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Opportunities for Synergy Between Natural Gas and Renewable Energy in the Electric Power and Transportation Sectors

April Lee, Owen Zinaman, and Jeffrey Logan
National Renewable Energy Laboratory

Technical Report
NREL/TP-6A50-56324
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List of Acronyms

CAFE	Corporate Average Fuel Economy
CAES	compressed air energy storage
CC	combined cycle
CNG	compressed natural gas
CSAPR	Cross-State Air Pollution Rule
CSP	concentrating solar power
CT	combustion turbine
DME	dimethyl ether
DSM	demand-side management
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
FAC	fuel adjustment clause
FCEV	fuel cell electric vehicle
FERC	Federal Energy Regulatory Commission
GDE	gallon diesel-equivalent
GHG	greenhouse gas
GTL	gas-to-liquid
GW	gigawatts
IPCC	Intergovernmental Panel on Climate Change
IRP	integrated resource planning
ISO	independent system operator
ITC	investment tax credit
LDC	local distribution company
LNG	liquefied natural gas
MATS	Mercury and Air Toxics Standards
MISO	Midwest Independent System Operator
MMBtu	million British thermal units
MPG	miles per gallon
NGL	natural gas liquids
NGV	natural gas vehicle
NPC	National Petroleum Council
NSPS	New Source Performance Standards
PEV	plug-in electric vehicle
PGA	purchased gas adjustment
PHEV	plug-in hybrid electric vehicle
PTC	production tax credit
REC	renewable energy certificate
RFS	Renewable Fuel Standard
RNG	renewable natural gas
RPS	renewable portfolio standard
RTO	regional transmission operator
Tcf	trillion cubic feet
TRR	technically recoverable resources
TWh	terawatt-hours
WTW	well-to-wheel

Abstract

Use of both natural gas and renewable energy has grown significantly in recent years. Both forms of energy have been touted as key elements of a transition to a cleaner and more secure energy future, but much of the current discourse considers each in isolation or concentrates on the competitive impacts of one on the other. This paper attempts, instead, to explore potential synergies of natural gas and renewable energy in the U.S. electric power and transportation sectors.

Part I of this paper offers nine platforms for dialogue and partnership between the natural gas and renewable energy industries, including development of hybrid technologies, energy system integration studies, analysis of future energy pathways, and joint myth-busters initiatives.

Part II provides a brief summary of recent developments in natural gas and renewable energy markets. It is intended mainly for non-experts in either energy category.

Part III, on the electric power sector, discusses potential complementarities of natural gas and renewable energy from the perspective of electricity portfolio risk and also presents several current market design issues that could benefit from collaborative engagement.

Part IV, on the transportation sector, highlights the technical and economic characteristics of an array of alternative transportation technologies and fuels. Opportunities for natural gas and renewable energy transportation pathways are discussed, as are certain relevant transportation policies.

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1 Initiating Collaborative Engagement

1.1 Introduction

Natural gas and renewable energy have been touted as key elements of a transition to a cleaner and more secure energy future.[1] Still, the specific roles, values, and merits of natural gas and renewable energy in relation to long-term goals of energy security and climate change mitigation have been, and continue to be, debated.

In the energy security arena, both natural gas and renewable energy are building blocks for a robust domestic energy economy. However, there are currently large, but not insurmountable, barriers to harnessing natural gas and renewable energy to meaningfully reduce our national reliance on imported oil for transportation. These include the current state of the petroleum-dependent transportation sector and a lack of clarity and consensus on how many alternative pathways to pursue and which ones are best. Early adopters are testing alternatives and will provide valuable experience, but full deployment of one or more alternative fuels will require broader structural shifts.

Regarding climate change, the Intergovernmental Panel on Climate Change (IPCC) reports that to avoid the largest negative impacts, global greenhouse gas emissions would need to decline by 50%–85% from 1990 levels by 2050.[2] Some have argued that, given the difficulty in meeting this goal, an exclusive focus on natural gas would distract from and impede progress toward the ultimate goal of large-scale deployment of a suite of low-carbon technologies, including renewable energy, energy efficiency, nuclear energy, and carbon capture and storage.[3] Others have offered roadmaps for how cost-effective deployment of natural gas and low-carbon technologies to meet emissions targets might occur,[4] while many more have provided insightful analyses and framed relevant issues.[5]

Much of the current discourse is narrowly focused on either natural gas or renewable energy as distinctly separate components or concentrates on the competitive impacts of one over the other. This paper attempts, instead, to build upon embryonic efforts[6] to more closely examine the nexus of natural gas and renewable energy and explore untapped complementarities and potential synergies on a number of levels.

