Paper #4-3
NATURAL GAS END-USE GHG REDUCTION TECHNOLOGIES

Prepared by the Technology Team
of the
Carbon and Other End-Use Emissions Subgroup

On September 15, 2011, The National Petroleum Council (NPC) in approving its report, *Prudent Development: Realizing the Potential of North America's Abundant Natural Gas and Oil Resources*, also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the study's Task Groups and/or Subgroups. These Topic and White Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

These Topic and White Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents, but approved the publication of these materials as part of the study process.

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

The attached paper is one of 57 such working documents used in the study analyses. Also included is a roster of the Team that developed or submitted this paper. Appendix C of the final NPC report provides a complete list of the 57 Topic and White Papers and an abstract for each. The full papers can be viewed and downloaded from the report section of the NPC website (www.npc.org).

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Abstract

This working paper identifies natural gas end-user technologies that could reduce greenhouse gas (GHG) emissions below 2030 projections on an economy-wide and sectoral basis. The research team that prepared this report distilled data from 35 publicly available academic and industry studies that quantified the volume and cost of projected GHG emissions. Quantitatively incomplete studies and studies that did not differentiate impacts on a technology-specific basis were excluded from consideration if researchers could not obtain additional data from study authors or independent industry experts. The final study sample set consisted of 15 studies detailing 15 end-user technologies in 32 cost-volume data points. For technologies where multiple data points were available, researchers computed weighted averages of cost, volume and a proxy index for "uncertainty" (the variation in results across different studies).

CONTENTS

EXECUTIVE SUMMARY

This working paper identifies natural gas end-user technologies that could reduce greenhouse gas (GHG) emissions below 2030 projections on an economy-wide and sectoral basis.

The research team that prepared this report distilled data from 35 publicly available academic and industry studies that quantified the volume and cost of projected GHG emissions. Quantitatively incomplete studies and studies that did not differentiate impacts on a technology-specific basis were excluded from consideration if researchers could not obtain additional data from study authors or independent industry experts. The final study sample set consisted of 15 studies detailing 15 end-user technologies in 32 cost-volume data points. For technologies where multiple data points were available, researchers computed weighted averages of cost, volume and a proxy index for "uncertainty" (the variation in results across different studies).

The final sample set included a broad range of technology-specific costs and reduction volumes. Cost-weighted average volumes (CWAV) within the sample set ranged from 7 MM $MtCO_2e$ (appliance conversions in the commercial sector) to 571 MM $MtCO_2e$ (natural gas CCS), with a median CWAV of 80 MM $MtCO_2e$. Volume-weighted average costs (VWAC) for the technologies within the sample set ranged from negative \$40/$MtCO_2e$ (new industrial appliances and commercial CHP) to \$317/$MtCO_2e$ (natural gas fuel cells) with a median VWAC of \$38/$MtCO_2e$.

Researchers also "scored" technologies (the sum of each technology's cost rank, from lowest to highest, and GHG emissions reduction rank, from highest to lowest). These scores implied most beneficial results from deployment of new residential appliances (CWAV: 150 MM $MtCO_2e$, VWAC: negative \$8/$MtCO_2e$), new commercial appliances (CWAV: 84 MM $MtCO_2e$, VWAC: negative \$16/$MtCO_2e$), CHP facilities in the industrial sector (CWAV: 82 MM $MtCO_2e$, VWAC: negative \$15/$MtCO_2e$), and electric generation refueling to burn natural gas (CWAV: 110 MM $MtCO_2e$, VWAC: \$37/$MtCO_2e$). Scores implied less beneficial (but still beneficial) results from industrial efficiency gains (CWAV: 34 MM $MtCO_2e$; VWAC: \$41/$MtCO_2e$), appliance conversions in the commercial sector (CWAV: 7 MM $MtCO_2e$; VWAC: \$49/$MtCO_2e$) and natural gas fuel cells (CWAV: 75 MM $MtCO_2e$; VWAC: \$317/$MtCO_2e$.)

For 9 of the 15 technologies within the sample set, only one data point was available, making it impossible to compute a geometric uncertainty proxy. The uncertainty metric among the six remaining technologies ranged from a low of 5 (industrial combined heat and power) to a high of 150 (natural gas CCS generation).

INTRODUCTION

This working paper distills data from studies prepared by universities, industry groups, consultants and independent analysts regarding the greenhouse gas (GHG) emissions reduction potential that could be achieved by deploying natural gas end-user technologies. The resulting analysis considers three attributes of each technology:

(1) Projected GHG reduction **volumes**[1]**;**

(2) The projected marginal **cost**[2] associated with those reductions; and

(3) A proxy measure of the **uncertainty** of these projections.

Limitations and Caveats

Uncertainty

The uncertainty metric calculated for each technology is intended to encapsulate the diversity of volume and cost projections that may result from differences across studies.

These differences may include:
- methodology;
- underlying assumptions taken by study authors;
- lack of clarity regarding deployment parameters for evolving technologies; and/or
- challenges associated with data collection and data resolution.

This uncertainty metric offers a way to gauge the relative variance in study conclusions as a potentially useful input to policy formation and should not be interpreted as a statistical assessment of error.

Statistical Limitations

The very act of "comparing apples and oranges" – in this case, comparing a relatively small sample set of studies written, for the most part, by different authors who may have used different methodologies – cannot produce a statistically significant result.

This comes with the territory. Although Global Positioning System (GPS) data and improvements in real-time data processing technologies have improved energy statistics in recent years, the vast scale of the energy sector imposes prohibitively high measurement costs.

To minimize these costs, economists often rely on aggregates and extrapolations of data sets that may be further limited by governments and private entities seeking to protect national security and intellectual property. These underlying limitations can contribute further bias to any subsequent computation of aggregates, including the measure of uncertainty calculated in this working paper.

Because this working paper's uncertainty "bubbles" may reflect the frontiers of study authors' knowledge, uncertainty should not be interpreted as a recommendation for or against a specific technology option.

