Applied Energy 108 (2013) 66–73

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

The complex future of CO_2 capture and storage: Variable electricity generation and fossil fuel power

Richard S. Middleton [a,*], Jordan K. Eccles [b]

[a] Los Alamos National Laboratory, Earth and Environmental Sciences, Los Alamos, NM 87545, USA
[b] Duke University, Nicholas School of the Environment, Durham, NC 27705, USA

HIGHLIGHTS

- Natural gas (NG) is an increasingly integral part of the US energy portfolio.
- CO_2 capture and storage (CCS) is a mitigation technology suitable for NG electricity.
- Daily variations in NG electricity & CO_2 generation massively impact CCS potential.
- CCS economic studies and infrastructure models must include daily variations.
- Power plant onsite storage might alleviate CCS issues with variable CO_2/electricity.

ARTICLE INFO

Article history:
Received 19 October 2012
Received in revised form 21 February 2013
Accepted 26 February 2013
Available online 30 March 2013

Keywords:
Carbon price
Shale and natural gas
Hydraulic fracturing
Electricity generation
CO_2 capture and storage (CCS)
CO_2 emissions

ABSTRACT

Fossil fuels are an integral part of the US energy portfolio, playing a prominent role for current and future domestic energy security. A sustainable, low-carbon future will require CO_2 to be captured from major coal and natural gas power plants. However, fossil fuel electricity generation CO_2 emissions are typically highly variable throughout each day with daily generation profiles varying greatly between plants. We demonstrate that understanding this variability is absolutely critical for setting a suitable carbon price as well as identifying if and how much CO_2 a power plant will capture. For example, we show that a CO_2 emissions price (or tax) of anywhere between \$85/tCO_2 and \$135/tCO_2 will be required to incentivize a gas power plant to manage all its capturable CO_2; this range is solely due to differences in CO_2 emissions profile. Further, we show that the setting a carbon price is very sensitive to system-wide costs including the CO_2 value for enhanced oil recovery and, in particular, the costs for CO_2 transport and storage. We also find that, even though coal-fired plants are more CO_2-intensive and thus incur greater CO_2 management costs, coal plants require a significantly lower carbon price (\$15/tCO_2 lower) in order to encourage CO_2 capture. We conclude that integrating fossil fuel power, particularly natural gas, into a large-scale CO_2 capture and storage system is a complex problem that will require detailed research and modeling.

1. Introduction

Natural gas is assuming an increasingly important role in the current and future US energy portfolio. For example, the proportion of the US' electricity generated by natural gas rose from under 18% in 2002 to almost 25% in June 2012 [1], an increase of around 40% (coal use fell from 50% to 42% and non-hydro renewables rose from 2% to 5% in the same time period). And current conventional and unconventional gas reserves of 1106 trillion cubic feet (tcf) [2] will last at least 45 years at the current consumption rate of ~24 tcf/d) [1]. In contrast, proved US conventional oil reserves of 23 billion barrels is equivalent to less than 3.5 years of domestic oil consumption [1]. Similarly, the US holds the world's largest estimated recoverable reserves of coal of around 237 million tonnes [1], equivalent to over 200 years of domestic consumption. Access to vast reserves of shale gas is dramatically increasing as hydraulic fracturing, or fracking, proves cost-effective for the extractive industry. Demand in electricity production for this gas is driven by its long-term low cost forecast, its low CO_2 emissions compared with coal, and its ability to balance intermittent renewable power generation. In many cases, natural gas power plants are used to meet daily peaks in electricity demand because they are able to quickly ramp up and down generation, unlike coal-fired plants which generally meet base load power needs. A typical natural gas power plant might generate as much as two or three times more electricity—and therefore CO_2 emissions—at its daily peak compared with its floor. In the future, because the US will likely more heavily rely on wind and solar energy, it will also rely even more on natural gas in order to balance power fluctuations as a

* Corresponding author. Tel.: +1 505 665 8332; fax: +1 505 665 6459.
E-mail addresses: rsm@lanl.gov, richardmiddleton@gmail.com (R.S. Middleton).

0306-2619/\$ - see front matter Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.apenergy.2013.02.065

result of weather patterns. Consequently, the US will continue to increase its use of natural gas in electricity production and increase the variability with which natural gas generation facilities are dispatched.

CO_2 capture and storage (CCS) is a climate mitigation technology that has massive potential to reduce CO_2 emissions without impacting existing energy infrastructure [3,4]. CCS involves capturing and compressing CO_2 at large industrial sources (e.g., fossil fuel power plants and cement factories), transporting the CO_2 through dedicated CO_2 pipelines, and injecting and storing the CO_2 in sequestration reservoirs (e.g., deep saline aquifers, depleted oil and gas fields) to keep it out of the atmosphere for hundreds or thousands of years. Natural gas power plants are a potential target for CCS technology, particularly considering natural gas's increasingly important role. Further, natural gas power plants are already proximal to pipeline right of ways (ROWs), ROWs that might already connect to depleted gas fields suitable for CO_2 storage and/or enhanced oil/gas recovery (EOR).

