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Balance Between Fueling the Economy with Shale Gas and its Carbon Management – Life Cycle Assessment Review

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***Abstract*: Climate activists have long been in opposition of Shale Gas' resource development because of the environmental and land impact related to its development on surface water, ground water sources and air emissions along with potential earthquakes due to induced seismicity. There is a knowledge gap in understanding of carbon footprint of shale gas' resource development because of lack of engineering design detail in previous Life Cycle Analysis of this resource. The objective of this study is to add value and reduce the scientific gap with respect to understanding of shale gas resource development techniques and it's environmental and land impact. The work establishes the Shale gas' resource development foundation by in depth understanding of characteristics of shale reservoirs, generation and distributions of shale gas and key techniques for shale gas construction, production, and processing. The study utilizes ISO 14040 series of standard, which uses Life Cycle Assessment approach and understands the cradle-to-gate, cradle-to-grave and gate-to-gate previous Life Cycle Analysis of shale gas' resource development. The work does systematic analysis and summarizes the previously published Life Cycle Analysis to understand further the potential environmental impacts of resource development of Shale Gas. This will help academia, industry, climate activists, policy makers and public in general to simply understand the field development and its operation of shale gas in terms of carbon numbers thereby optimizing the operations through carbon management thus reducing the potential impacts and meet the sustainability target for future generations.**

***Keywords*: carbon management, life cycle analysis, unconventional hydrocarbons, sustainability.**

1. Introduction

Unconventional hydrocarbon gas reservoirs refer to those gas accumulations that, owing to their special properties i.e. low matrix permeability, presence of natural fractures, adsorbed gas in self-sourced reservoirs, are only commercially recoverable with advanced technologies and substantial stimulation treatments (Vanegas 2007).

Wells in unconventional reservoirs produce from low permeability (tight) formations such as tight sands and carbonates, coal, and shale (Holditch 2006). In unconventional gas reservoirs, the gas is often sourced from the reservoir rock itself (tight gas sandstone and carbonates are an exception). Due to the low permeability of these formations, it is typically necessary to stimulate the reservoir to create additional permeability (Zee Ma 2016). Unconventional gas reservoirs broadly include tight gas, shale gas and coal bed methane (Clarkson, Jensen et al. 2011). Figure 1 classifies the conventional and unconventional formations based on the permeability (CSUR 2012).

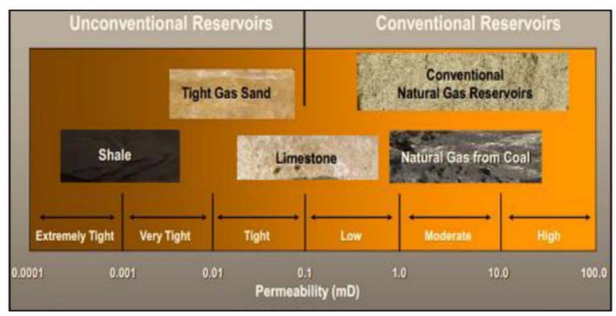

Fig. 1. Classification of conventional and unconventional formations based on permeability (CSUR 2012)

Tight Gas – Wells produce from regional low-porosity sandstones and carbonate reservoirs. The natural gas is sourced (formed) outside the reservoir and migrates into the reservoir over time that is typically millions of years (Holditch 2006). Many of these wells are drilled horizontally and most are hydraulically fractured to enhance production.

Shale Gas – Wells produce from low permeability shale formations that are also the source for the natural gas. The natural gas volumes can be stored in a local macro-porosity system (fracture porosity) within the shale, or within the micro pores of the shale, or it can be adsorbed onto minerals or organic matter within the shale (Zendehboudi and Bahadori 2017). Wells may be drilled either vertically or horizontally and most are hydraulically fractured to stimulate production.

