The carbon dioxide concentrations in the atmosphere have increased to over 400 ppm in the year 2014 compared to nearly 320 ppm over the last 50 years (NOAA, 2015). This rapid increase in carbon dioxide concentrations results in an overall warming of the earth that could prove harmful to the environment. Drastic reductions in carbon dioxide and greenhouse gas (GHG) emissions have been called for to combat deleterious changes to climate (AGU, 2008). While conversion to renewable sources of energy can significantly reduce emissions, these technologies are not mature enough to be widely adopted on a large scale. Furthermore, solar and wind energies tend to be intermittent and as such, often have to be backed by more reliable fossil-fuel-based sources. As such, our reliance on fossil fuels will continue at least in the foreseeable future.
A comparison of emission rates for various fossil fuels for a given unit of energy consumed is presented in Table 1. It can be seen that natural gas has lowest emissions of carbon dioxide and other harmful pollutants compared to coal, crude oil and its derivatives. As such, natural gas has been called the bridge fuel to a low carbon emission future. In addition, natural gas can be extracted at relatively low costs even in many otherwise unfavorable reservoirs and requires limited processing prior to its end use. Replacement of coal and oil use with natural gas is therefore particularly advantageous. In particular, conversion of older coal-fired power plants to natural gas and greater utilization of existing combined cycle natural gas power plants is seen to provide a short-term, low cost opportunity to cut the emissions from the U.S. power sector by nearly 20% with the added benefit of reductions in other harmful atmospheric pollutants (Moniz et al., 2012). Given these benefits, the natural gas consumption has grown at a substantial pace worldwide, particularly in China and the U.S. (EIA, 2014). Needless to say, the natural gas production has also increased significantly over the last few years to meet this growing demand. As shown in Figure 1, the production of natural gas in the United States has increased tremendously over the last decade with over a million MCF (million cubic feet) of production added each year. The United States became the largest producer of natural gas in the world in the year 2012 and nearly 25% of the total energy demand of the U.S. is currently being met using natural gas.

Environmental Impacts of Natural Gas

Substitution of other fossil fuels with natural gas in residential and commercial heating, industrial processes, transportation and energy sectors is clearly advantageous in reducing the overall emissions of carbon dioxide and other greenhouse gases (GHG). However, as with any operations, the extraction, processing and usage of natural gas poses certain environmental risks. Understanding the nature and extent of these risks is critical to evaluate the true benefits of natural gas and as such these environmental impacts are briefly discussed next.

Direct Methane Emissions

Natural gas is primarily comprised of methane (87% – 97%) but may also contain trace quantities of other volatile organics – ethane (1.5% – 7.0%), propane (0.1% – 1.5%), butane (0.01% – 0.3%), pentane (trace – 0.04%) as well as nitrogen (0.2% – 5.5%), carbon dioxide (0.1% – 1%) on a molar basis (Union Gas, 2015). While methane’s lifespan in the atmosphere is much shorter than carbon dioxide, it is much more efficient in trapping solar radiation that contributes to global warming. Pound per pound, comparative impacts of methane on climate change is estimated to be 84 times greater than carbon dioxide emissions over a 20 year period or 28 times greater than carbon dioxide emissions over a 100 year period (EDF, 2015, IPCC, 2013). Direct emissions of methane during the production, transmission and storage of natural gas and oil as well as from other industrial processes, transportation and energy sectors is expected to increase at least till the middle of the 21st century and the fraction obtained from shale resources is projected to be over 60% in the year 2045 (Vidas and Hugman, 2008).
processes are estimated to account for nearly 30% of the total methane emissions (U.S. EPA, 2013). While estimating emissions has been a controversial topic, large-scale field measurement studies have provided great insights in recent years. Allen et al., (2013) found that emission factors for pneumatic pumps and controllers as well as equipment leaks were higher than estimates in the national inventory carried out by U.S. Environmental Protection Agency (EPA). In a follow up study, Allen et al., (2015) indicate that methane emissions from liquid unloadings—a process used to clear wells of accumulated liquids to enhance production—are about 270 Gg/yr and within a few percent of the 2012 national emissions inventory conducted by EPA. Brantley et al. (2015) indicate that while a direct relationship exists between methane emissions and gas production, only approximately 10% of the variation in emission rates is explained by variation in production levels. The weak correlation likely indicates the importance of on-site production designs and control equipment in determining emissions. Significant progress has however been made in curtailing methane emissions from upstream activities. The long-run data indicate that methane emissions from natural gas systems have declined by about 17% since 1990.