[1] Volumes are usually measured in metric tons of carbon dioxide equivalent ($MtCO_2e$), either on a cumulative or annual basis.
[2] Abatement costs are typically measured in dollars per metric ton of carbon dioxide equivalent ($\$/MtCO_2e$).

Palette of Options, Not a Prescriptive Path

The "marginal abatement cost curves" (MACCs) prepared by some study authors offer a convenient visual presentation of technology and policy options in order of increasing price on an x-y coordinate plate.

Most MACCs chart cost on the vertical axis and reduction volumes on the horizontal axis. In some cases, study authors intend MACCs to represent true "supply curves," where concurrent deployment of different technologies will result in greater reductions and increasing price.

In other cases, study authors employ MACCs as a visual metaphor for a palette of different options that avoids overlapping data, but these options may not necessarily be available concurrently (e.g. it would be impossible to simultaneously shut down and retrofit the same power plant).

The goal of this working paper is to present a palette of options, not a prescriptive path.

Accordingly, the visual depictions of technology options are not intended to represent cumulative reduction potential from the concurrent deployment of different technologies.

METHODOLOGY

Preparation of this working paper consisted of three functional steps:

(1) Collecting and standardizing study data;

(2) Identifying and closing data gaps; and

(3) Synthesizing and analyzing the final data sets.

Collecting and Standardizing Study Data

The results presented in this white paper derive exclusively from studies that projected emissions reduction volumes and associated costs on a technology-specific basis and do not reflect the universe of GHG emissions reduction literature.

The quantitative nature of the research methodology required the research team to exclude studies from consideration for two primary reasons:

(1) The studies "bundled" technology performance projections with policy assumptions and did not identify whether GHG emissions reductions derived from technology or policy; and/or

(2) The studies did not include a complete set of volume and cost data for the technologies they addressed.

The research team began with a universe of 35 studies that described 61 emissions reduction cases.

The first cull, for quantitative focus and technology-specific analysis, reduced the sample set to 27 studies that described 57 cases.[3]

The second cull, for data completeness, reduced the final sample set to 15 studies that described 32 cases.

The methodologies of the 15 remaining studies varied, but most incorporated the four common analytical components described in Figure 1:

(1) Establishing an emissions baseline;

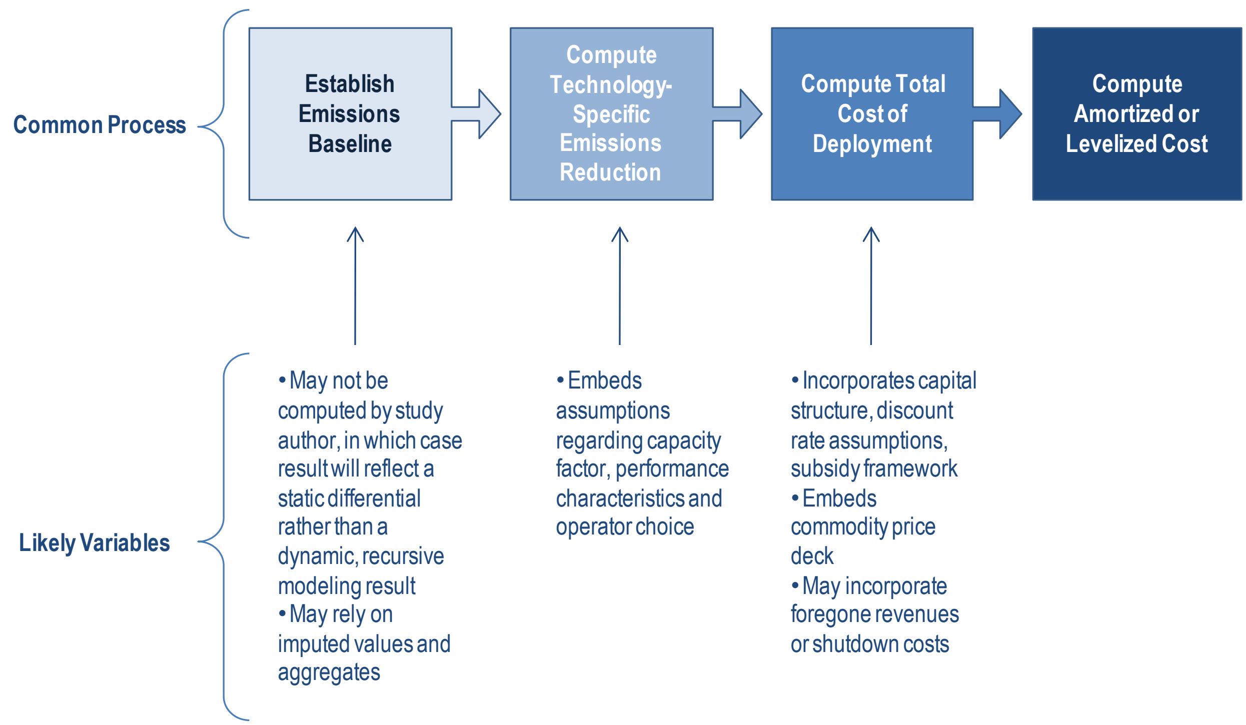
(2) Computing technology-specific reductions associated with deployment of a natural gas end-user technology (the **volume** metric);

(3) Computing total fixed and variable costs associated with this deployment; and

(4) Amortizing projected deployment costs across reductions (the marginal **cost** metric).

[3] In the first cull, additional study candidates were identified that were omitted from the original study set.

Figure 1 – Common Process Components and Sources of Potential Variation



Variable assumptions, standard units. Study authors typically incorporate clarifying or simplifying assumptions at each juncture.

The methodology of reducing each study's conclusions regarding a given end-user technology and/or case to "common-size" cost-volume coordinates tolerates wide variations in assumptions taken by study authors. This methodology does not tolerate disparate units of measure, however.

Study data in this chapter expressed in different units (e.g. dollar-years) or using different metrics (e.g. cumulative, rather than annual, emissions reductions) were normalized using linear conversion factors, as presented in Figure 2, below.

