sample was well mixed during the measurement period. Emission flux was calculated according to Equation 2.

$$F = \frac{dC}{dt} \times \frac{V_c}{A}$$ Equation 2

where *dC/dt* is the initial rate of increase in concentration, V_c is the volume of the chamber and *A* is the area covered by the chamber.

Quantification of equipment leak rates

At a number of well pads, leakage rates were measured from individual pieces of equipment such as separators, wellheads and pipework. Initial screening of equipment was made by measuring the ambient CH_4 concentration within about 50 mm of potential leak points such as flanges, valves, instrumentation sensors etc. Where elevated levels were found, the leaking item was enclosed with a plastic sleeve or other suitable container. A vacuum pump was connected to the sleeve to draw air across the leaking component at a flow rate of between 1 and 5 L min^{-1}. In cases where the leak rate resulted in CH_4 concentrations outside the range of the analyser, an alternative technique was used. Here air was pumped into the enclosure at a known rate up to 20 L min^{-1} and the concentration in the exhaust air measured in the same manner as described above. In both cases, the concentration in the air stream and flow rate yielded the emission rate from the leak. Although this method can provide accurate quantitative measurements of leak rates it is relatively slow and sometimes impractical when access to equipment is restricted.

Results and Discussion

Controlled Release Experiments

To check the level of uncertainty associated with the plume traversing results, we performed a number of experiments where CH_4 was released from a cylinder of compressed gas at a known rate while traverses were made downwind of the source. Measurements were made at a site near the CSIRO laboratories in Newcastle where there were no other sources of methane present. To simulate field conditions, traverses were made between 15 and 50 m downwind of the controlled release point. Each experiment comprised at least six individual traverses across the plume from which an average maximum concentration and plume width were determined. The plume height was calculated from the σ_z estimates as described above but since σ_z is affected by atmospheric stability, the choice of the stability class can introduce another level of uncertainty. To gauge this effect, emissions for each experiment were calculated for both Pasquill-Gifford Class B (moderately unstable) and Class C (slightly unstable) atmospheric conditions (Table 1). However, because the downwind distances in these experiments were small, there is only a minor difference between the flux estimates for the two classes.

The results of the traverse experiments are summarised in Table 1 where the actual release rate of methane is compared to the average emission rate determined by traversing through the plume.

Table 1. *Summary of emission fluxes determined during controlled methane release experiments*

Downwind Distance (m)	Wind Speed (m s^{-1})	Actual Release Rate (mg s^{-1})	Average Measured Flux (mg s^{-1})	
			Class B	Class C
50	5.1	58.0	72.8	66.1
20	4.1	12.6	11.8	11.7
30	4.1	11.5	11.9	11.3
15	4.4	11.6	7.7	7.2
30	4.1	11.6	6.4	6.2

While there is significant variability between the actual and measured fluxes, the range is broadly consistent with a previous study of controlled releases of CH_4 [14]. In all our controlled release experiments the measured emission rate was within about 50 % of the actual rate.

Emissions from Production Facilities

Ground level surveys were conducted by driving the vehicle through CSG production fields. In the Region 1 gas field, a route of approximately 300 km was driven over two consecutive days in January 2013. In general, ambient methane concentrations measured over most of the areas surveyed were close to 1.75 ppm, which is within the range of typical ambient background CH_4 concentrations but there were a number of locations where elevated methane concentrations were detected. At one location, methane levels up to 5 ppm were detected near cattle grazing on the road verge. Slightly elevated methane concentrations were also measured in some locations close to CSG operations. One of these locations was near a large gas processing plant where a plume about 200 m wide with a maximum CH_4 concentration of 2.0 ppm was measured (Figure 1). The average wind speed at the time of the traverse was ~1.5 m s^{-1}. Assuming that σ_z was approximately 15 m gives a plume height of 45 m so the emission flux from this facility was estimated to be about 0.4 g s^{-1} or about 13 t y^{-1}. However, these measurements were made under very unstable atmospheric conditions so the estimate of the plume height is very uncertain. Using a more conservative estimate where the plume was assumed to have a semicircular section with a height of 100 m and an average CH_4 concentration enhancement of 0.125 ppm (i.e. half the peak maximum) across the entire plume section resulted in an annual CH_4 emission of about 58 t y^{-1}.

