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Communication

Reducing the greenhouse gas footprint of shale gas

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ABSTRACT

Shale gas is viewed by many as a global energy game-changer. However, serious concerns exist that shale gas generates more greenhouse gas emissions than does coal. In this work the related published data are reviewed and a reassessment is made. It is shown that the greenhouse gas effect of shale gas is less than that of coal over long term if the higher power generation efficiency of shale gas is taken into account. In short term, the greenhouse gas effect of shale gas can be lowered to the level of that of coal if methane emissions are kept low using existing technologies. Further reducing the greenhouse gas effect of shale gas by storing CO_2 in depleted shale gas reservoirs is also discussed, with the conclusion that more CO_2 than the equivalent CO_2 emitted by the extracted shale gas could be stored in the reservoirs at significantly reduced cost.

1. Introduction

With the declining of natural gas reserves, tapping unconventional gas resources has become a focus worldwide and is expected to dictate the future of the energy sector. Shale gas, or natural gas stored in shale formations, is an unconventional gas resource that is making a huge impact on the Northern American gas market. With shale gas development the United States has shifted from a declining producer of natural gas to a growing producer, and it is forecasted that nearly half of US natural gas will come from shale gas by 2035 (Rahm, 2011).

Combustion of shale gas generates less CO_2 than combustion of coal, and use of shale gas in place of coal, which generates over 80% of CO_2 emissions from the US electric power sector (EIA, 2009), is hoped to reduce greenhouse gas (GHG) emissions. However, there are growing objections to this expectation given that methane, the principal component of shale gas, is a more powerful GHG than CO_2. Shale gas production emits more methane than conventional gas production does, and the overall equivalent CO_2 emission could therefore be more than that of coal. In a 2010 letter to US President Obama, the Council of Scientific Society Presidents, who represents 1.4 million US scientists and science educators, urged great caution in shale gas development, noting that shale gas may actually worsen global warming, rather than help mitigate it. A recent study suggests that the life-cycle GHG footprint of shale gas could be far worse than that of coal (Howarth et al., 2011). The major points are discussed in the following section.

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2. The life-cycle GHG footprint of shale gas

The GHG emissions of shale gas over its life-cycle have two components: methane emissions and CO_2 emissions. Methane emissions consist of emissions during well completion, routine venting and equipment leaks at well sites, emissions during liquid unloading, emissions during gas processing, emissions during transport, storage and distribution. The total methane emissions have been estimated to be 3.6–7.9% of the shale gas consumed (Howarth et al., 2011). CO_2 emissions consist of direct CO_2 emissions related to end-use, and indirect CO_2 emissions related to use of fossil fuels for extracting, developing and transporting the shale gas. Indirect CO_2 emissions are relatively small and the total CO_2 emissions are predominantly from the direct emissions. Methane has a large global warming potential (GWP) but a relatively short lifetime. In the study by Howarth et al. (2011), a new GWP value (Shindell et al., 2009), which is higher than previously reported values, has been used: on a mole-to-mole basis, the GWP of methane is 38-fold that of CO_2 in a 20-year time scale, and 12-fold that of CO_2 in a 100-year time scale. Coal production also results in methane emissions and deep-mined coal emits more than surface-mined coal. However, the life-cycle GHG emissions of coal related to methane is small. According to the evaluations by Howarth et al. (2011) using the new GWP value, in the 20-year time scale methane contributes 1.4–3 times more than CO_2 does to the life-cycle GHG emissions of shale gas. In the 100-year time scale, the contribution of methane reduces to 40–95% of that of CO_2. As a result, the overall GHG footprint of shale gas is from 115% to over twice as large as that of coal in the 20-year time scale, but becomes comparable to that of coal over the100-year time scale, as illustrated in Fig. 1.