Figure 2 – Conversion Factors for Disparate Units or Metrics

Unit or Metric	Description	Conversion Factor
Dollar Year	Studies generally estimated costs in nominal dollars per metric ton. Nominal dollar years varied from 2005 to 2010.	Dollars were normalized to a 2009 base year.
Target Year	Studies assessed emission reduction potential on varying time horizons.	Reduction potentials were normalized to annual reductions in the year 2030.
Reduction Metric	Studies assessed emission reduction potential either on an annual basis or cumulative basis.	Reduction potentials were normalized to an annual basis.

Identifying and Closing Data Gaps

In cases where published reports did not stipulate, specify or disclose parameters necessary to evaluate whether technologies could be deemed equivalent technologies addressed in other studies, the research team contacted study authors to obtain additional data and clarifications.

The research team excluded those studies where authors did not respond to data requests or data gaps could not be closed.

In cases where the research team could not obtain usable, quantitative data for potentially significant natural gas end-user technologies, team members asked several study authors to prepare reasonable estimates of potential reduction volumes and marginal costs. Please refer to the Appendix for further details on the author's estimates of natural gas CCS and repowering reduction volumes.

Synthesis and Analysis

Final analysis required four further steps:

(1) Sorting standardized study data into discrete technology categories and subcategories;

(2) Tabulating **volume** and **cost** data for each technology category and/or subcategory;

(3) Computing **volume-weighted average cost (VWAC)** and **cost-weighted average volume (CWAV)** for each category and/or subcategory; and

(4) Computing the associated uncertainty score[4] associated with each category and/or subcategory.

[4] Uncertainty scores were calculated on a geometric basis using U = $\sqrt{((Cmax - Cmin)^2 + (Vmax - Vmin)^2)}$.

NATURAL GAS TECHNOLOGY CATEGORIES

During the preparation of this working paper, the research team collected and standardized study data and sorted them into three discrete technology categories: appliances and equipment, power generation and industrial applications.

The research team further subdivided these categories on the basis of material differences in deployment characteristics.

Figure 3 details each end-user technology category or subcategory and summarizes potential advantages and disadvantages associated with its deployment.

Figure 3 – Natural Gas Technologies: Descriptions and Implementation Advantages and Disadvantages

	Description	Implementation Advantages	Implementation Disadvantages
Appliances and Equipment			
Residential Appliances and Equipment	Heating, cooling and water appliances and equipment that serve residential buildings and are fueled by natural gas.	• Economic benefit	• Principal/agent conflicts • Payback period exceeds consumer preferences historically
Commercial Appliances and Equipment	Heating, cooling and water appliances and equipment that serve commercial buildings and are fueled by natural gas.	• Economic benefit	• Principal/agent conflicts • Payback period exceeds consumer preferences historically
Industrial Appliances and Equipment	Heating, cooling and water appliances and equipment that serve industrial facilities and are fueled by natural gas.	• Economic benefit	• Principal/agent conflicts • Payback period exceeds consumer preferences historically
Power Generation			
Power Generation: Redispatch	Run (dispatch) existing natural gas combined cycle electric generation ahead of cheaper, higher emitting coal-based generation.	• Can use existing under-utilized natural gas capacity • Does not require any capital investment	• Potentially expensive depending on power prices and price differential between natural gas and coal
Power Generation: Repower	Conversion of existing coal or oil-fired generating station by retaining a portion of steam generation equipment for use with new natural gas combustion turbine or combined cycle equipment.	• Can increase overall plant efficiency • Efficient use of existing infrastructure	• Capital cost can be large • Requires adequate gas supply
Power Generation: Refuel	Conversion of existing coal or oil-fired boiler to burn natural gas as a replacement or supplement to coal or oil.	• Low capital cost compared to new generation • Relatively easy to implement	• Lower efficiency than combined cycle • Requires adequate gas supply
Power Generation: Combustion Turbine	A rotary engine in which energy is extracted from fuel during the combustion process (e.g. jet engine) to turn an electric generator.	• Relatively low capital cost • Can quickly ramp to full electric output	• Lower efficiency than combined cycle • Only economic to run for short periods during the year
Power Generation:	An electric generation technology in which the exhaust of a	• Highest efficiency among fossil-fuel based electric	• Higher capital cost than combustion turbine

	Description	Implementation Advantages	Implementation Disadvantages
Combined Cycle	combustion turbine is linked to a heat recovery steam generator and a steam turbine to produce additional electric output.	generation technologies • Less expensive on a capacity basis than coal, wind, hydro or nuclear	
Power Generation: Combined Cycle with Carbon Capture and Storage	Use of technology to physically separate CO2 from other gases either pre-combustion or post-combustion. Captured CO2 is then disposed of via sequestration or conversion into other compounds.	• Significant reductions in CO_2 emissions	• Expensive and reliant on public subsidy and/or a carbon price • Unproven technology • Requires suitable disposal site and/or conversion of CO2 to other compounds
Power Generation: Combined Heat and Power	Form of on-site generation in which a heat engine or a power station simultaneously generates both electricity and useful heat. Heat output can be used for industrial and commercial processes and power consumed onsite with excess power sold to the grid.	• Higher total efficiency than separate heat and power generation • Reduced CO_2 emissions • Fuel cost savings for industrial and commercial users • Proven, commercially available technology	• Requires suitable use for heat • Best suited for new installations as opposed to retrofit/conversion • Retrofit/conversion requires production downtime • Can increase onsite air emissions • Large up-front capital investments required
Power Generation: Fuel Cells	Form of on-site generation in which electricity conversion occurs via an electrochemical reaction.	• Low emissions • Small, quiet footprint • Potentially high efficiency	• Very expensive • Unproven technology at large-scale
Industrial Technologies			
Industrial: Efficiency Gains	Industrial facilities can improve the efficiency of their natural gas-fueled processes and systems through such measures as waste heat recovery, improved maintenance, process energy monitoring, and new processes.	• Fuel cost savings for industry; some efficiency measures can be NPV positive • Some efficiency gains possible via small investments and changes • Many efficiency measures take advantage of proven, commercially available technologies	• Some efficiency improvements require large up-front capital investments with longer payback periods • Implementing efficiency measures may entail production disruptions
Industrial: Fuel Switching	Industrial facilities in energy intensive industries, such as cement and metals, switch to natural gas for thermal energy.	• Low capital cost compared to new installations • Relatively easy to implement	• Limited potential and impractical in many sectors

KEY FINDINGS

Data set. The sample set of study data contained 15 individual natural gas end-use technologies.