Coal Bed Methane (CBM) – Wells produce from the coal seams which act as source and reservoir of natural gas. Wells frequently produce water as well as natural gas (Haldar 2018). Natural gas can be sourced by thermogenic alterations of coal or by biogenic action of indigenous microbes on the coal. There

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are some horizontally drilled CBM wells and some that receive hydraulic fracturing treatments (Simpson, Lea et al. 2003).

2. Genesis and Characteristics of Unconventional Hydrocarbons

Unconventional gas sources are unconventional only in the sense that, given current economic conditions and states of technology, they are more expensive to exploit and may produce at much slower rates than conventional gas fields.

Tight gas occurs in either blanket or lenticular sandstones that have an effective permeability of less than one millidarcy (or 0.001 darcy) (Fuels 2012). These relatively impermeable sandstones are reservoirs for considerable amounts of gas that are mostly uneconomical to produce by conventional vertical wells because of low natural flow rates.

Shale gas is generated from organic mud deposited at the bottom of ancient bodies of water (Fuels 2012). Over time, heat, overburden pressure and subsequent sedimentation transforms the mud into shale and also generates natural gas from the organic matter contained in it. Over long spans of geologic time, primary migration takes place to adjacent sandstones and gets trapped in them, forming conventional gas reservoirs. The rest of the gas remains sealed in the nonporous shale (Zendehboudi and Bahadori 2017).

Large volumes of methane are trapped within coal seams. Even though a considerable amount of gas that is formed during the initial coalification process is lost to the atmosphere, a significant portion remains as free gas in the joints and fractures of the coal seam. Moreover, large quantities of gas are adsorbed on the internal surfaces of the micro pores within the coal itself (Fuels 2012). This gas can be retrieved by drilling wells into the coal seam and pumping out large quantities of water that saturate the seam. Removing the water decreases the pressure in the seam, thereby enabling the adsorbed methane to desorb and migrate as free gas into fractures in the coal (Fuels 2012). Figure 2 classifies the unconventional gas reservoirs based on their characteristics.

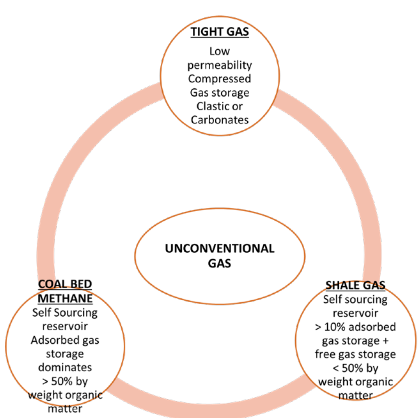

Fig. 2. Classification of unconventional gas based on their characteristics

3. Key Technologies for Unconventional Hydrocarbons Exploration, Construction, Production and Processing

Most of the unconventional gas reservoirs particularly tight gas, shale gas and coal bed methane cannot be economically produced unless advanced technologies are utilized. Novel and innovative techniques have been developed for exploration, drilling, stimulation and production (Bieletzki 2010). The fundamental aim of these technologies to reduce the capital and operational costs over time while improving the production rates. A continued advancement in research and development is needed to safeguard the future prospects of unconventional gas reservoirs Furthermore, the development of these unconventional resources is instigated by the growth in the global natural gas demand (Bieletzki 2010).

Producing natural gas reservoirs abundantly found in low permeability formations is the focus of unconventional gas producers. Due to the peculiar characteristics of these formations, a thorough subsurface study must be conducted to understand the geological features before the production can be realized commercially (Bieletzki 2010). The starting point of the production process is determined by identifying the most productive gas zones. The sweet spots are chosen where the permeability is maximum and provides least restriction to the flow of gas (Holditch and Chianelli 2008). Most of the logging techniques do not provide sufficient information when applied to unconventional reservoirs, since they had been developed for high permeability and high porosity formations. Improved methods and fit for purpose tools are essential to enhance the sub surface assessment quality of unconventional reservoirs. Accurate estimates on the formation permeability and porosity are crucial for successful exploitation of unconventional gas reservoirs (Soleimani, Jahanpeyma et al. 2019). The precise assessment of subsurface features would also be beneficial for deciding the production technology.