Previous analysis and modeling studies of large-scale integrated CCS infrastructure—including our own work—typically assume that each source produces a steady stream of CO_2 [e.g., 5–11], based on an annual emissions rate. Indeed, studies that focus on just CO_2 capture at natural gas or coal plants also often assume steady CO_2 emissions rates [e.g., 12–15]. This is potentially inappropriate for natural gas plants, especially the gas plants of the renewable-heavy future. For instance, a hypothetical plant generating 1 GWh at its daily hourly peak, equivalent to annually emitting 3.8 $MtCO_2$/yr (of which ~3.4 $MtCO_2$/yr is capturable), might only actually emit a total of 1.9 $MtCO_2$ each year. Thus, the CCS infrastructure on average might only be utilized at 50% of its maximum capacity.

In this paper we show the impact of variability in electricity production has a critical impact: it will control whether an individual plant manages none, some, or all of its capturable CO emissions, and will help define a suitable regional or nationwide carbon price. We explore and analyze how variable electricity generation can and will impact CCS technology (focusing on retrofitting natural gas and coal-fired power plants), and how this variability will make capture decisions particularly sensitive to CO_2 capture and storage costs and other economic–engineering assumptions.

2. Variable electricity generation and CO_2 emissions

Electricity generation from natural gas power plants varies on an hourly basis. Typically this is because it is easy to ramp generation up and down and dispatch natural gas power at short notice for changing demand throughout the day unlike, say, nuclear power that tends to fulfill steady base load requirements. Fig. 1 illustrates the daily pattern in electricity generation and capturable CO_2 emissions for a typical or average power plant capable of generating 1 GWh at its peak. The generation profile is an average (median) of actual electricity output from 41 gas plants in Ontario, Canada for April–June 2012 [16]; generation is normalized to 1 GWh maximum and emissions assumed to be 3.8 $MtCO_2$/yr per 1 GWyr based on an average >100 MWe capacity US plant [17]. Although the standardized plant produces an annual capturable equivalent 3.42 $MtCO_2$/yr at its peak, the plant produces a capturable total of 2.53 $MtCO_2$ over the course of a year. The Ontario data is released for 90 day reporting periods. We use this dataset because it is publically available, though in principle any generation data could have been used.

The "average" generation profile in Fig. 1 consists of a heterogeneous range of profiles from the 41 different plants over 90 days. This profile may change due to seasonal variations in electricity generation. Fig. 2 shows the variability in the individual hourly generation profiles. Three broad profile types exist: (1) plants that meet daily peak demand but no base load (i.e., little/no nighttime generation), (2) plants that generally satisfy base load needs (i.e., steady generation), and (3) plants that meet daily peak demand and satisfy base load requirements at night. Roughly, half the Ontario gas plants fall into the first category, 20% in the second, and

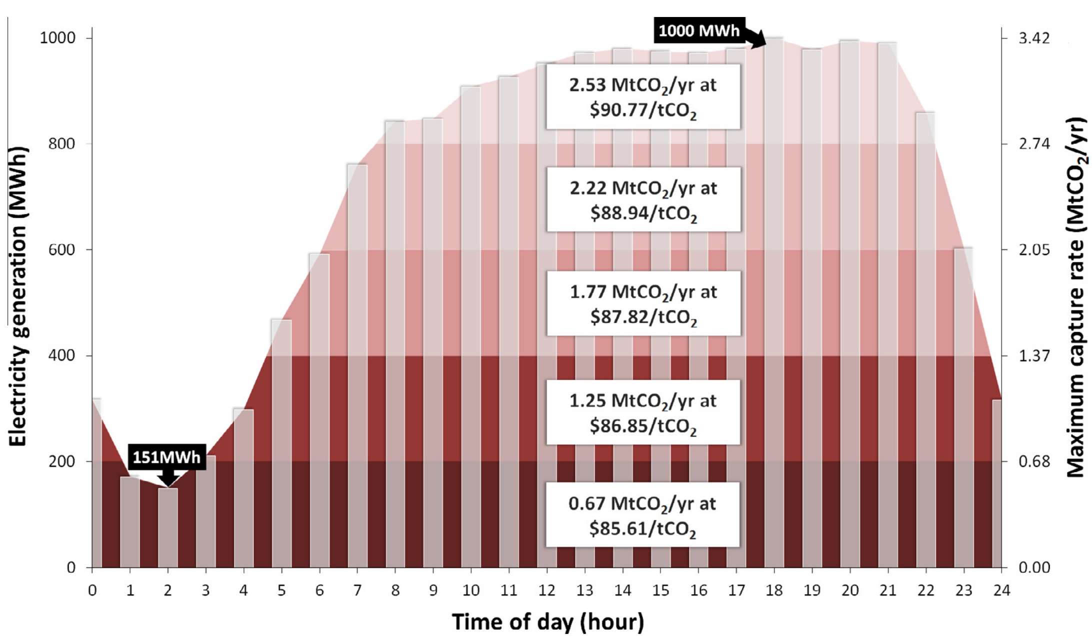

Fig. 1. Electricity generation (columns, primary *y*-axis) and *capturable* CO_2 (solid areas, secondary *y*-axis) over a 24 h period for the average (median) natural gas power plant peaking at 1000 MW h. All assumptions, including capturable CO_2 rate, are listed in Table 1. The five solid red areas represent the amount of CO_2 that can be captured by installing retrofit equipment on 200, 400, 600, 800, and 1000 MWe of generation capacity. Text in the boxes indicates the exact amount of CO_2 captured and CO_2 management cost for the five capture levels. As an example, installing capture equipment on 1000 MW h output could capture CO_2 at a maximum rate of 3.42 $MtCO_2$/yr, but in reality can only capture 2.53 $MtCO_2$/yr at a cost of \$90.77/tCO_2.