Volume. Cost-weighted average volumes (CWAV) for the technologies within the sample set ranged from 7 MM $MtCO_2e$ (commercial appliance conversions) to 571 million $MtCO_2e$ (natural gas CCS) with a median CWAV of 80 MM $MtCO_2e$.

Cost. Volume-weighted average costs (VWAC) for the technologies within the sample set ranged from a <u>negative</u> \$40/$MtCO_2e$ (new industrial appliances and commercial CHP) to \$317/$MtCO_2e$ (fuel cell generation) with a median VWAC of \$38/$MtCO_2e$.

Uncertainty. Only one data point was available for 9 of the 15 technologies within the sample set. The uncertainty score among the remaining technologies ranged from a low of 5 (industrial combined heat and power) to a high of 150 (NG CCS generation).

Ordinal ranking. Ranking technologies by VWAC from lowest to highest (with all negative costs tied at 1) and CWAV from highest to lowest yields a combined "score" that assigns the lowest sum to technologies with lowest costs and/or greatest volume yields. These un-weighted ordinal scores are presented in Figure 4.

Figure 4 – Technologies and Ordinal Rankings by VWAC, CWAV, Combined (Minimum Cost, Maximum Volume) and Uncertainty

Category/Subcategory	VWAC Rank	CWAV Rank	Combined Score	Uncertainty Rank
Appliances: Residential New	1	2	3	
Appliances: Commercial New	1	6	7	
Generation: CHP Industrial	1	7	8	2
Generation: Refuel	7	3	10	5
Generation: CHP Commercial	1	10	11	
Appliances: Industrial New	1	11	12	
Generation: Redispatch	9	4	13	6
Generation: CCS	14	1	15	7
Generation: Build New CCGT	11	5	16	4
Appliances: Residential Conversion	6	14	20	3
Industrial: Fuel Switching	8	12	20	
Generation: Repower	13	8	21	
Industrial: Efficiency	10	13	23	
Generation: Fuel Cells	15	9	24	
Appliances: Commercial Conversion	12	15	27	

This ordinal, un-weighted ranking implies that greater beneficial outcomes may come from deployment of:

- New residential appliances (CWAV: 150 MM $MtCO_2e$, VWAC: <u>negative</u> \$8/$MtCO_2e$);
- New commercial appliances (CWAV: 84 MM $MtCO_2e$, VWAC: <u>negative</u> \$16/$MtCO_2e$); and
- CHP industrial (CWAV: 82 MM $MtCO_2e$, VWAC: <u>negative</u> \$15/$MtCO_2e$);
- Refueling electric generation (CWAV: 110 $MtCO_2e$, VWAC: \$37/$MtCO_2e$).

Similarly, less beneficial outcomes may come from:

- Appliance conversions in the commercial sector (CWAV: 7 MM $MtCO_2e$; VWAC: \$49/$MtCO_2e$).
- Fuel cells (CWAV: 75 MM $MtCO_2e$; VWAC: \$317/$MtCO_2e$).
- Efficiency in the industrial sector (CWAV: 34 MM $MtCO_2e$; VWAC: \$41/$MtCO_2e$).
- Repowering existing power plants (CWAV: 80 MM $MtCO_2e$; VWAC: \$67/$MtCO_2e$).

Among technologies for which multiple samples were available, greatest uncertainty may surround natural gas CCS (CWAV: 571 MM $MtCO_2e$; VWAC: \$79/$MtCO_2e$) and least uncertainty may surround industrial sector combined heat and power (CWAV: 82 MM $MtCO_2e$; VWAC: negative \$15/$MtCO_2e$).

BREAKOUT OF TECHNOLOGIES, BY COST AND REDUCTION POTENTIAL

Figure 5 summarizes potential emission reduction **volumes** and associated marginal **cost** for 15 different natural gas end-use technologies.

The source data that provided input for Figure 5 came from different studies by different authors, some of whom took different assumptions and employed different methodologies. Moreover, the scope of this working paper, and the "study of studies" it is intended to support, does not provide for new economic modeling.

As a result, the weighted-average projections for the technologies in Figure 5 should be considered independently and not cumulatively[5]. The conclusions presented in Figure 5 represent a palette of independent abatement options rather than an incremental abatement supply curve.

Figure 5 – Technologies, Costs, Volumes and Uncertainty Spreads, by VWAC

Category/Subcategory	VWAC	CWAV	Cmin	Cmax	Vmin	Vmax	Uncertainty
Appliances: Industrial New	-\$40	59	-\$40	-\$40	59	59	N/A
Generation: CHP Commercial	-\$40	70	-\$40	-\$40	70	70	N/A
Appliances: Commercial New	-\$16	84	-\$16	-\$16	84	84	N/A
Generation: CHP Industrial	-\$15	82	-\$16	-\$14	80	84	5
Appliances: Residential New	-\$8	150	-\$8	-\$8	150	150	N/A
Appliances: Residential Conversion	\$7	15	-\$14	\$49	12	24	65
Generation: Refuel	\$37	110	\$10	\$50	14	137	129
Industrial: Fuel Switching	\$38	41	\$38	\$38	41	41	N/A
Generation: Redispatch	\$40	95	\$30	\$73	60	182	129
Industrial: Efficiency	\$41	34	\$41	\$41	34	34	N/A
Generation: Build New CCGT	\$46	89	\$13	\$70	57	133	95
Appliances: Commercial Conversion	\$49	7	\$49	\$49	7	7	N/A
Generation: Repower[6]	\$67	80	\$67	\$67	80	80	N/A
Generation: CCS[7]	\$79	571	\$53	\$114	502	639	150
Generation: Fuel Cells	\$317	75	\$317	\$317	75	75	N/A