Unlike conventional reservoirs, a combination of vertical and horizontal drilling is required to produce from unconventional formations. Initially, vertically wells are drilled to touch the surrounding subsurface area of the reservoir that is usually deep. Later on, horizontal or directional wells are drilled to enhance the drainage area (Joshi 1991). Since, unconventional reservoirs are greatly spread horizontally as compare to their vertically thickness, therefore, horizontal wells are drilled parallel to them that enables natural gas to be produced effectively (Engerer and Horn 2010). This improves the contact area between the well and the formation, thereby increasing the surface area for unconventional gas to flow into the well (Andrews 2009).

Since, unconventional gas reservoirs are low permeable, hence additional stimulation treatments are required to achieve sufficient production rates. Hydraulic fracturing is one of the key techniques to complete horizontal wells and allow the flow of gas at economic rates (Bieletzki 2010). Fracturing fluid is injected under high pressure, thereby generating fractures and cracks within the subsurface structure. The fracturing fluid consists of water and additives along with proppant (e.g. sand) which prevents the fractures to close (Schlager 2004). The design parameters of the fracturing process such as injection pressure, injection fluid volume, additives and types of proppants are determined based on the characteristics of the formation (Chermak and Patrick 1995).

After the horizontal well is drilled and completed with hydraulic fracturing, gas is produced together with water as a byproduct. The produced water consists of injected water during the fracturing process as well as formation water. The produced water is contaminated and requires proper discharge, recycling or reinjection (GWPC 2009).

Another revolutionary technology that has enabled natural gas producers to economically produce unconventional gas is the use of multi-well drilling pads (Bieletzki 2010). This technique reduces the number of wells as multiple wells can originate from single vertical well. Moreover, surface footprint is optimized as less equipment is required on the above-ground production site. Therefore, multi-well drilling pads positively influence the economic efficiency of the unconventional gas production (GWPC 2009).

4. Shale Gas Exploration and Development

1) Characteristics of shale reservoirs

Shale is a sedimentary rock that is predominantly comprised of consolidated clay-sized particles. Shales are deposited as mud in low-energy depositional environments such as tidal flats and deep-water basins where the fine-grained clay particles fall out of suspension in these quiet waters (Darling 2005). During the deposition of these very fine-grained sediments, there can also be deposition of organic matter in the form of algae, plant, and animal-derived organic debris. The naturally tabular clay grains tend to lie flat as the sediments accumulate and subsequently become compacted as a result of additional sediment deposition (Link 1982). Typical unfractured shales have matrix permeabilities on the order of 10 to 0.01 nanoDarcies. This low permeability means that gas trapped in shale cannot move easily within the rock except over geologic expanses of time (Carlson 1994).

Many factors impact the gas production from shale gas reservoirs, where the most prominent is the number and the structural complexity of fracture network. The effective conductivity of fractures and the actual permeability of the shale rock are also crucial for the productivity (Cipolla, Lolon et al. 2009).

B. Generation and distribution of shale gas

There are three processes through which the organic matter passes as it matures to produce hydrocarbons within the shale formation (Link 1982). The processes are:

Diagenesis – During early Diagenesis, one of the main agents of transformation is microbial activity. Depending on the oxygen content of the sea water and sediments, microbial transformation of organic matter is either aerobic or anaerobic (D.H. 1978). Biological polymers (lipids, proteins, etc.) are destroyed by microbial activity and mild chemical reactions occur during this time. The constituent units of these biopolymers become progressively engaged in new polymer structures. The recombined polymers are the result of geological conditions and are thus called geopolymers. This early diagenetic geopolymer material is often called humin. As the humin is buried deeper by increasing overburden, it becomes progressively more polymerized and more chemically inert. A large carbon ring network develops and the material is then called kerogen (Link 1982).

