Progress in Energy and Combustion Science 000 (2017) 1–31

Contents lists available at ScienceDirect

Progress in Energy and Combustion Science

journal homepage: www.elsevier.com/locate/pecs

The role of natural gas and its infrastructure in mitigating greenhouse gas emissions, improving regional air quality, and renewable resource integration

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ARTICLE INFO

Article History:
Received 24 April 2017
Accepted 7 October 2017
Available online xxx

Keywords:
Air quality
Greenhouse gas
Natural gas
Methane
Fuel cells
Co-benefits

ABSTRACT

The pursuit of future energy systems that can meet electricity demands while supporting the attainment of societal environment goals, including mitigating climate change and reducing pollution in the air, has led to questions regarding the viability of continued use of natural gas. Natural gas use, particularly for electricity generation, has increased in recent years due to enhanced resource availability from non-traditional reserves and pressure to reduce greenhouse gasses (GHG) from higher-emitting sources, including coal generation. While lower than coal emissions, current natural gas power generation strategies primarily utilize combustion with higher emissions of GHG and criteria pollutants than other low-carbon generation options, including renewable resources. Furthermore, emissions from life cycle stages of natural gas production and distribution can have additional detrimental GHG and air quality (AQ) impacts. On the other hand, natural gas power generation can play an important role in supporting renewable resource integration by (1) providing essential load balancing services, and (2) supporting the use of gaseous renewable fuels through the existing infrastructure of the natural gas system. Additionally, advanced technologies and strategies including fuel cells and combined cooling heating and power (CCHP) systems can facilitate natural gas generation with low emissions and high efficiencies. Thus, the role of natural gas generation in the context of GHG mitigation and AQ improvement is complex and multi-faceted, requiring consideration of more than simple quantification of total or net emissions. If appropriately constructed and managed, natural gas generation could support and advance sustainable and renewable energy. In this paper, a review of the literature regarding emissions from natural gas with a focus on power generation is conducted and discussed in the context of GHG and AQ impacts. In addition, a pathway forward is proposed for natural gas generation and infrastructure to maximize environmental benefits and support renewable resources in the attainment of emission reductions.

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http://dx.doi.org/10.1016/j.pecs.2017.10.002

1. Introduction and background

The current interchange between energy and the environment is prompting fundamental shifts in societal management of energy systems, including electricity generation. Climactic change by anthropogenic emissions of greenhouse gasses (GHG) is perhaps the most important driver of environmentally-influenced societal change [1]. Deep reductions in GHG emissions (e.g., 50 to 80% below 2005 levels by 2050) are being required from developed nations for prevention of detrimental climate impacts [2,3]. Of similar concern, pollution in the air is expected to be the single largest global cause of environmentally-related premature mortality by 2050 [4]. Many regions of the United States (U.S.) experience air quality (AQ) challenges with atmospheric concentrations in excess of Federal health-based standards; and reducing pollutants such as ground-level ozone and particulate matter (PM) is necessary to improve public health [5]. Emphasizing the scale of necessary displacement, note that stabilizing the climate may require the complete de-carbonization of energy sectors [6]. Hence, technological and fuel shifts that can contribute to both GHG mitigation and regional AQ improvement represent good solutions for energy systems [7,8].

Electricity generation will likely receive a major focus in future U. S. GHG mitigation policies (perhaps even disproportionately relative to other sectors) because (1) it is currently the highest GHG emitting sector in the U.S. [9], (2) many alternative strategies exist to generate electricity with little to no GHG emissions [10], (3) electrification in additional end-use sectors (i.e., transportation, industrial, building demands) achieves GHG reductions if the electricity is decarbonized [11], and (4) emissions from many sources (e.g., large capacity generators) are concentrated and more suitable for emissions control applications, including carbon capture and storage (CCS) [12]. It is clear then that any meaningful U.S. GHG mitigation effort must have mechanisms to institute extensive changes to existing electrical supply chains in pursuit of emission reductions – including regulating carbon dioxide (CO_2) emissions from existing and future power plants [13].