Category/Subcategory: *Category of technology within study sample set*

Volume-Weighted Average Cost (VWAC): *The average marginal cost of avoiding one metric ton of CO2e by deploying the end-user technology in question, weighted in proportion to the volumes projected in the study sample set.*

Cost-Weighted Average Volume (CWAV): *The average volume of potential emission reductions projected to result from deploying the end-user technology in question, weighted in proportion to the costs projected in the study sample set.*

Cmin*: The lowest projected abatement cost within the study sample set for the end-user technology in question.*

Cmax*: The highest projected abatement cost within the study sample set for the end-user technology in question.*

Vmin: *The lowest projected reduction volume within the study sample set for the end-user technology in question.*

Vmax: *The highest projected reduction volume within the study sample set for the end-user technology in question.*

[5] Calculating the effects of technologies in combination would require an integrated model that merges each study's calculations into a cohesive model of supply, demand and price interactions and provides for either an iterative, recursive simulation or a logical sequencing that avoids double-counting. Notwithstanding the challenging intellectual property negotiations that such an effort might require, this lies outside the scope of this working paper.

[6] Please see Appendix II for details on the study author's repowering volume assumptions.

[7] Please see Appendix I for details on the study author's CCS volume assumptions.

Uncertainty: *A proxy metric for the variance of projected results across available studies for each technology, calculated using a geometric average:* $U = \sqrt{((Cmax - Cmin)^2 + (Vmax - Vmin)^2)}$. *No uncertainty calculation is possible for technologies where only one study case was available; these values are presented graphically as fixed-size bubbles in the absolute and "reduction cost curve" charts.*

Figure 6 plots each technology described in Figure 5 as a "bubble" on an x-y coordinate plane, as follows:

(1) **The y-axis represents cost** (VWAC in 2009 dollars per $MtCO_2e$);

(2) **The x-axis represents reduction volumes** (CWAV in $MtCO_2e$); and

(3) **The size of the bubble corresponds to the uncertainty metric** derived from the variation within the sample set of study data for each end-user technology option: bigger indicates greater variation; a smaller bubble indicates lesser variation.

(4) **The color of the bubble indicates the end-use sector** to which the technology option belongs, green for industrial, blue for appliances, silver for power generation;

(5) **A small, red bubble indicates that no uncertainty calculation was possible** because only one data point was available within the fully-rationalized sample set of study data used in the preparation of this paper.

<u>Figure 6 presents a palette of technology options in terms of cost, volume and uncertainty and does not imply that technology options may be combined to achieve cumulative benefits, as a "supply curve" or "marginal abatement cost curve" (MACC) might.</u>

Figure 6 – Volume-Weighted Average Cost (2009 $/MtCO$_2$e), Cost-Weighted Average Volume (MM MtCO$_2$e) by 2030 and Uncertainty

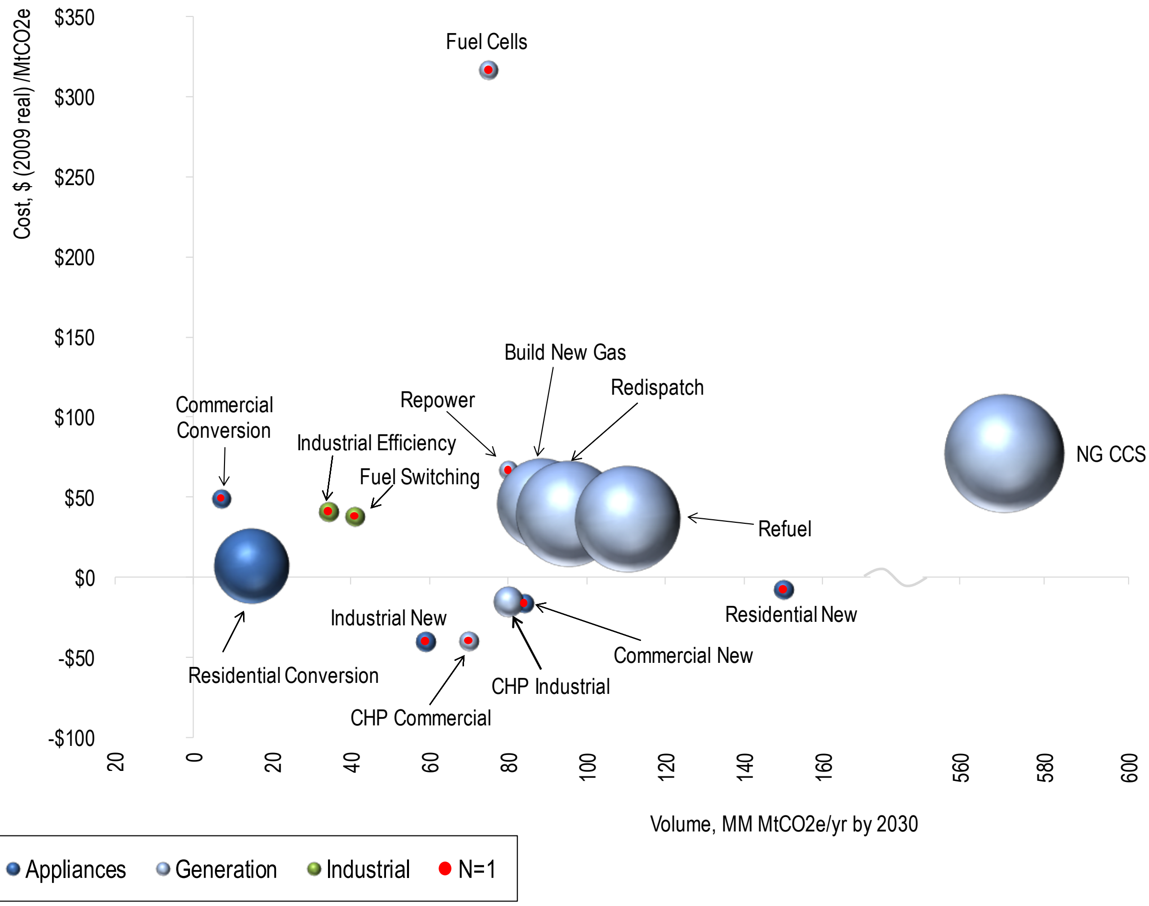


Figure 7 offers context for the projections outlined in Figure 5 and depicted in Figure 6 by presenting cost-weighted average volumes (CWAV) of emissions reductions for each technology as a percentage of:

(a) The 2005 CO_2 emissions baseline as published by the U.S. Energy Information Administration (EIA) for the end-use sector to which that technology belongs; and

(b) EIA's 2030 CO_2 emissions projection for that end-use sector as published in the *Annual Energy Outlook for 2010*.