Catagenesis – As burial continues, the kerogen formed during Diagenesis is exposed to increasing temperatures and pressures. Catagenesis is the stage of thermal degradation of kerogen that forms oil and gas. This stage typically occurs between depths of several hundred to several thousand meters (Link 1982).

Metagenesis – The metagenesis stage is reached at great depths, or in areas of high geothermal gradients at shallower depths. At this stage, kerogen has very little hydrogen remaining and is forming methane as its only hydrocarbon product. Towards the end of metagenesis, virtually no hydrocarbons are being generated from the kerogen. The completion of metagenesis occurs at vitrinite reflectance values of around 4% (Link 1982).

Shale gas is both created and stored within the shale bed. Natural gas (methane) is generated from the organic matter that is deposited within and present in the shale matrix (D.H. 1978). In order for a shale to have economic quantities of gas, it must be a capable source rock. The potential of a shale formation to contain economic quantities of gas can be evaluated by identifying specific source rock characteristics such as total organic carbon (TOC), thermal maturity, and kerogen analysis (Alam 2010).

Shale rocks contain very fine grains of minerals separated by very small spaces called pores. Natural gas or oil molecules that have been created from the organic matter are trapped within the numerous organic micro-pores or are attached to the organic material by a process called adsorption (CSUG 2009).

The amount of pore space within the shale usually ranges between 2-10% allowing a large volume of natural gas to be stored within the rock. The amount of natural gas that is stored within shale is variable depending on the amount of organic material present, reservoir pressure and thermal maturity of the rock (CSUG 2009). Figure 3 depicts the storage mechanism in shale gas reservoirs (Zhang 2019).

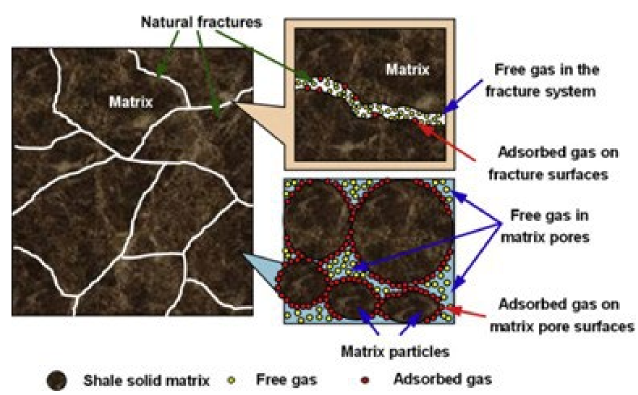

Fig. 3. Gas storage mechanism in shale gas reservoirs (Zhang 2019)

1) Key techniques for shale gas construction, production, and processing

Most unconventional natural gas reservoirs tend to have a lower permeability and require methods to increase the amount of reservoir in contact with the borehole. In shale gas, the two most common methods are horizontal drilling and hydraulic fracturing (CSUG 2009).

Horizontal drilling first entails drilling a vertical well to a predetermined depth above the shale gas reservoir. The well is then drilled at an increasing angle until it meets the reservoir interval in a horizontal plane (CSUG 2009). Once horizontal, the well is drilled to a selected length, which could extend to as much as 2500m. This portion of the well, called the horizontal leg, allows significantly increased contact of the wellbore with the reservoir compared to a vertical well (Zendehboudi and Bahadori 2017).

Upon completion of drilling, production casing is placed in the wellbore. A perforating gun is used to create a series of holes in the casing to connect the rock formation to the wellbore. The technological key to the economic recovery of shale gas is hydraulic fracturing (Energy 2009).