The prospect that shale gas is worse than coal in terms of GHG emissions alone would strongly affect the rational for using shale

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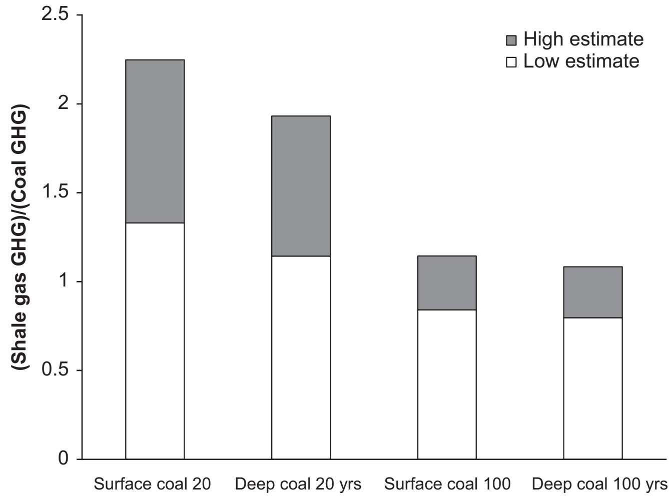

Fig. 1. Life-cycle GHG ratio of shale gas to coal (surface-mined and deep-mined, respectively) according to the data of Howarth et al. (2011) for the timescale of 20 year and 100 years, respectively.

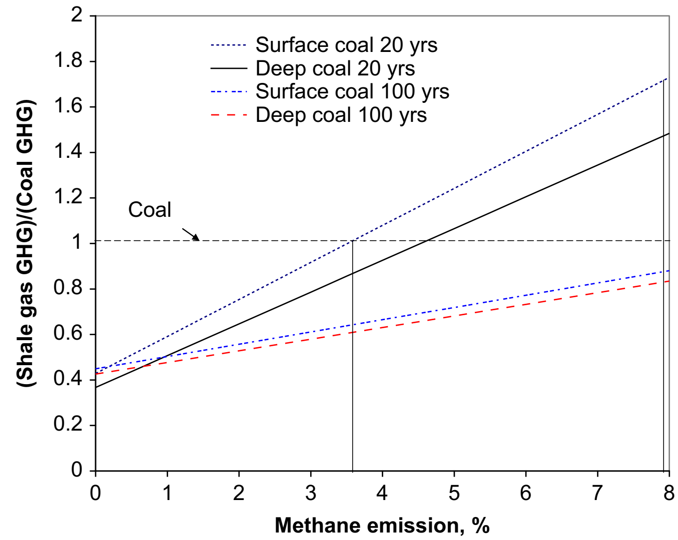

Fig. 2. Life-cycle GHG ratio of shale gas to coal (surface and deep mined, respectively) taking into account of power generation efficiency. The horizontal line represents the level of coal GHG, and the two vertical lines represent the current low and high limits of shale gas methane emissions (3.6 and 7.9%, respectively).

gas for power plants. However, the above numbers are based on the high heating values (HHV) of shale gas and coal for CO_2 emissions, without taking into account the higher efficiency of shale gas in power generation, which would result in less CO_2 per unit power output. Besides, the numbers do not take into account the effects of carbon capture and storage (CCS), which should be considered for future use of fossil fuels. If shale gas development is linked to CCS, the above picture would change further.

3. Effect of power generation efficiency on the GHG footprint of shale gas

First we discuss the effect of higher power generation efficiency of shale gas, which will result in smaller numbers for the life-cycle GHG footprint. Combined cycle is used in modern gas power plants, whose efficiency is substantially higher than that of coal power plants. Here we use the data of US Department of Energy's National Energy Technology Laboratory (NETL) for new natural gas combined cycle (NGCC) and coal power plants (NETL, 2007). The efficiency for NGCC power plants is 50.8% (HHV), and the efficiency for new coal power plants is 38.9% (HHV), which is an averaged value for integrated gasification combined cycle (IGCC), supercritical and subcritical pulverized coal (PC) plants. The same values for direct CO_2 emissions from the fuels as those used by Howarth et al. (2011) are used, i.e., 15 g carbon/MJ (HHV) for natural gas and 25 g carbon/MJ (HHV) for coal, along with the same values for methane emissions from coal (2.3 m^3 and 7.8–9 m^3 per ton of coal for surface-mined and deep-mined coals, respectively). With these values, the recalculated life-cycle GHG footprint of shale gas is 1.01–1.71 of that of surface-mined coal and 0.87–1.47 of deep-mined coal over 20 years, respectively, as illustrated in Fig. 2. By contrast, over a longer period of 100 years, the life-cycle GHG footprint of shale gas becomes 0.64–0.88 of that of surface-mined coal and 0.61–0.83 of that of deep-mined coal. It can thus be seen that the life-cycle GHG footprint of shale gas over long term is smaller than that of coal.