Figure 7 – Reductions Relative to 2030 Energy-Related CO_2 Emissions, by Technology Category/Subcategory

Sector/Technology	Cost-Weighted Average Volume, MM $MtCO_2e$[a]	EIA Projections for Sector's 2030 Energy-Related CO_2 Emissions, MM $MtCO_2e$[b]	Technology's Reduction Potential as Percentage of Sector's Energy-Related CO_2 Emissions[c]
Residential			
Appliance and Equipment Conversions	15	1,255	1%
New Appliances and Equipment	150		12%
Power Generation			
Build New Gas	89	2,533	3%
Natural Gas CCS	571		23%
CHP, Commercial	70		3%
CHP, Industrial	82		3%
Fuel Cells	75		3%

Redispatch	95		4%
Refuel	110		4%
Repower	80		3%
Industrial			
Efficiency	34	1,578	2%
Fuel Switching	41		3%
New Appliances and Equipment	59		4%
Commercial			
Appliance and Equipment Conversions	7	1,261	1%
New Appliances and Equipment	84		7%

a) The average volume of potential emission reductions projected to result from deploying the end-user technology in question, weighted in proportion to the costs projected in the study sample set. b) EIA's AEO 2010 reference case projection for energy-related CO2 emissions in 2030 for relevant sector. For residential, industrial and commercial sectors, emissions associated with electricity purchases are included. c) The quotient of a technology's cost-weighted average volume (CWAV) and the total emissions of the corresponding sector.

Figure 8 examines the maturity of each natural gas end-use technology option, relying on quantitative data (e.g. market penetration or deployment) where possible and anecdotal data otherwise.

Figure 8 – Market Penetration, Deployment or Maturity, by End-Use Technology

Technology	Market Penetration, Deployment or Maturity	Source
Generation: CHP Commercial	Mature	
Appliances: Commercial	Mature: 3.157 quadrillion Btu delivered energy to commercial sector, 41.1% of energy for appliances.	EIA AEO2010 (2009 data)
Generation: Repower	Mature	
Generation: CHP, Industrial	Mature	
Appliances: Residential	Mature: Of 114 MM households, 60.1 MM heating (59.65 MM water heating); 39.11 MM cooking; 19.86 clothes drying.	EIA AEO2010 (2009 data)
Generation: Refuel	Mature: 21.9 GW of net summer capacity (39.2% of petroleum-fired capacity) capable of fuel switching	EIA Electric Power Annual 2009 (2007 data)
Industrial: Fuel Switching	Mature: 11.9% of CHP could switch from petroleum to natural gas; 16.6% of industrial coal could switch to natural gas	EIA Electric Power Annual 2009 (2007 data), MECS 2006 (2006 data)
Generation: Redispatch	Mature	
Industrial: Efficiency	Mature	
Generation: Build New CCGT	Mature: Natural gas fueled 21% of generation in 2008	EIA AEO2010
Generation: CCS	Emerging	
Generation: Fuel Cells	Emerging	

STUDIES USED AND CAPSULE SUMMARIES

Capturing Costs: The Economics of CCS
Bloomberg New Energy Finance (BNEF), 2009
This research note presents the underlying assumptions and output from BNEF modeling of carbon capture and storage. Assuming a $5.68/MMBtu natural gas price, a levelized cost of abatement of \$81/MtCO_2 was projected. Please see Appendix I for details on assumptions for estimating reduction volumes for natural gas CCS.

Global Energy and Emissions Model (GE2M)
Bloomberg New Energy Finance, 2010
The BNEF model looks at multiple technologies and forecasts both associated costs and also potential captured volume, on a national basis. The model estimates the carbon price for natural gas fuel cells to be prohibitive for the foreseeable future at \$322/MtCO_2. Fuel switching at industrial facilities is relatively limited and primarily in pulp and paper production at a cost of \$41/MtCO_2. Refueling electric power plants to burn natural gas ranges from \$10/MtCO_2 to \$50/MtCO_2.

Prospects for Natural Gas under Climate Policy Legislation

The Brattle Group, 2010
This study looks at the potential for coal-to-natural gas switching in the power industry based on natural gas and CO_2 prices. In the study, the potential for fuel-switching is 283 TWh, which results in an increase in gas demand of 4.6 Bcf/d, given a $5/MMbtu natural gas price and a $30/Mt CO_2 price, resulting in an annual emission reduction of 182 MM $MtCO_2$ below 2010 emission levels. The study also describes the impact that renewable power sources could have on this switching potential (could reduce the switching amount by 1.4 Bcf/d) as well as the impact of higher natural gas prices or lower CO_2 prices on switching (both changes would lower the possible switching volumes).

Natural Gas Fueling Lower Emissions
BP, 2009
This study looks at the potential of natural gas to reduce greenhouse gas emissions primarily in the power sector and considers policy options and mechanisms to achieve early, significant reductions. The study recommends incentives to retire the nation's oldest, least efficient and most carbon-intensive coal-fired power plants and finds that building new gas-fired units could reduce 517 million metric tons of greenhouse gas emissions cumulatively through 2030 at a cost of $13/ $MtCO_2$ versus existing coal, equal to approximately 7% of the reductions required under the American Clean Energy Security Act (H.R. 2454). The study finds carbon capture and storage (CCS) on natural gas combined cycle (NGCC) units to have an abatement cost of $66/$MtCO_2$ compared to new NGCC without CCS. Please see Appendix I for details on assumptions for estimating reduction volumes for natural gas CCS.