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The natural gas transmission system in the U.S. is extensive and consists of nearly 300,000 miles of major pipelines and an addition 2 million miles of low pressure (distribution) pipelines that move natural gas to homes and businesses (EIA, 2015) (see Figure 3). The risks of potential methane leaks due to infrastructure failure must therefore be borne in mind. Subramanian et al., (2015) conclude that compressor vents, leaky isolation valves, reciprocating engine exhaust, and equipment leaks were major sources, and substantial emissions were observed at both operating and standby compressor stations in the transmission and storage sector. While the observed emissions generally agreed with the EPA emission inventory estimates, the results were skewed by a few sites that exhibited significantly higher emissions. Like most infrastructure in the U.S., there are also aging problems associated with natural gas transmission lines. For example, Philip et al., (2012) report 3,356 separate leaks under the city of Boston and a similar situation can be expected at other cities as well due to aging infrastructure. Natural gas leaks into the atmosphere have fueled the debate as to whether the environmental benefits accrued from reduced emissions of priority pollutants are nullified by increased methane emissions. Life-cycle assessment studies appear to indicate that there are net positive benefits to be accrued from conversion to natural gas and this can be further improved using appropriate policy and treatment technologies (Burnham et al., 2011).

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>CO₂ Factor (kg CO₂ per mmBtu)</th>
<th>CH₄ Factor (g CH₄ per mmBtu)</th>
<th>N₂O Factor (g N₂O per mmBtu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal Coke</td>
<td>113.67</td>
<td>11</td>
<td>1.6</td>
</tr>
<tr>
<td>Natural Gas (per scf)</td>
<td>53.06</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Crude Oil</td>
<td>74.54</td>
<td>3</td>
<td>0.6</td>
</tr>
<tr>
<td>Motor Gasoline</td>
<td>70.22</td>
<td>3</td>
<td>0.6</td>
</tr>
<tr>
<td>Petroleum Coke</td>
<td>102.41</td>
<td>3</td>
<td>0.6</td>
</tr>
<tr>
<td>Kerosene</td>
<td>75.2</td>
<td>3</td>
<td>0.6</td>
</tr>
<tr>
<td>Biodiesel (100% Liquid)</td>
<td>73.84</td>
<td>1.1</td>
<td>0.11</td>
</tr>
<tr>
<td>Other fossil fuels</td>
<td>39.80</td>
<td>3.00</td>
<td>Per ton of carbon content of the fuel</td>
</tr>
</tbody>
</table>

Table 1: Emission factors for Natural Gas and other fuels. (Data from: EPA, 2014a)
Criteria Air Pollutants

In addition to direct methane releases, oil and gas exploration activities can also affect other air pollutants such as VOCs, NOx, and ozone. Litovitz et al., (2013) observed that NOx emissions from all shale gas activities were 20 to 40 times higher than what is allowable for a single minor source and indicate that most emissions are related to ongoing activities such as gas production and compression and are not necessarily depend on the fact that the oil and gas are being extracted from unconventional sources. Figure 4 depicts the non-attainment areas in the U.S. for various priority pollutants and their geographic context with respect to major shale gas basins. It is clear that shale gas exploration near urban areas (e.g., Marcellus Shale and Barnett shale) represents an additional source in areas already experiencing significant air quality stresses. Control technologies, best practices and policy instruments such as emission taxes will likely be required to achieve net reductions in the long-run (McLeod et al., 2014). It is however, important to evaluate these increased emissions in the context reductions obtained by combustion of natural gas over other fossil fuels. Life cycle assessment studies indicate that overall emission from shale gas are generally lower than or at least comparable to conventional natural gas emissions and substantially lower than gasoline and coal (Burnham et al., 2011).

Landuse and Community-Level Impacts

Development of unconventional oil and gas resources leads to habitat fragmentation, deforestation and noise pollution all of which are known to increase the overall risks to biodiversity (Kiviat, 2013). Potential impacts to listed threatened and endangered species that are protected by the federal endangered species act (ESA) are of particular concern and in the year 2012, the U.S. Fish and Wildlife Service (FWS) began listing endangered species based on the threat of fracturing (Robbins, 2013). Induced seismicity due to injection (or withdrawal) of fluids underground is also a concern with unconventional oil and gas development. Induced seismicity is known to occur when the excess fluid pressure caused due to injection propagates and is taken up to the surface through geological faults. Changes in solid stress caused due to injection or withdrawal of water can also induce seismicity by increasing the shear stresses and/or reducing the normal stresses acting on the fault (Ellsworth, 2013). A majority of recorded induced seismicity events appear to be related to the injection of produced water into Class II injection wells. The magnitude of induced earthquakes appear to be related to the injected volume (McGarr, 2014) and also the rate of water injection (Ellsworth, 2013). This understanding is useful to guide unconventional oil and gas production in seismically active shale basins.