Hydraulic fracturing involves the pumping of a fracturing fluid into a formation at a calculated, predetermined rate and pressure to generate fractures or cracks in the target formation (Energy 2009). For shale gas development, fracture fluids are primarily water-based fluids mixed with additives which help the water to carry sand proppant into the fractures. The sand proppant is needed to prop open the fractures once the pumping of fluids has stopped. Once the fracture has initiated, additional fluids are pumped into the wellbore to continue the development of the fracture and to carry the proppant deeper into the formation (Spellman 2012). The additional fluids are needed to maintain the downhole pressure necessary to accommodate the increasing length of opened fracture in the formation (Zendehboudi and Bahadori 2017).

The process of designing hydraulic fracture treatments involves identifying properties of the target formation including fracture pressure, and the desired length of fractures (Energy 2009).

Modern formation stimulation practices are sophisticated, engineered processes designed to emplace fracture networks in specific rock strata. A hydraulic fracture treatment is a controlled process designed to the specific conditions of the target formation (thickness of shale, rock fracturing characteristics, etc.) (Energy 2009).

Additional advances in hydraulic fracturing design target analysis of hydraulic fracture treatments through technologies such as micro seismic fracture mapping and tilt measurement. These technologies can be used to define the success and orientation of the fractures created, thus providing the engineers with the ability to manage the resource through the strategic placement of additional wells, taking advantage of the natural reservoir conditions and expected fracture results in new wells (Energy 2009).

Hydraulic fracturing of horizontal shale gas wells is performed in stages. Lateral lengths in horizontal wells for shale gas development may range from 1,000 feet to more than 5,000 feet. Due to the length of exposed wellbore, it is usually not possible to maintain a downhole pressure sufficient to stimulate the entire length of a lateral in a single stimulation event (Spellman 2012).

Prior to performing a hydraulic fracture treatment of a well (vertical or horizontal), a series of tests is performed (Spellman 2012). These tests ensure that the well equipment and hydraulic fracturing equipment are in proper working order and will safely withstand the application of the fracture treatment pressures and pump flow rates (Pokalai, Fei et al. 2015).

In most horizontal wells that have an extended horizontal leg section multiple fracturing operation are necessary to effectively stimulate the reservoir rock. This process is called “multi-stage fracking” and consists of dividing the horizontal leg into sections which are then fractured independently (Pokalai, Fei et al. 2015). During the fracking operation each “stage” is isolated from the rest of the wellbore using various types of plugs or packers (seals). Upon completion of all fracture stages the plugs or packers are removed and all stages of the wellbore are allowed to flow back to the surface (CSUG 2009). Figure 4 shows are multi stage hydraulic fracturing job in a shale formation (Majid 2014).

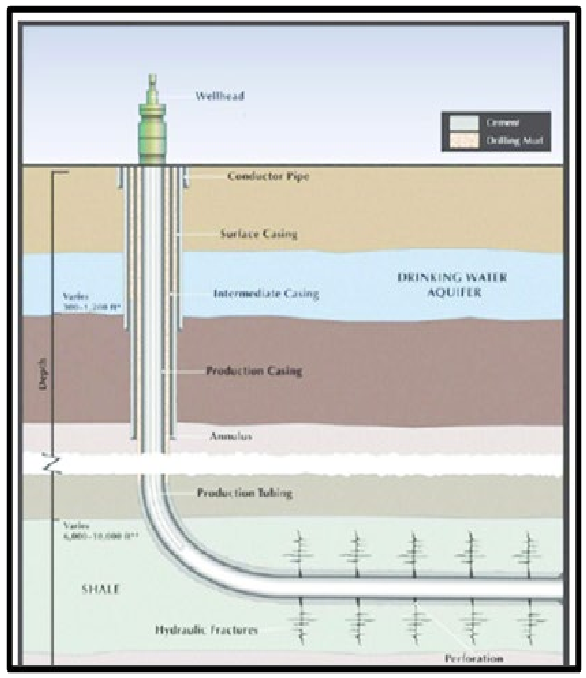

Fig. 4. Multi stage hydraulic fracturing (Majid 2014)