***Figure 1**. A plot of CH_4 concentration measured during a mobile survey indicating a plume downwind of a gas compression plant in Region 1 (note that the image is several years old and shows the plant under construction; the plant is now operational). The background CH_4 concentration was 1.75 ppm; the peak concentration was 2.0 ppm.*

Although the estimate of emissions from this plant has a high level of uncertainty, it does provide some sense of the scale for comparison with other methane emission sources. For example, a study of a feedlot located close to this gas plant and with 13,800 head of cattle, found that CH_4 emissions were 166 g CH_4

per animal per day [15]. This is equivalent to an annual emission from the feedlot of more than 800 t CH_4 per annum.

Measurements were also made at two CSG wells close to public roads. At one well it was possible to drive to within about 5 m of the well but no CH_4 above ambient was detected at this site indicating that there were no emissions from the well. The other well was located on private land about 100 m from the closest access. A small CH_4 plume was intersected downwind of the well with a maximum concentration of 1.82 ppm (i.e. 0.07 ppm enhancement above background) and plume width of about 70 m. Again, the wind speed was 1.5 m s^{-1} which yielded an emission rate of around 13 mg s^{-1} or about 0.4 t y^{-1} although like the estimate for the gas plant, this value is subject to considerable uncertainty.

More detailed surveys were made during April 2013 on six wells in Region 2 where access to each site had been provided by the company that operated the wells. At these sites, plume traverses were made within about 50 m of each well so that plume disturbances such as trees and structures were avoided. Like the controlled release experiments, multiple traverses were made at each site, (usually between 3 and 10), which were then combined to yield an average plume transect representing an approximately 15-minute period. The plume CH_4 concentration and wind data were used to calculate the emissions flux using the method described above.

Figure 2 shows an example of the traverse data where downwind CH_4 concentration is plotted as a function of distance across the plume for three traverses made at the R2-5 well site. In this example the plume was approximately 10-15 m wide and ranged in concentration from background (~1.78 ppm CH_4) to a maximum of about 1.90 ppm CH_4.

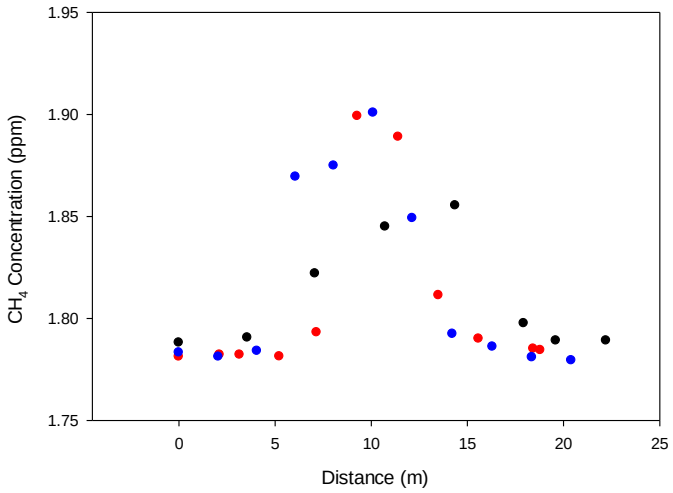

***Figure 2**. Methane concentration as a function of distance across the plume emanating from CSG well No R2-5.*

Table 2 provides a summary of the results for the six Region 2 wells and shows the average downwind CH_4 enhancement peak (i.e. the background subtracted from the averaged peak maximum), the gas production rate, where known, and the emission flux. For comparison, results for the two Region 1 wells are also shown. In Table 2 we have extrapolated the results to estimate the emission rate per year because emission inventories are frequently reported on an annual basis. However, it is important to note that inferring annual emissions from single results is itself a large source of uncertainty. There may be significant temporal variation in the actual emission profile over the course of a year. For instance, regular maintenance would be expected to detect and repair leaking equipment. Although a suitable set of

measurements made over a longer time would provide an operational average, this is not the case here and substantially more measurements are required to properly define the true annual emission profile from the wells and production facilities.