Use of natural gas and renewable energy has grown significantly in recent years. The two forms of energy appear complementary in many respects: natural gas electricity generation enjoys low capital costs and variable fuel costs, while renewable energy generators have higher capital costs but generally zero fuel costs, excluding bioenergy (see Table 1 for selected examples). Natural gas is a key input for corn starch-based ethanol fuel production, and new transportation infrastructure and technology experiences could enable use of both natural gas and renewable fuels in vehicles. Both forms of energy support a future orientation toward a built environment that utilizes local energy supply and use, including distributed generation and home vehicle fueling.

Despite the complementarities and potential for greater coordinated use, the natural gas and renewable energy industries have at times viewed each other as direct competitors, especially in the power sector. As of mid-2012, the primary competitive impact of inexpensive natural gas has been over 300 terawatt-hours (TWh) of fuel switching from coal- to natural gas-fired electricity since 2008. If natural gas prices remain below roughly $5/million British thermal units (MMBtu), many developers of renewable electricity projects might be hard pressed to offer competitive power purchase prices, thus limiting the number of projects deployed. Similarly, natural gas producers and biofuel producers might compete over water, especially during drought conditions.[7]

Table 1. Matrix of Selected Natural Gas and Renewable Energy Characteristics

	Natural Gas Power	**Wind**	**Solar**	**Bioenergy**
Resource Distribution	Relatively diverse for unconventional supplies; less so for conventional	Diverse but often far from load centers	Diverse but best in Southwest	Diverse but best in Midwest and Southeast
Capital Cost	Low, stable	Moderate, some fluctuation	Relatively high, declining	Moderate-high, stable (early generation biofuels)
Fuel Cost	Variable but currently low	None	None	Moderate
Output	Dispatchable; flexible	Variable and somewhat predictable	Variable and mostly predictable	Dispatchable power and fuel
Carbon Impact	Most recent life cycle assessments conclude that both conventional and unconventional less than half that of coal	Very low	Very low	Depends; corn starch-based may be slightly less than gasoline
Environmental and Social Concerns	Some opposition to hydraulic fracturing; relatively clean-burning fossil fuel	Some opposition to siting; no combustion emissions; low water use	Some opposition to siting of large projects for ecosystem reasons; no combustion emissions or water use for PV	Concern over ecosystem impacts for many biofuels, water use

This paper attempts to identify how the natural gas and renewable energy communities might:

- Promote a new systems approach to natural gas and renewable energy technologies
- Jointly research mutually beneficial policy and market structure options
- Communicate with each other, and jointly to the public, to clarify misconceptions.

The structure of this paper is:

1. **Part I** offers nine platforms for dialogue and partnership between the natural gas and renewable energy industries, including development of hybrid technologies, energy system integration studies, analysis of future energy pathways, and joint myth-busters initiatives.
2. **Part II** provides a brief summary of recent developments in natural gas and renewable energy markets. It is intended mainly for non-experts in either energy category.

3. **Part III**, on the electric power sector, discusses potential complementarities of natural gas and renewable energy from the perspective of electricity portfolio risk and also presents several current market design issues that could benefit from collaborative engagement.
4. **Part IV**, on the transportation sector, highlights the technical and economic characteristics of an array of alternative transportation technologies and fuels. Opportunities for natural gas and renewable energy transportation pathways are discussed, as are certain relevant transportation policies.

1.2 Platforms for Partnership

Partnerships between the natural gas and renewable energy industries have not historically been a source of significant dialogue, yet today there are many opportunities for the two industries and other energy stakeholders to jointly develop vibrant and robust hubs of integrated research and development, information exchange, planning, and policymaking. The first step in reaching this goal is laying the groundwork of open dialogue and engagement in all possible arenas within which further collaboration might grow.