Natural gas is believed to have greater potential to increase efficiency than coal (Hayhoe et al., 2002; Howarth et al., 2011; Lanzy et al., 2011) New technologies, for instance high temperature fuel cells, could make natural gas more advantageous in this regard and bring down the shale gas GHG further.

4. The sensitivity of shale gas GHG to methane emission

In the short term, the GHG footprint, which is very sensitive to the level of methane emission, could be reduced by reducing methane losses. As can be understood from Fig. 2, with every one percent reduction of methane emission from shale gas, the GHG footprint ratio of shale gas to coal will reduce by 10–16%. If the methane emissions of shale gas are controlled at the low estimate level (3.6%) given by Howarth et al. (2011), the GHG footprint of shale gas will be equivalent to or smaller than that of coal even for the 20-year timescale. There are a range of measures for methane emission reduction, which are recommended by the US Environmental Protection Agency (EPA) (EPA, 2011a). Howarth et al. (2011) have also noted that existing means, such as the Reduced Emission Completions (EPA, 2011a), and better tanks/compressors, could largely reduce methane emissions but have not been widely used. Strong regulations would result in significant reduction of methane emissions. With the recently proposed regulations by US Environmental Protection Agency (EPA) for oil and gas production that require reduction of methane emissions (EPA, 2011b), the level of methane emissions is expected to drop soon.

5. Offsetting the GHG footprint with CCS

CCS is the principle means for controlling CO_2 emissions from fossil-fuel fired power plants, and an important component of GHG reduction strategies. By capturing CO_2 from large emitters and storing it underground, a significant reduction of CO_2 emissions could be achieved. Promising storage sites that have been explored include deep saline aquifers, oil and gas fields and unmineable coal seams. Depleted shale gas reservoirs could also make a contribution to CO_2 storage, hence, offsetting the GHG footprint. Here we discuss the potential of CO_2 storage in depleted shale gas reservoirs in terms of storage capacity, CO_2 containment, CO_2 injectivity and CO_2 transport, the major parameters for CO_2 storage evaluations.

5.1. Storage capacity

In shale gas plays, methane exists both as a free phase in pores and fractures and as sorbed gas on organic matter. After the methane is extracted, CO_2 could be stored by the same mechanisms as methane in two populations. The total amount of CO_2, which can be stored, may be estimated from the methane extracted, in the way:

$$\gamma = (\rho_{CO_2}/\rho_{CH_4})X + (A_{CO_2}/A_{CH_4})(1-X) \quad (1)$$

where γ is the molar ratio of CO_2 to be stored to methane extracted. X is the fraction of free-phase methane in the gas plays. ρ_{CO_2} and ρ_{CH_4} are the molar density of CO_2 and methane, respectively. A_{CO_2} and A_{CH_4} are the adsorption affinity of CO_2 and methane to the surface of organic matter, respectively. As CO_2 has higher molar density and adsorption affinity than methane, the extracted methane could be replaced by a greater amount of CO_2 in the depleted fields. First we consider the space for free phase CO_2. The density of gases is dependent on pressure and temperature, which are functions of depth. In the depth range 1000 to 4000 m of North America's largest shale gas reservoirs, the molar density ratio ρ_{CO_2}/ρ_{CH_4}(calculated assuming 0.01 MPa/m pressure gradient, 0.025 °C/m temperature gradient and 20 °C ground temperature) varies from 1.3 to 2.4. At an average depth of 2500 m, ρ_{CO_2}/ρ_{CH_4} is 1.6. Accordingly, one mole of extracted CH_4 could create the space for 1.6 moles of CO_2. As for the adsorption affinity to organic matter, there is an indication that five moles of CO_2 can be adsorbed for one mole of CH_4 produced in shale (NETL, 2010). The fraction of the free-phase CH_4 in shale gas plays ranges from 15 to 80% (Lewis et al., 2004). With the above values, the calculated CO_2 storage capacity in terms of Eq. (1) is shown in Fig. 3 as a function of the fraction of the free-phase CH_4. It can be seen that, for every mole of CH_4 produced, at least more than two moles of CO_2 could be stored. This capacity is substantially above the high estimate of equivalent CO_2 emission of shale gas in comparison with coal.