Table 2. *Summary of emission rates derived from plume traverses for coal seam gas wells in Queensland and NSW*

Well	Production Rate (m^3 day^{-1})	Average Peak Downwind CH_4 Enhancement (ppm)	Emission Rate (mg s^{-1})	Emission Rate (kg y^{-1})
R1-1	Not Known	0.07	13	400
R1-2	Not Known	0.00	0	0
R2-1	14,900	0.40	1.9	60
R2-2	13,700	0.17	0.4	13
R2-3	0 (workover in progress)	0.02 0.02 (repeat)	0.3 0.2 (repeat)	9 6 (repeat)
R2-4	0 (suspended)	0.00	0	0
R2-5	1,500	0.12	0.7	23
R2-6	7,800	17.6 15.6 (repeat)	88 111 (repeat)	2,800 3,600 (repeat)

At the time of the field measurements, only four of the Region 2 wells were producing gas. One (R2-3) was shut down for maintenance while another (R2-4) was suspended and no longer in use. Traverses made at five of the six Region 2 wells registered some level of methane emission although, except for R2-6, these were very low with methane enhancements substantially less than 0.5 ppm within 20 m of the well pad. We observed no methane emission from the suspended well (R2-4).

When a methane plume was detected, attempts were made to trace the source on the well site. In two instances, (R2-1 and R2-5) methane emissions were found to be from pneumatic devices associated with the emergency shutoff valve on each wellhead. Pressure to these devices was supplied by gas from the well and consequently on each operation, a small amount of CH_4 was vented. The venting rates of the pneumatic devices were measured and found to be approximately 5 L h^{-1} (0.9 mg s^{-1}) at R2-1 and 6.7 L h^{-1} (1.2 mg s^{-1}) at R2-5. Very small emissions were also detected from equipment leaks at these two wells; at R2-1 methane was detected leaking from around the seal on the water pump on the well head and on R2-5, a small leak was found on a pipe fitting. However, these leaks were extremely small with rates at least two orders of magnitude lower than the pneumatic venting. The total leak rates measured on the well pads at R2-1 and R2-5 compare reasonably well with the plume traverses (Table 2), especially given the level of uncertainty associated with atmospheric methods. The results suggest that for these wells, the principal source of fugitive CH_4 was the operation of pneumatic devices.

Two other wells (R2-2 and R2-3) were also found to have equipment leaks but at the time the measurements were made, venting from pneumatic equipment was not contributing to these emissions. In the case of NSW2, methane was leaking from a loose plug on a branch pipe. The leak rate from the fitting was determined to be 0.4 mg s^{-1}, which is consistent with the plume traverse (0.4 mg s^{-1}). After the leak was identified, it was repaired by gas company personnel, which eliminated any significant emissions from this well.

At R2-3, a leak was found near the gathering line (i.e. the pipe that carried the gas to a remote compression plant) at the point where it went underground. A series of closely spaced flux chamber measurements over a total area of around 1 m^2 made at this location confirmed that a small amount of gas

was leaking from below the ground surface. However, the measured rate was small at about 0.1 mg s^{-1}, again in reasonable agreement with the traverse results.

The final well examined (R2-6) had much higher emissions than any of the other wells. Two separate sets of traverses yielded emission rates of 88 and 111 mg s^{-1} (average 100 mg s^{-1}) or 3.2 t y^{-1}. This is more than 50 times greater than the next highest NSW well examined during this study. Two equipment leaks from a valve and a pipe fitting were detected at this well, however, the combined rate of these two leaks accounted for less than 1 mg s^{-1} so the bulk of the methane release was from another source. This well was on a pad with three other wells within close proximity, which were not examined in detail during this campaign, so it is possible that some of the observed methane in the plume may have originated from these other wells. Flux chamber measurements on gravel covering a buried gathering line from the four wells on the pad indicated that gas was leaking from below the surface, possibly from a leak within the line. The diffuse nature of the emissions through the gravel, however, meant that we were unable to reliably quantify the leak rate from the source using the small flux chamber.