Opportunities exist for natural gas and renewable energy technologies to be integrated at multiple levels, from tightly coupled hybrid technologies to more loosely coupled integrated system and market designs. The following are a few ideas for potential platforms from which to initiate dialogue:

- **Hybrid technology opportunities.** Hybrid technologies can uniquely capture the respective benefits and minimize drawbacks of individual technologies. Examples include hybrid concentrating solar power (CSP) and natural gas-fired power generation systems; biogas and natural gas co-fired combined cycle gas turbines; natural gas-powered compressed air energy storage (CAES) to store non-peak renewable electricity generation for peak period usage; and alternative transportation fuel production processes that can use both biomass and natural gas as feedstocks.
- **Systems integration.** Broader complementarities of natural gas and renewable energy technologies can be realized through co-optimized system integration. Effective system integration studies require the input and deep understanding of all components to determine ideal system configurations. Additionally, the growing deployment of innovative electricity systems utilizing real-time energy pricing, smart grids, demand response, energy storage, and other emerging technologies further amplifies the need for ever-finer levels of compatibility across system components. Lastly, proactive engagement on planning for and investing in new infrastructure can significantly improve the ability of energy systems to handle changing consumption patterns and future industry trajectories.
- **Power sector market design.** Collaborative development of electricity market structures and regulations, coordination of daily operations, and joint transmission planning can optimize the use and abilities of natural gas and renewable energy technologies in lieu of isolated energy planning that does not maximize potential complementarities of these diverse technology options.

- **Comparative analysis of alternative transportation pathways.** Deeper analysis of alternative transportation pathways is required to answer questions on the ideal evolutionary path of the U.S. transportation sector. One immediate question is whether natural gas vehicles or electric vehicles are a better choice in view of cross-sectoral interests and public policy goals. Another question might be whether natural gas could serve as a useful conduit toward a hydrogen-based transportation sector.
- **Enhanced quantitative tools and models.** Somewhat overlapping with the topic of systems integration is the need for current energy reliability and planning models to better incorporate cross-sectoral impacts, particularly arising from natural gas. One example is the need for electricity reliability models to accurately reflect risk probabilities of gas plant outages due to fuel supply constraints.
- **Public policy goals.** More dialogue and analysis is needed to better understand the potential roles of natural gas and renewable energy in enhancing energy diversity, economic prosperity, and climate change mitigation. Integrated action plans can realize the opportunities of all options in achieving public policy goals at federal and state levels.
- **Portfolio approach to research and development (R&D).** Renewable energy, energy efficiency, nuclear energy, and carbon capture use and sequestration all present opportunities to decarbonize the energy sector; however, the options are often pitted against each other, particularly when it comes to funding and support. Instead, given the uncertainties surrounding the ability of each to reach expected heights of decarbonization potential, a portfolio approach to supporting all for future flexibility might be pursued. In addition, a portfolio approach could focus efforts to further develop technology complementarities.
- **Joint myth-busters and frequently asked questions (FAQ) initiative.** Natural gas and renewable energy both experience enduring misinformation and inaccurate portrayals regarding their respective industries. A significant preparation for further collaboration could involve a joint initiative to dispel popular myths and inaccurate beliefs about each industry and answer the most frequently asked questions that each industry may have about the other.
- **Optimized long-term and cross-sectoral utilization of energy resources.** One potential effort could be to jointly research and analyze which industry and technology pathways represent optimal utilization of the country's diverse energy resources across sectors and timescales. From this, opportunities for natural gas and renewable energy technologies to support the other's role may be elucidated and implemented.

The joint efforts of the natural gas and renewable energy industries to engage on these and other platforms of dialogue and collaboration in good faith can bring new insights to existing bodies of knowledge that will help define and frame current and future policy questions. Policymakers and regulators can then use this foundation to craft well-designed and complementary energy policies and regulations to successfully guide the evolution of the U.S. energy industry along desired long-term pathways.