5.2. CO_2 containment

Shale gas reservoirs have proven the ability to retain the gas over geologic timescales. The generally low permeability of shales is ideal for caprocks, which contain injected CO_2. As long as the caprocks are not damaged by the hydraulic fractures introduced for shale gas production, CO_2 could be securely retained as shale gas has been.

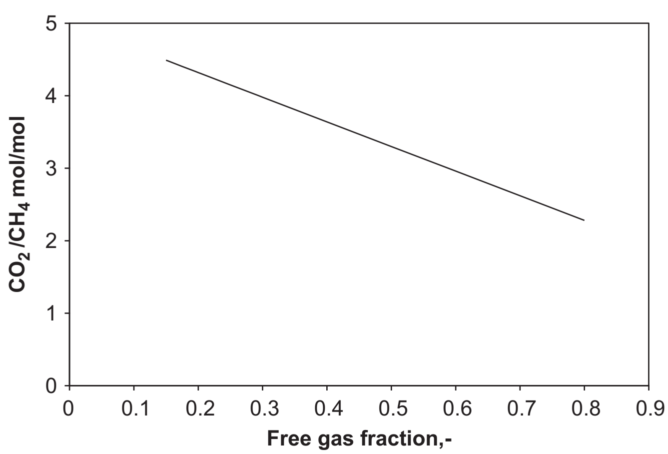

Fig. 3. Molar ratio of CO_2, which could be stored, to methane produced, as a function of the fraction of the free gas phase methane in shale gas reservoirs.

5.3. CO_2 injection

Shale gas wells could be used for injection of CO_2 for storage. Particularly, the horizontal and multilateral wells for shale gas production ideally suit CO_2 injection. Such wells can minimize the disturbance to the surface, but would be too costly to construct for normal CO_2 storage sites. The horizontal and multilateral wells can also reduce the chance of CO_2 leakage, as the passage to the surface is minimized. In addition, the microseismic monitoring system for shale gas production would be useful for monitoring the response of the reservoirs to CO_2 injection.

The low permeability shales, while good as seals, is unfavorable for CO_2 injection. However, the hydraulic fractures introduced for shale gas production have increased the permeability. To estimate the injectivity for CO_2, we modify the formula of the Darcy's law to

$$\dot{M} = \frac{-\rho k}{\mu} \nabla p \quad (2)$$

where $\dot{M}$ is the molar gas flow rate per unit area; ρ is the molar density of the gas flow; k is rock permeability; ∇ is the gradient operator; p is the pressure; μ is the viscosity of the gas. For the same pressure gradient Eq. (2) leads to

$$\dot{M}_{CO_2}/\dot{M}_{CH_4} = (\rho_{CO_2}/\rho_{CH_4})\,(\mu_{CH_4}/\mu_{CO_2}) \quad (3)$$

The left-hand term $\dot{M}_{CO_2}/\dot{M}_{CH_4}$ represents the injectivity for CO_2 measured by the flow rate of methane, which is dependent on the ratios of density and viscosity. The density and viscosity depend on pressure and temperature, and thus depend on the depth of the wells. Fig. 4 is a plot of the injectivity in terms of $\dot{M}_{CO_2}/\dot{M}_{CH_4}$, as a function of the depth for a single well. As can be seen, the injectivity is below unity and decreases with increasing depth to about 52%, showing that the molar flow of CO_2 could be as low as about half of that of methane under the same pressure gradient level. Although it should be possible to increase the CO_2 flow by raising the injection pressure, there is the constraint on allowable pressure set by the hydraulic fractures. On the other hand, with an adequate number of wells, the total CO_2 injection flow could match the CO_2 streams from power plant(s). For instance, the US Marcellus Shale has over 1300 wells (by 2010), and many of the wells can produce millions of cubic feet of gas a day. Such reservoirs would be able to take CO_2 streams from coal-fired power plants of thousands of megawatts.