For all of the wells examined, the amount of gas lost due to fugitive emissions represented a very small proportion of the total gas production from each well. In the case of R2-6, which had the highest emission rate, the production flow at the time of the emission measurements was 7,800 m^3 day^{-1}. The emission rate determined by the plume traverses averaged at 100 mg s^{-1} which is equivalent to about 13.0 m^3 day^{-1} or 0.17 % of production (assuming that all of the leaking CH_4 was in fact from this well). While this is a low emission rate compared to estimates made for shale gas and other unconventional gas production, it is worth noting that it has been suggested that a large proportion of emissions from shale gas has been attributed to flow-back from hydraulic fracturing operations [5]. Fracture stimulation in Australian CSG wells is currently applied to less than 10 % of wells although this is expected to increase in the future as less permeable seams are targeted [16]. The results from this study do not include any data from hydraulic fracturing operations and is an area that requires further research.

The small number of wells examined in this study are not necessarily representative of the thousands of CSG wells currently producing gas in Australia. A much larger, randomised sample of wells should be examined before it is possible to draw statistically valid conclusions about emissions from Australian CSG operations more generally.

Methane Seep Site

In addition to CSG production infrastructure, emission measurements were made at a site in Queensland that was located away from active CSG operations but which was nonetheless found to be emitting methane from the ground. A survey of the area in light winds showed ambient concentrations up to 18 ppm CH_4 although multiple plume traverses yielded an average peak concentration of around 5 ppm. Figure 3 shows the location of the source and the CH_4 concentration profiles made over a number of traverses about 50 m downwind. The background methane concentration was 1.75 ppm and the average wind speed 2 m s^{-1}. The emission flux for this site calculated from the traverse data was 522 mg s^{-1} or 16.6 t y^{-1}, which is five times higher than the highest emitting well (R2-6) measured.

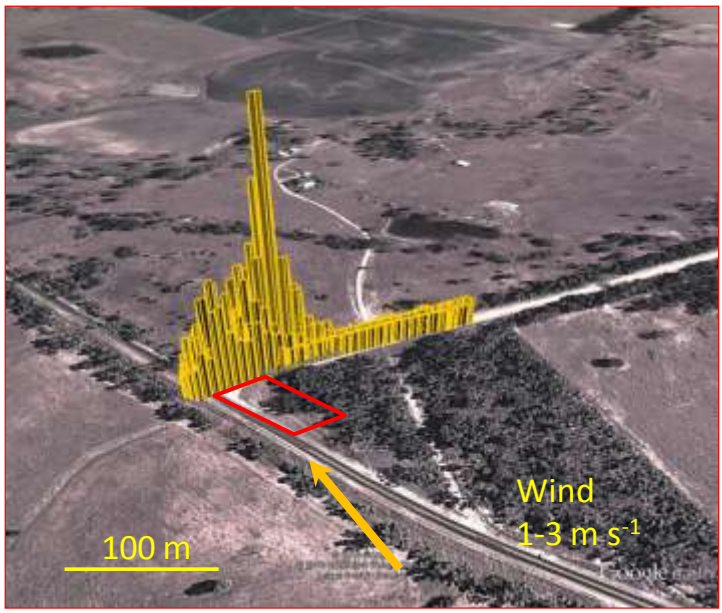

Figure 3. *Location of the methane seep showing the CH_4 concentration across the resultant plume. The background CH_4 concentration was 1.75 ppm; the maximum concentration in the profile is about 18 ppm.*

To better define the spatial extent of this source, a 40 × 80 m area, shown as the rectangle marked in Figure 3, was subject to flux chamber measurements on the ground surface. Fifty individual flux measurements were made within this area and the location of each determined using a GPS. Emission rates ranged from zero up to 3.1 mg s^{-1} m^{-2} or 103 kg y^{-1} m^{-2}. Surface CH_4 emissions in areas away from this site were generally zero. A plot of the emission flux as a function of location within the seepage site is shown in Figure 4.