2 Background

2.1 History and Recent Developments of Natural Gas

2.1.1 Natural Gas Consumption in the United States

No energy source supplies a more diverse range of sectors and uses than natural gas: heating and cooking in the residential and commercial sectors; feedstock for manufacturing processes in the industrial sector; peak, intermediate, and base-load electricity generation in the electric power sector; and fuel to power natural gas pipelines and vehicles in the transportation sector. In comparison, almost all of the coal consumed in the United States is for electricity generation while nearly three-quarters of U.S. petroleum consumption is for transportation.[8]

U.S. natural gas consumption is roughly equally divided across the residential and commercial (32% in 2011), industrial (33%), and electric power sectors (31%) (Figure 1). Within each of these sectors, natural gas accounted for a significant portion of energy consumption: in 2011, 75% of residential and commercial, 41% of industrial, and 20% of electric power sector energy consumption.[9] The only sector currently consuming little natural gas is the transportation sector, which includes both the use of natural gas to power natural gas pipeline transmission networks as well as natural gas used as vehicle fuel. Of total natural gas consumed in 2011, 2.8% was used for pipeline operations, while 0.1% was used as vehicle fuel.[10]

2.1.2 Recent Developments and Market Effects of Shale Gas

U.S. natural gas production has traditionally come from conventional oil and gas wells. However, in the 2000s, developments in drilling technology, notably the combined use of horizontal drilling and hydraulic fracturing, along with access to private and public minerals, high natural gas prices, and increasingly upward shale gas resource estimates, spurred a wave of drilling activity in previously uneconomic shale basins, unlocking an abundant supply of domestic natural gas. U.S. Energy Information Administration (EIA) data shows that shale gas production grew by more than 15-fold from 0.32 trillion cubic feet (tcf) in 2000 to nearly 5 tcf in 2010—23% of natural gas production in 2010.[11] With continued growth, shale gas is now estimated to provide more than one-third of total gas production.[12] Together, shale gas, tight gas, and coalbed methane now account for more than half of total gas production (Figure 2). The rapid growth of shale gas production has offset declining production from conventional wells and helped maintain year-on-year increases in overall gas production.

As a result of the volume and speed of rising shale gas production in recent years, the following impacts have occurred:

- Lowest natural gas prices in a decade
- Widening oil-to-gas price spreads
- Widening U.S. gas-to-international gas price spreads
- Immediate coal-to-gas switching in the electric power sector
- Decreasing net imports of natural gas
- Evolving supply estimates.