5.4. CO_2 transport

Depleted shale gas fields would have gas pipelines, which may be reused or converted to transport CO_2. CO_2 pipelines are similar

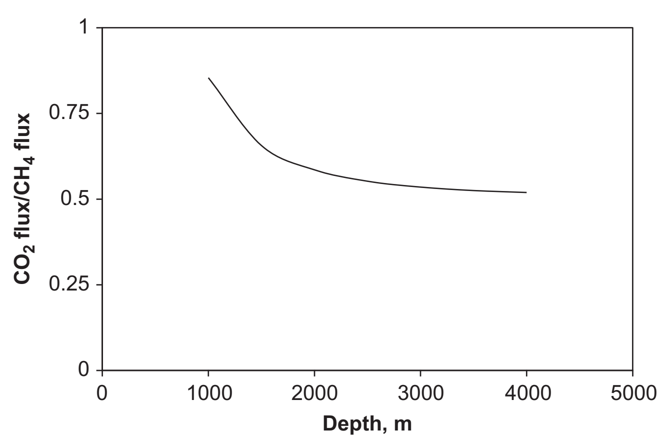

Fig. 4. Molar flux ratio of CO_2 to methane as a function of well depth.

in design to natural gas pipelines, and CO_2 is not corrosive to conventional pipe materials if it is dry. Existing carbon steel pipelines for natural gas are considered suitable for transporting CO_2, as long as the quality of CO_2 is controlled to avoid corrosion (Cronenberg et al., 2009; Serpa et al., 2011). Making use of shale gas pipelines for transporting CO_2 will not only reduce the cost, but also reduce further CO_2 emissions from manufacture of new pipelines.

The distance between shale gas reservoirs and CO_2 emission sources would be a limiting factor for transport of CO_2 if no existing pipelines are available. The CO_2 sources are likely close to more populated areas whereas the reservoirs may not always be. However, in some densely populated parts of the world where large reserves of shale gas could exist, such as Europe, China, India, etc., the distance should not be a significant issue.

5.5. Other benefits

Another important consideration for linking CCS to shale gas development is efficient use of resources and reduction of costs. The depleted shale gas reservoirs would be otherwise unused, leaving a greater environmental footprint of shale gas development. The geological settings of the reservoirs have been well investigated by gas producers, saving the cost for finding storage sites for CO_2. Strict regulations for hydraulic fracturing of gas shale would work favorably for CO_2 storage integrity. Existing shale gas pipelines and other surface infrastructures may be utilized for CO_2 storage.

For both shale gas production and CO_2 storage, drilling wells is a major component of cost. As has been discussed earlier, horizontal and multilateral wells ideally suit CO_2 injection/storage, but could be too costly for CCS alone. The hydraulic fractures will serve to promote permeation of CO_2. Without combining CCS not only the cost for creating the wells and fractures, but also the energy and associated CO_2 emissions are not fully compensated. By combining CCS with shale gas the overall environmental footprint and costs would be significantly lower.

There could be other synergies in CCS combined shale gas production. For example, CO_2 may be used to enhance shale gas production (like enhanced coal bed methane production) and reduce storage costs (IPCC, 2005). CO_2 may also be used as the fracturing fluid in place of water. This would reduce the cost of water and associated treatment and/or disposal, and reduce fugitive emissions of methane, which would be released when water flows back.

6. Other shale gas issues

Shale gas has other advantages for power generation, such as negligible emissions of sulphur dioxide, mercury and particulate matter. On the other hand, shale gas has given rise to environmental worries in addition to GHG emissions, including gas leaks and contamination of drinking water due to hydraulic fracturing. Even so, the production boom is not likely to stop (Rahm, 2011). Discussion of these issues is not in the scope of this work, which focuses on efficient use of available resources to meet growing demand for energy and reduce GHG emissions from the electric power sector. In this context, shale gas could be utilized together with coal during the transition to new and clean energy, provided CCS and other measures (regulating hydraulic fracturing, for example) are incorporated to minimize the environmental impact.

7. Conclusions

The GHG footprint of shale gas could be reduced by reducing methane emissions and incorporating CCS. Depleted shale gas reservoirs have the potential to store more CO_2 than the equivalent CO_2 emitted by the shale gas produced. This would enable cost-effective use of resources and reduced environmental impact.

Appendix A. Supplementary materials

Supplementary materials associated with this article can be found in the online version at doi:10.1016/j.enpol.2011.10.013.

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