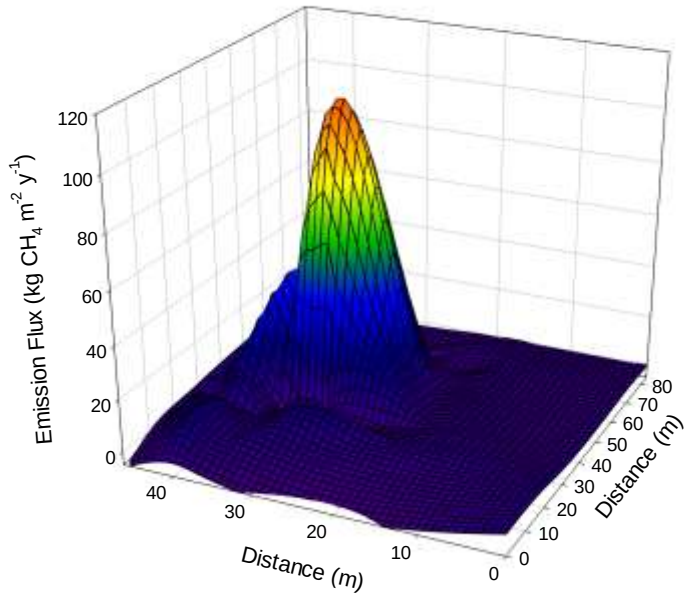

Figure 4. *Methane emission flux profile of a methane seepage site in Queensland. The area of the test site was approximately 40 × 80 m.*

Figure 4 shows that there was a strong CH_4 source at this site which was mostly localised to an area of about 20 m × 20 m square. Calculating the emission flux over this local area yielded an emission rate of 17.0 t y^{-1} which agrees well with the estimate derived from the plume traverse.

The CH_4 source at this site is not known but it did not appear to be directly related to current CSG activity. The site was located on a roadside and surrounded by agricultural land. The nearest CSG well was about 2.5 km away and there are no buried pipelines in the area so it is unlikely that the emission source was leaking infrastructure. A recent study conducted within this gas field suggested that drilling and fracture stimulation operations may cause cracking in the overlying strata thus providing a pathway for gas leakage [17]. Given the distance from the nearest well, this seems improbable at this site. Another explanation is that methane is naturally seeping from this site. This region of Queensland is known to have significant amounts of gas close to the surface and there have been numerous reports over almost 100 years of gas blowouts during drilling of water bores for agricultural purposes [18]. Whatever the cause, this seep clearly requires further investigation.

The presence of significant emissions of methane from sources other than CSG operations has implications for emissions accounting. Measurement of emissions from individual wells and other infrastructure is one approach for developing industry emission inventories but given the large number of wells currently operating and the expected level of growth, this may not be practical in the long term. Because of this, alternative top-down methodology has been proposed where atmospheric methods may be used for measuring emissions over entire gas producing fields [3]. This approach has already been used to estimate emissions from unconventional gas fields in the U.S. [8]. For such methods to be viable, it is essential to properly attribute other CH_4 sources to avoid overestimating emissions from gas related activities.

Conclusions

Initial measurements of fugitive CH_4 emissions from CSG production facilities in Australia have been made using a combination of plume traversing methods and direct measurement of leak rates from wellhead equipment.

Emissions from a gas compression plant were estimated to be between about 13 and 58 t CH_4 y^{-1}. This compares to about 800 t CH_4 y^{-1} previously estimated for a nearby cattle feedlot. Most of the production wells examined showed some level of CH_4 leakage but the emission rates were generally very low. In two cases CH_4 emissions were traced to venting of gas from pneumatic equipment. Equipment leaks accounted for the remainder. At one well CH_4 appeared to be leaking from a buried pipe adjacent to the well pad and at a rate considerably higher rate than for the other wells examined. The annualised leak rate at this well was equivalent to about 3.2 t CH_4 y^{-1}, which represented about 0.17 % of the well's gas production.

A methane seep site distal to CSG infrastructure was examined and found to be emitting 17 t y^{-1} CH_4, which was substantially more than any of the wells examined. The source of the emission at this site is not known but it did not appear to be associated with CSG production. The presence of seeps and other methane sources such as cattle feedlots illustrates the importance of conducting baseline monitoring ahead of gas development projects so as to properly attribute emissions, particularly if top-down monitoring methodology is employed for estimating emissions from production.

The measurements made during this study represent only a very small proportion of CSG production wells in Australia and hence it is not yet possible to drawn general conclusions about emissions from CSG production in Australia. Substantially more measurements are required to make valid conclusions about emissions from the Australian CSG industry.

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