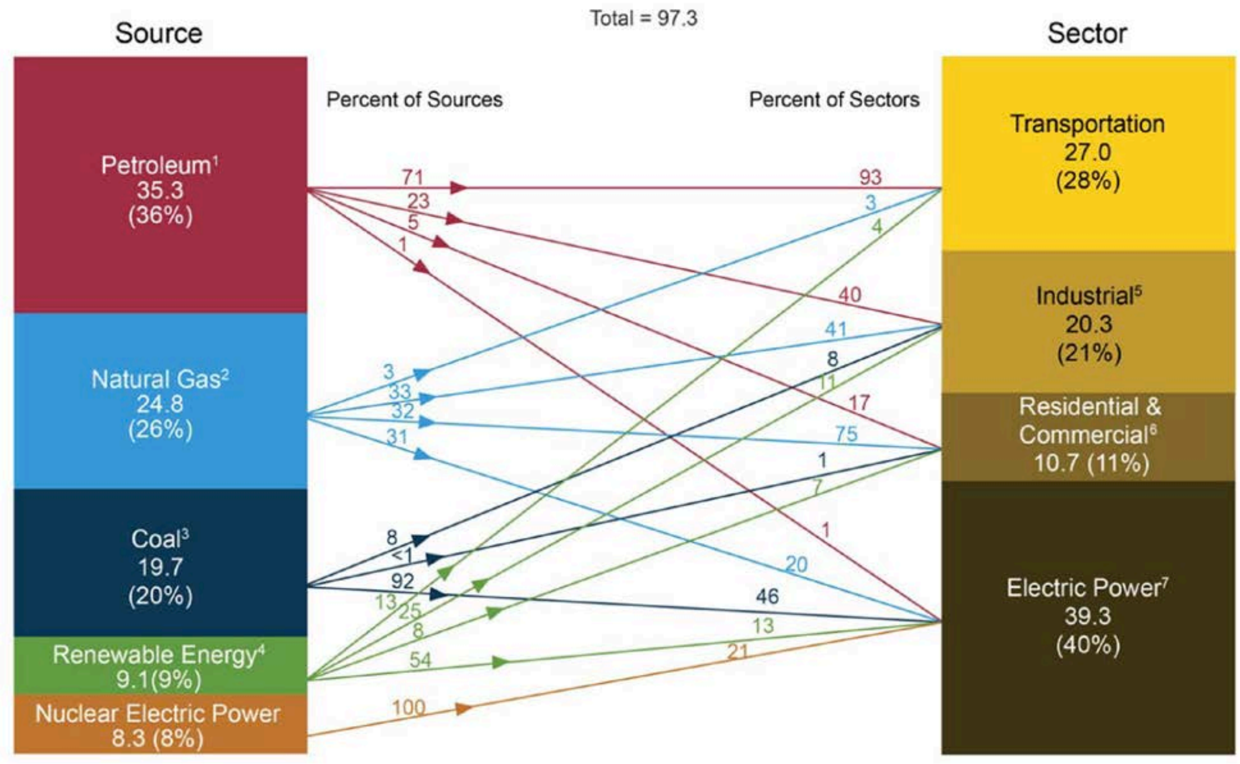

Figure 1. U.S. primary energy consumption by source and sector, 2011[13]

Note: For figure notes, see source.

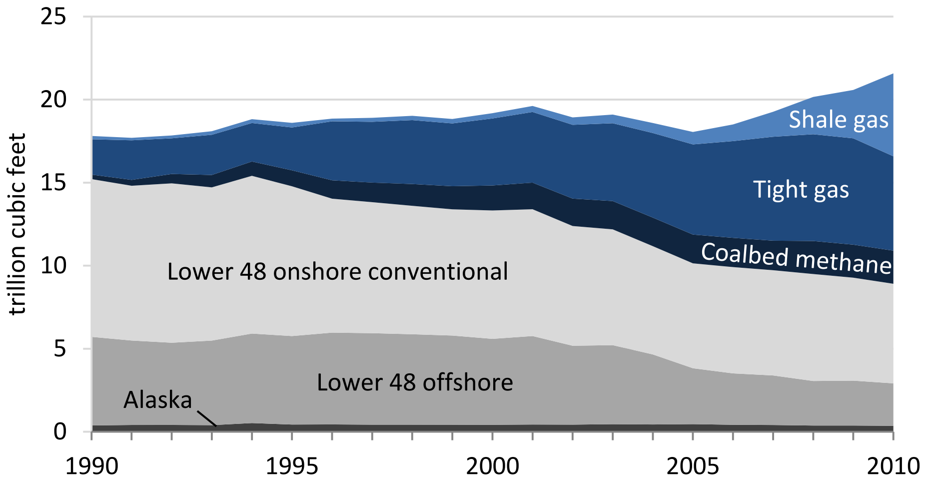

Figure 2. U.S. natural gas production by source, 1990–2010[14]

2.1.2.1 Lowest Natural Gas Prices in a Decade

Natural gas wellhead prices are currently at their lowest in more than a decade, averaging below $2/MMBtu in April and May 2012 (Figure 3).[15] Prices climbed throughout the 2000s to a monthly average peak of $10.52/MMBtu[a] in July 2008[16] and a yearly average peak of $7.78/MMbtu[b] for 2008.[17] From there, prices fell sharply to their current lows as shale gas production began to oversupply markets. A warmer-than-average 2011–2012 winter also drove prices down by decreasing heating demand.[18] This decrease was partially offset by increased demand from the power sector but still resulted in the lowest overall winter natural gas demand in five years.[19] Correspondingly, natural gas storage levels in underground facilities have been substantially higher so far in 2012 compared to the five-year range over the same months.[20] Residential and commercial natural gas prices have also dropped, albeit to a lesser extent, from their 2008 peaks.[21]