Figure 1 (top): U.S. Natural Gas Production for the past 15 years. (Data from: EIA, 2015a)
Figure 2 (bottom): Sources for Natural gas production. (Data from: EIA, 2015b)
While natural gas production from shale basins has been an economic boon to many rural communities in the U.S., accidents, injury and health damage due to acute and chronic exposures are of concern both to the workers as well as the general public. Many small communities are not fully equipped to handle challenges such as increased crime rate and stresses on medical infrastructure commonly associated with sudden spurts in population (MSSRC, 2014). Most rural roadways are not built to handle the heavy load traffic associated with hydraulic fracturing. Transportation risks are therefore not just limited to vehicular damage (e.g., broken windshields), increased accidents but also damage to pavements which increase the costs of infrastructure maintenance to the communities (Senadheera, 2015). Increased emissions from mobile sources due to increased traffic, congestion and idling must be factored to properly assess the impacts of increased natural gas production (Hernandez et al., 2015).

**Impacts on Water Resources**

Construction of hydraulic fracturing pads can increase runoff, sediment and pollutant loadings to rivers and as such affect the aquatic flora and fauna in the receiving bodies. These risks again vary across different shale plays and regions. There is greater rainfall and a denser network of perennial streams and rivers in the eastern United States and such increased activity in shale basins underlying these areas increase sediment and pollutant runoff risks. Produced water...
generated at hydraulic fracturing sites contain many harmful chemicals including volatile organic compounds such as benzene, radioactive substances and heavy metals (Lester et al., 2015). Jiang et al., (2014) performed a life cycle analysis and concluded that direct untreated discharge from a shale gas well in Marcellus shale play would have an eutrophication potential of 300 – 3000 kg N-eq and an eco-toxicity potential of 900 – 23000 kg 2,4 D-eq. As shown in Figure 5, the produced water generated from hydraulic fracturing operations are extremely saline. Desalination of such highly saline water is technologically challenging and cost-prohibitive. It is estimated that treatment costs can be as high as $2.50 – $4.00 per barrel depending upon the quality of the produced water and the treatment targets (Duraisamy et al., 2013; Jiang et al., 2014). Naturally occurring radioactive materials (NORMs) have also been cited as a major source of concern with produced waters (Kargbo et al., 2010). Limited data on NORMs in produced waters indicates that the values can be above the maximum contaminant levels (MCLs) prescribed by EPA for potable water (Figure 6). However, data on radionuclides in produced water is extremely sparse and Figure 6 presents an aggregated range using measurements made across several basins. Additional data are therefore necessary to understand the basin specific characteristics of these chemicals.

Methane leakage from shallower aquifers used for drinking water purposes is also another major concern that has received wide media attention particularly in light of hydraulic fracturing. Methane in subsurface emanates from both thermogenic
(oil and gas related) and biogenic (biologically mediated) sources. While specific isotopes and hydrocarbon ratios (methane to higher chain hydrocarbon ratios) are used to separate these sources, there is much controversy in terms of the relative importance of these sources (Osborn et al., 2011; Molofsky et al., 2013; Jackson et al., 2013). Casing and cement impairment are noted to be higher in shale gas wells compared to conventional wells possibly due to rushed development and often a major pathway for subsurface methane emissions (Ingraffea et al., 2014). Methane emissions from abandoned oil and gas wells are predominantly of thermogenic origin and as such an important pathway that is currently not accounted for in greenhouse gas emission inventories (Kang et al., 2014).

Summary and Path Forward
Conversion to natural gas from other carbon intensive fossil fuels is clearly advantageous to reduce carbon dioxide emissions to the atmosphere and slow down the rate of climate change. The recent boom in natural gas production in the U.S. from unconventional shale basins is a major step towards the nation’s energy independence and contributed positively to the economy as well. However, the rapid growth has been challenging on several fronts and has had an impact on land, water and air resources in shale basins.

While natural gas is viewed as a bridge fuel to a renewable-energy-based economy, methane is a major constituent of the natural gas that is more potent than carbon dioxide in terms of trapping solar radiation. Therefore the true benefits of

References
natural gas conversion can only be realized if fugitive methane emissions are curtailed. The life cycle of natural gas production, storage, transmission and use of natural gas presents several weak spots at which methane emissions can occur. While uncertainties and data gaps exist, a significant body of knowledge has been amassed in the last few years that helps us better understand the nature and extent of methane emissions across the shale-derived natural gas life cycle. It is imperative that regulators, policy makers and social planners base their decisions related to shale gas development rooted in this nascent yet burgeoning science and carefully weigh the economic benefits and environmental impacts in a balanced manner. In a similar manner, impact information is not uniformly available across all major shale basins. Rigorous scientific and engineering endeavors are needed to close these data gaps. Holistic life cycle approaches where the scientific and regulatory communities are working towards reducing the environmental and health risks are essential to fully realize the true benefits of low carbon emission fuels.

Natural gas leaks into the atmosphere have fueled the debate as to whether the environmental benefits accrued from reduced emissions of priority pollutants are nullified by increased methane emissions.