Electricity generation also contributes to regional AQ concerns, including ground-level concentrations of pollutant species such as ozone and fine particulate matter ($PM_{2.5}$) [14]. Combustion processes and other life cycle stages associated with conventional technologies and fossil fuels, including natural gas, result in atmospheric releases of gaseous and particulate pollutants; including nitrogen oxides (NO_x), sulfur dioxide (SO_2), volatile organic compounds (VOC), carbon monoxide (CO) and particulate matter (PM) [15]. For example, stationary fossil fuel combustion for electricity is by far and away the largest source of domestic anthropogenic SO_2 [9]. It follows then that emissions of GHGs and pollutant species are highly correlated as a result of shared generation sources and processes. Thus, an important opportunity exists to simultaneously address U.S. GHG and AQ concerns by deploying alternative, low emitting generation strategies. Conversely, pursuit of GHG mitigation must seek to avoid unforeseen tradeoffs with pollutant emissions, and vice versa.

In this context, it is generally agreed that increasing renewable electricity generation (including from solar, wind, geothermal, ocean, hydropower and biopower resources) is necessary to satisfactorily meet demands commensurate with achieving environmental quality goals [16]. Given the challenge of sufficiently decarbonizing energy systems to meet long-term GHG goals, assessments generally show that we must replace natural gas (and all other fossil fuels) at high levels – both with electrification in end-use sectors and with renewable resources for electricity generation (e.g., see [11,17–19]). Renewable technologies are often proposed as replacements for fossil power generation, including natural gas, as they are perhaps the best solution for electricity generation [20]. Some have suggested the immediate displacement of natural gas generation to avoid GHG-producing technology lock-in [20]. Additional low-carbon technologies commonly considered for GHG mitigation include energy storage to address the controllability and intermittency of renewable power generation, various forms of nuclear energy, fossil generation equipped with CCS, and methods to reduce demand via improvements in the efficiency of generation, transmission, distribution and end-use.

However, the role of natural gas is somewhat unique in that it can represent both a means of obtaining carbon reductions, and an essential target for displacement with lower-carbon alternatives, depending upon the considered sector and strategy and the dynamics of operation. While it is generally accepted that shifts away from coal and petroleum are required for significant emissions mitigation (or the deployment of additional measures such as CCS), the potential role of natural gas infrastructure in a future sustainable energy supply is less clear. Current natural gas electricity generation strategies primarily utilize combustion, which generates emissions of both pollutants and GHG, while the natural gas system directly emits GHG, primarily methane. Still others have warned against the utility of natural gas as a bridging fuel since it may slow the development of needed advanced, “ending” technologies [21] or represent an unacceptable environmental risk when resources are obtained from unconventional resources [22]. The concerns over natural gas generation are amplified by increasing awareness of significant methane emissions from the natural gas system, concerns that were heightened by the recent occurrence of a major leakage event in California [23].

On the other hand, natural gas can potentially represent a cleaner and more efficient fuel relative to other fossil options (e.g., coal, petroleum) and direct replacement can have immediate emission benefits,[1] e.g., increases in gas generation have recently led to reductions in total domestic GHG emissions [24]. Due to this, natural gas has been advocated for as an effective short- to mid-term “bridge” fuel to a low-carbon future, most notably in the context of providing a cost-effective option for displacing coal-fired power plants [25–27]. Further, natural gas is a cost-effective and established energy source with many applications in various energy sectors including power generation, transportation, industry, and the built environment. Natural gas currently represents an important component of the U.S. energy system amongst all sectors with the exception of transportation. The use of natural gas in the U.S. has steadily increased in the last decade – mirroring the rise in availability of unconventional reserves – and the trend is expected to continue in

[1] This is in-part because natural gas is predominantly composed of methane which has the lowest carbon to hydrogen ratio of commonly used fossil fuels and in-part because of the high efficiency and low emissions characteristics of modern natural gas combined cycle power plants

Please cite this article as: M.A. Mac Kinnon et al., The role of natural gas and its infrastructure in mitigating greenhouse gas emissions, improving regional air quality, and renewable resource integration, Progress in Energy and Combustion Science (2017), http://dx.doi.org/10.1016/j.pecs.2017.10.002