Current natural gas prices of $2–$4/MMBtu are challenging for shale gas producers, who generally require closer to a $5–$8/MMBtu range to maintain business operations,[22] particularly in dry gas plays. Many have been operating at a loss for some time in hopes that prices will soon rise again.[23] In the meantime, drilling has shifted over to liquids-rich fields in search of more profitable oil and natural gas liquids (NGL).[24] Energy markets continue to equilibrate in response to changing market dynamics of gas, oil, and NGL supplies and prices. How these dynamics will settle in the long term and around what prices is uncertain, though EIA's latest forecast anticipates wellhead prices to be in the range of $4.00–$5.50/MMBtu for 2020–2030.[25]

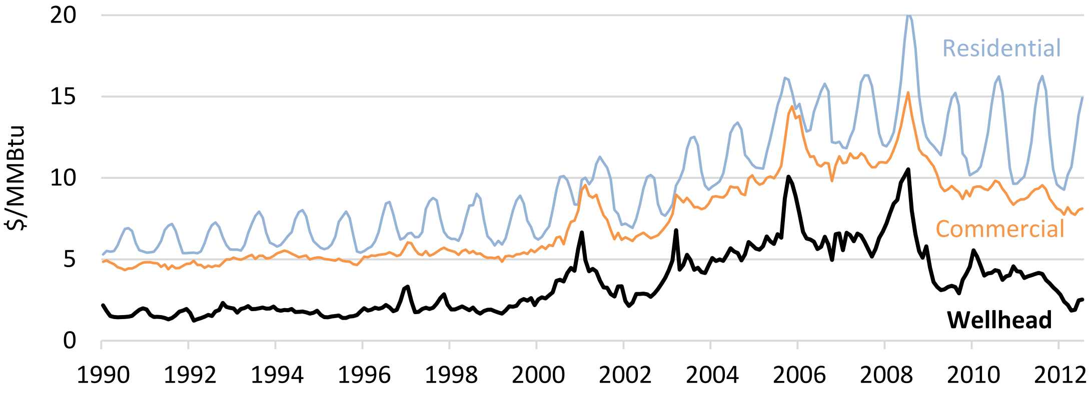

Figure 3. U.S. monthly natural gas prices, January 1990–July 2012[26]

2.1.2.2 Widening Oil-to-Gas Price Spreads

U.S. spot prices for crude oil and natural gas, historically strongly correlated, have become increasingly decoupled as natural gas prices remain dampened by domestic oversupply and oil prices continue to rise, mostly in line with global markets. This growing price spread has led to increased interest in gas-for-oil substitution opportunities, particularly in the transportation sector. Natural gas at $4/MMBtu roughly translates to an energy-equivalent price of $23/barrel

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[a] Converted from $10.79/thousand cubic feet (Mcf) using 2010 average heat content of natural gas in the United States of 1 Mcf = 1.025 MMBtu. (EIA. "What are Mcf, Btu, and Therms? How Do I Convert Prices in Mcf to Btus and Therms?" Accessed August 29, 2012: http://www.eia.gov/tools/faqs/faq.cfm?id=45&t=7.)

[b] Converted from $7.97/Mcf.

of oil.[c] Given the low fuel cost, compressed natural gas (CNG) and liquefied natural gas (LNG) vehicles present increasingly competitive alternatives to conventional gasoline vehicles. Indeed, commercial and public sector investments in natural gas vehicle (NGV) fleets are already occurring. But to achieve wider consumer adoption, significant refueling infrastructure investments would be required and consumer concerns, such as vehicle range, would need to be addressed (see Part IV). Another area of interest lies in converting gas into liquid fuels that can be used in place of gasoline and diesel. This pathway may skirt infrastructure issues but is subject to a number of financial uncertainties (see Part IV).

2.1.2.3 Widening U.S. Gas-to-International Gas Price Spreads

Natural gas markets across the globe have thus far remained localized due to the expense, and sometimes geopolitical challenges, of transporting gas over long distances, which requires extensive pipeline networks or costly liquefaction/re-gasification facilities for importing and exporting LNG. Consequently, U.S. natural gas is experiencing a significant price advantage over other international gas supplies, presenting potentially large profit opportunities even after factoring in the additional liquefaction and overseas transport costs.[27] Several companies have already applied for federal regulatory approval to build LNG export facilities.[28] In April 2012, the Federal Energy Regulatory Commission (FERC) gave its first authorization for construction of export capacity of up to 2.6 billion cubic feet per day (bcf/d) at the existing Sabine Pass LNG terminal in Louisiana.[d] Preliminary analysis of the domestic market effects of exporting substantial volumes of LNG predicts a combination of higher domestic gas prices, increased production, reduced domestic demand, and fuel substitution. The eventual magnitude of these effects is highly dependent on the scenario assumptions.[29]