5. Previous Life Cycle Assessment Applications in Shale Gas Reservoir

To assess the environmental burdens of shale gas production, a life cycle inventory (LCI) model has been created using the ISO 14040 standards and was used to carry out the life cycle assessment of a given shale gas production facility. The system boundaries chosen to follow a cradle-to gate approach, with the primary aim to estimate the methane and overall greenhouse gas emissions of shale gas production. These comprise all infrastructure installation and production operations, starting from initial well-pad construction, through to the stage of gas compression. The three main processes and related sub-processes considered are construction, production, and processing. In order to provide a complete assessment of the entire life cycle impact of shale gas production, each activity that takes place, the function of equipment and the corresponding operations within the system boundary are considered. However, due to data limitations (so far) only major operations and individual equipment involved in natural gas extraction from shale gas resources and the processing of produced gas are considered.

The increased awareness of the importance of environmental protection and the possible environmental impacts associated with emission of GHG and toxic gas because of exploration, drilling and fracturing, production and processing of the natural gas produced from shale gas reservoirs, has heightened interest in the development of methods to better understand and address these impacts. One of the techniques that can be used for this purpose is life cycle assessment (LCA), which according to the ISO 14040, can assist in,

- Identifying opportunities to improve the environmental performance of the production process of shale gas at various points in their life cycle.
- Informing decision-makers in industry, government, or non-government organisations (e.g., for strategic planning, priority setting, product or process design or redesign)
- The selection of relevant indicators of environmental performance, including measurement techniques.
- Marketing (e.g., Implementing an eco-labelling scheme, making an environmental claim, or producing an environmental product declaration)

There are four phases in a LCA study (ISO 14040), namely the goal and scope definition, inventory analysis, environmental impact assessment and the interpretation phases, all of which are described in detail in the ISO 14040 series of standards.

Recent studies using LCA methods aimed to estimate the GHG emissions associated with the upstream, midstream and downstream operations of shale gas. Mohan et al. studied the life cycle GHG emissions from the production of Marcellus shale gas and compared its emissions with national average US natural gas emissions produced in the year 2008, prior to any significant Marcellus shale development. The life cycle GHG emissions of Marcellus shale gas was estimated to be ~68g CO2 eq/MJ of gas produced representing an 11% increase in GHG emissions relative to average domestic gas (excluding combustion) and a 3% increase relative to the life cycle emissions when combustion is included (Jiang, Griffin et al. 2011). In a similar research work, Laurenzi et al. presented results on a life cycle assessment of Marcellus shale gas used for power generation indicating that a typical Marcellus gas life cycle yields 466 kg CO2eq and 224 gal of freshwater consumption per MWh generated. This GWP footprint of Marcellus gas is thought to be 53% lower than coal according to these authors. The paper concluded that substantial GHG reductions would result from the replacement of coal-fired power generation with gas-fired power generation (Laurenzi and Jersey 2013). In another research, Hultman et al. published a detailed comparison about the life-cycle emissions of conventional gas, shale gas and coal for only electricity generation sector. It was found that the GHG impacts of shale gas are 11% higher than those of conventional gas, and only 56% of that for coal (Hultman, Rebois et al. 2011). Although the above-mentioned studies of Mohan et al., Hultman et al. and Laurenzi et al. presented extensive work related to shale gas field emissions during operation, these estimations lack engineering and operational detailing estimating the GHG and water consumption. In addition, the field closure and post closure operational emissions are not covered.