Cost and Performance of Fossil Fuel Power Plants with CO_2 Capture and Storage
Carnegie Mellon University, 2007
This study describes the performance and costs of carbon capture technologies at pulverized coal, natural gas combined cycle (NGCC) and integrated gasification combined cycle (IGCC) plants. The study does not attempt to quantify the total potential captured tons on a national basis, but rather focuses on newly updated capital costs, natural gas prices, utilization rates, and performance metrics on a unit-by-unit basis. Using the Integrated Environmental Control Model (IECM), the study found a CO2 avoidance cost of $62.6/$MtCO_2$ for NGCC CCS employing an amine-based system for post-combustion CO2 capture compared to the same NGCC 500 MWe plant without CCS. Please see Appendix I for details on assumptions for estimating reduction volumes for natural gas CCS.

Of GHG Bridges and Demand Opportunities: Natural Gas Policy Options
ClearView Energy Partners, 2010
This model considers possible emissions reduction and natural gas demand catalysts that could result from policies that employ natural gas as a "bridge" fuel. The study examines transportation and power generation potential. It finds that the theoretical gas-for-coal opportunity set is considerable: replacing the nation's lowest-efficiency pulverized coal-fired power (PC) plants with recent-vintage combined cycle gas turbine (CCGT) generation capacity could deliver GHG emissions reductions of approximately 133.2 million metric tons of CO_2e per trillion cubic feet of natural gas at a price of $58/$MtCO_2$ to $103/$MtCO_2$.
Updated Cost and Performance Estimates for Clean Coal Technologies Including CO_2 Capture
Electric Power Research Institute (EPRI), 2006
This report updates both cost and performance data for U.S. clean coal technologies. The study does not attempt to quantify a total volume of captured reductions from clean technologies but rather focuses on costs and performance on a unit-by-unit basis. According to EPRI, assuming an 80% capacity factor, a $6/MMBtu natural gas price translates to a $55/$stCO_2$ cost of avoided CO_2 for NGCC plants. Please see Appendix I for details on assumptions for estimating reduction volumes for natural gas CCS.

How Energy Efficiency, Natural Gas and Renewables Can Substantially Reduce U.S. Carbon Dioxide Emissions
Gas Technology Institute, 2009
This study considers the synergies between renewables, energy efficiency and natural gas to dramatically reduce CO_2 emissions using existing technologies coupled with the expansion of the U.S. electric and natural gas infrastructure. The study finds that direct use of high-efficiency natural gas appliances and processes in homes, buildings and factories to displace less-efficient appliances can reduce emissions relative to EIA's 2007 Annual

Energy Outlook reference case for 2030 largely at negative costs, ranging from \$-7.67/MtCO_2 in the residential sector to \$-16.40/MtCO_2 in the commercial sector to -\$40.60/MtCO_2 in the industrial sector. Converting existing residential appliances to natural gas is also possible at an average cost of -\$14.25/MtCO_2 with an annual reduction potential of 24 MM MtCO_2e in 2030.

Energy Technology Essentials: Carbon Capture and Storage
International Energy Agency (IEA), 2006
This study is part of IEA's Energy Essential series and focuses on carbon capture and storage (CCS). The study summarizes the process, cost, status and potential of CCS. The report is internationally focused and provides cost numbers and potential on a global basis. The study arrives at a capture cost of \$54/MtCO_2 for NGCC CCS using chemical absorption compared to NGCC without CCS, while increasing the electricity cost by \$19/MWh. The study does not forecast domestic reduction potential but says that carbon capture can contribute between 20% and 28% of the required global effort to reduce emissions by 2050. Please see Appendix I for details on assumptions for estimating reduction volumes for natural gas CCS.

Impacts of Comprehensive Climate and Energy Policy Options on the U.S. Economy
Johns Hopkins University, 2010
This study examines the findings of 16 state climate action plans and extrapolates results to the nation. The study uses those results to project the national impact of these policies on macro-economic variables: employment, incomes, gross domestic product and consumer energy prices. Also, the study models the impact of major features of the Kerry-Lieberman bill. The study contained data behind its MACCs.

Reducing Greenhouse Gas Emissions
McKinsey & Company, 2007
This study estimates cost and potentials of different options to reduce or prevent GHG emissions within the United States over a 25-year period. The study considered more than 250 options, including the abatement potential of natural gas-fired power generation and appliances. For natural gas-fired power generation, the study estimates the cost of coal-to-gas shift in dispatching existing plants to be \$66/MtCO_2 and building new gas-fired generation instead of coal plants to be \$64/MtCO_2. For appliances, the study finds the average cost of improving the efficiency of HVAC equipment to be \$45/MtCO_2. Switching fuel for heating to natural gas in commercial HVAC equipment could provide a 7 megaton by 2030 abatement opportunity, while switching fuel from LPG or fuel oil to natural gas in residential HVAC systems could abate 12 megatons annually by 2030. The opportunity for combined heat and power facilities at commercial and industrial sites is estimated at \$-36/MtCO_2 and \$-15/MtCO_2, respectively, providing 70 MM MtCO_2 and 80 MM MtCO_2 in annual reductions by 2030 below the EIA 2007 Annual Energy Outlook reference case for 2030 emissions.

Natural Gas Combined-Cycle Plants With and Without Carbon Capture & Sequestration
National Energy and Technology Lab (NETL), 2007
This study analyzes and compares results of two combustion turbine generators (CTG) utilizing natural gas, one with carbon capture and one without carbon capture. The study assumes both units are greenfield projects, operating in the Midwest United States and have nameplate capacity of 520MW and 570MW respectively. The results demonstrated that at \$6.75/MMBtu natural gas prices, the avoided cost of CO_2 is \$83/MtCO_2. Please see Appendix I for details on assumptions for estimating reduction volumes for natural gas CCS.