Another significant contribution was made by Burnham et al. who investigated whether the fugitive methane emissions during natural gas production and transmission outweigh the lower CO2 emissions during combustion, when compared to coal and petroleum. The base case results showed that shale gas life-cycle emissions are 6% lower than conventional natural gas, 23% lower than gasoline, and 33% lower than coal (Burnham, Han et al. 2012). In 2014, Stamford et al. used the CML method to study the different life cycle impacts of shale gas, as opposed to the previous studies which considered mainly the GWP impact category (Stamford and Azapagic 2014). The main advantage of this paper was that it compared shale gas with all other fossil-fuel alternatives (conventional gas and coal) and with low-carbon options (nuclear, offshore wind and solar photovoltaics). The results suggest that the impacts range widely, depending on the assumptions. For example, the global warming potential (GWP100) of electricity from shale gas ranges from 412 to 1,102 g CO2-eq/kWh with a central estimate of 462 g CO2-eq/kWh. Their central estimates suggest that shale gas is comparable or superior to conventional gas and low-carbon technologies for depletion of abiotic resources, eutrophication, and freshwater, marine and human toxicities. Conversely, it has a higher potential for creation of photochemical oxidants (smog) and terrestrial toxicity than any other option considered. For acidification, shale gas is a better option than coal power but an order of magnitude worse than the other options. The impact on ozone layer depletion is within the range found for conventional gas, but nuclear and wind power are better options still. Burnham et al. and Stamford et al. contributions in comparing the life cycle emissions of shale gas as compared to other fossil fuels are very significant but these studies did not consider that these different fuels can have significantly different emissions when considering the geological subsurface environments they originate from, which affect the operational choices and requirements to produce these fluids and therefore affecting the field ultimate recovery and life cycle emissions of the facilities. Neither did they consider the effects of geographical constraints with regards to the source and market for the fuels.

In order to evaluate the water footprint from shale gas field development, Tagliaferri et al. presented a study reporting a detailed hot spot analysis of shale gas on the watersheds. The study assumed that the extraction of shale gas involves the same processes as the extraction of conventional gas except for all the operations associated with the hydraulic fracturing. The water use of shale gas extraction due to the hydraulic fracturing accounts for 91% of the water consumption in shale gas production (Tagliaferri, Clift et al. 2017). To further investigate the water footprint and emissions from the shale gas life cycle, Brown et al. published a cradle to gate life cycle assessment model to quantify the GHG emission and water consumption footprint of a U.S. unconventional shale gas well. Results showed that 7.1 kg CO2 are emitted per Mcf of gas produced, equal to an emission rate of 1.48 % across the system boundary. Sensitivity analysis showed that for a best-case scenario this rate can be as low as 0.55 % of the natural gas produced, whilst the worst-case suggests a CH4 emission rate of 4.3 %. The water consumption was found to be 11.2 litres per Mcf of gas production (Brown, Korre et al. 2017). The results presented in Tagliaferri et al. and Brown et al. provided a reasonably good estimation related to water footprint of shale gas field development, but these studies do not include the water consumption in the well abandonment at the stage of field decommissioning. Brown et al. provided fundamental basis for this research work and is most comprehensive study published so far.

In a series of studies by National Energy Technology Laboratory, a detailed bottom-up study of life-cycle emissions from electricity generated from conventional and shale gas from various sources are compared to the life cycle emissions from coal-fired electricity production. The study found that life cycle emissions of GHGs from natural gas fired electricity generation are 39% lower than coal fired electricity generation (NETL 2010). In 2011, Howarth et al. presented a study to specifically focus on the life cycle emissions from shale gas production, which gained a lot of attention due to its conclusion that shale gas has higher life-cycle GHG emissions than coal, largely due to methane emissions during the extraction process (Howarth, Santoro et al. 2011). Following from that, in 2014, Howarth et al. further concluded that when methane emissions are included, the GHG footprint of shale gas is significantly larger than that of conventional natural gas, coal, and oil (Howarth 2014). In another research study, Stephenson et al estimated that shale gas has life cycle GHG emissions about 1.8–2.4% higher than conventional gas, arising mainly from higher methane releases in well completion (Stephenson, Valle et al. 2011).

6. Conclusion

This paper presented a review on balance between fueling the economy with shale gas and its carbon management.

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