Near-Term Technologies for Retrofit CO2 Capture and Storage of Existing Coal-fired Power Plants in the United States
SFA Pacific, 2009
This study examines the economics of repowering old coal plants with natural gas combined cycle units. The authors identify an addressable market of 543 MWe and assume a 50.7% HHV and a 0.36 mt CO_2/MWHe emissions

factor. The authors find that repowering a paid-off subcritical pulverized coal unit with NGCC has a CO2 avoidance cost of $67/MtCO_2$. Please see Appendix II for details on assumptions for estimating reduction volumes for repowering.

Perspectives on CCS Cost and Economics
Society of Petroleum Engineers, 2010
This paper provides a comparison of the cost of electricity of five power generation options – coal and gas Combined Cycle Gas Turbine (CCGT,) with and without CCS and nuclear – and shows regions of carbon price and fuel prices where each can be economically viable. The study finds that gas based power generation is much more economical than coal CCS at carbon prices below \$60-\$100/$MtCO_2$. The avoided cost of gas CCGT-CCS relative to gas CCGT is \$96/$MtCO_2$ at a \$6/Mcf gas price, and gas CCS is more economical than coal CCS at less than \$8/Mcf gas. Please see Appendix I for details on assumptions for estimating reduction volumes for natural gas CCS.

Report on Carbon Capture and Storage (CCS)
Interagency Taskforce on Carbon Capture and Storage, 2010
This report was the work product from the President's February 2010 interagency task force, assembled to develop a plan that serves to overcome the barriers to the widespread, cost-effective deployment of CCS within ten years, with a goal of bringing five to ten commercial demonstration projects online by 2016. The report looked at various carbon capture technologies as well as transport and storage issues. The report concluded that the cost of CO_2 avoided for a first-of-a-kind 550MWe natural gas combined cycle unit was \$114/$MtCO_2$. The report found that the levelized cost of electricity for new NGCC without CCS would be approximately \$77/MWh versus \$121/MWh for new NGCC with CCS. Please see Appendix I for details on assumptions for estimating reduction volumes for natural gas CCS.

Appendix

Appendix I: Potential Deployment of Carbon Capture on Natural Gas Units

According to EIA's 2010 Annual Energy Outlook, natural gas fuels 46% of total electric generating capacity in the United States. Much of the capacity is in the form of newer natural gas combined cycle (NGCC) units, which consist of a natural gas combustion turbine coupled with heat recovery steam generator to maximize fuel efficiency. These units are typically designed for baseload or immediate load operation, making them favorable to installation of carbon capture technology.

Goal:

1. Identify a range of cumulative natural gas capacity (both existing and new) that could likely be retrofit or built with carbon capture **<u>at costs corresponding to the studies previously reviewed.</u>**
2. Develop a corresponding volume range of captured CO_2.

Underlying Assumptions:

1. Combustion turbines and gas steam units are not candidates for carbon capture given low efficiency, low utilization and lack of supporting studies.
2. Only newer NGCC facilities will retrofit CCS given that the remaining economic life of facility is an important consideration. Additionally, most NGCC CCS studies are based on operational parameters for current generation of technology.
3. Due to economies of scale, larger facilities are most likely to be cost effective retrofit candidates.

Caveats:

1. Not all NGCC units currently run as baseload units (I.e. high utilization or capacity factor (CF)). As most NGCC CCS cost calculations were based on baseload operation, CO2 output needs to be adjusted to this level.
2. The cost of redispatching run in baseload operation is unit, gas price and electricity market specific. These costs were not captured in this portion of the analysis. However, emission reductions and costs would be captured in the coal to gas switching analysis.
3. Improved efficiency of existing CC capacity in transition from intermediate to baseload operation was not assessed.
4. Volume range is meant to be indicative of a **possible** scenario for CCS deployment at the corresponding cost range. Actual deployment will be very unit and market specific.

Methodology:

1. Identify the universe of ALL natural gas fired electric generating units as of 2009 using Velocity Suite
    a. 430 GW of nameplate capacity
2. Refine the above universe to exclude combustion turbine and gas steam units.
3. Develop a range from the above universe to represent the high and low end of a potential carbon capture retrofit universe
    a. <u>Low End</u>:
        i. Units with a nameplate capacity of greater than 450 MW and,
        ii. Are less than 15 years old
    b. <u>High End</u>:
        i. Units with a nameplate capacity of greater than 250 MW and,
        ii. Are less than 30 years old
4. Identify potential captured CO_2 from the above High End and Low End ranges
    a. Assumed each units average heat rate; 80% capacity factor; 90% capture rate
5. Utilize EIA's 2010 AEO to identify universe of both planned and unplanned natural gas combined cycle capacity additions through 2030
    a. Assumed that ALL future capacity additions could be built or retrofit to include carbon capture by 2030
    b. Assumed EIA's average 7,000 Btu/MWh heat rate for new combined cycle units
    c. EIA projects 46 GW of new combined cycle capacity by 2030. This corresponds to 109 million metric tons of annually captured CO_2 by 2030.

6. Combine the High End and Low End case with EIA projections to arrive at cumulative capacity and volume ranges – See table below

	Low End	High End
Total Capacity (GW)	**199**	**251**
Total Captured CO2 (MMT)	**502**	**639**

Appendix 2: Potential of Repowering Existing Coal-Fired Power Plants

In order to estimate the potential reduction volume for repowering existing coal-fired power plants to natural gas, study authors identified an addressable market using parameters set forth in SEPRIL's "Repowering Existing Fossil Steam Plants." As the SEPRIL study authors highlight, repowering candidates are typically older units less than 250 MW.

For the purposes of identifying an addressable market for coal-to-gas repowering, study authors assumed units older than 50 years and less than 250MW were potential candidates for repowering, which returned an addressable market of approximately 36 GW of installed capacity for units, using 2009 plant level data from Velocity Suite. These 36 GW generate an upper-bound reduction potential of 80 MM MTCO2e, assuming an average heat rate of 10,734 Btu/kWh for the coal-plant candidates and an average heat rate of 8,000 Btu/kWh for the repowered natural gas plants.