2.1.2.4 Immediate Coal-to-Gas Switching in the Electric Power Sector

The largest near-term effect of excess natural gas supplies and low prices has been the rapid displacement of coal-generated electricity by natural gas generation. In the 1990s, the combination of electricity market and natural gas price deregulation, availability of new highly efficient natural gas combined cycle plant technology, developments in offshore production, and expectations of a substantial domestic supply increase led to the construction of a large fleet of natural gas plants.[30] Since demand did not eventually grow to expected levels, this fleet of natural gas plants has been underutilized.[e,31] In 2010, natural gas plants represented 39% of total

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[c] \$4/MMBtu x 5.8 MMBtu/barrel of oil based on 2011 U.S. production = \$23.20/barrel. (EIA. "Crude Oil Conversion Calculator." Accessed August 29, 2012: http://www.eia.gov/kids/energy.cfm?page=about_energy_conversion_calculator-basics#oilcalc.)

[d] As of July 2012, seven other proposals for export facilities have been submitted to FERC with total export capacity of 10.65 bcf/d. Four more potential sites have been identified to FERC by project sponsors with total export capacity of 6.18 bcf/d. If approved and built, these 11 facilities plus the approved Sabine Pass terminal could provide 19.43 bcf/d (or approximately 7 tcf/year) of export capacity, equivalent to 30% of total U.S. natural gas production in 2011. (FERC. *North American LNG Import/Export Terminals, Approved*. FERC, 2012. Accessed August 22, 2012: http://www.ferc.gov/industries/gas/indus-act/lng/LNG-approved.pdf.; FERC. *North American LNG Import/Export Terminals, Proposed/Potential*. FERC, 2012. Accessed August 22, 2012: http://www.ferc.gov/industries/gas/indus-act/lng/LNG-proposed-potential.pdf.)

[e] Natural gas plants experienced average utilization rates of 30%–40% of plant capacity between 1997 and 2008, compared to coal plant utilization rates of around 65%–75% over the same period (EIA. Electric Power Annual 2008, Table 5.2. Average Capacity Factors by Energy Source, 1997 through 2008. Accessed August 14, 2012: http://205.254.135.7/electricity/annual/archive/03482008.pdf).

installed capacity but only 24% of total generation. Meanwhile, coal represented 30% of capacity and 45% of generation.[32]

Because of this spare capacity, the electric power sector has been able to capitalize on the current abundance of natural gas supply, and low prices, with little need for additional infrastructure or system investments.[33] The switch has been exceptionally dramatic within the past six months, with coal and natural gas plants each supplying 32% of total monthly power generation in April 2012.[34] Further dispatch of natural gas will occur up to the constraints of current natural gas pipeline and electricity transmission networks. Beyond that, new infrastructure and market structures, particularly for natural gas supply, will be needed for greater deployment of natural gas generation (see Part III).[35] Forthcoming expected environmental regulations from the U.S. Environmental Protection Agency (EPA) on power plant emissions and scheduled age-based retirements of coal plants have also driven the coal-to-gas switch;[36] however, shale gas production has significantly advanced the timeline and reduced the cost of this transition.

2.1.2.5 Decreasing Net Imports of Natural Gas

U.S. net imports of natural gas have fallen to their lowest level in decades as imports declined and exports rose due to the growing domestic supply. The large majority of U.S. natural gas imports come by pipeline from Canada (more than 80% for the past two decades),[37] while exports go primarily to Canada and Mexico (roughly two-thirds and one-third, respectively).[38] LNG imports experienced strong growth in the early 2000s but have since subsided to around 10% of imports.[39] LNG exports have stayed virtually the same since the 1970s, representing 5% of exports today;[40] however, as mentioned previously, there is burgeoning interest in ramping up LNG exports, particularly to Europe and Asia. LNG exports are likely to contribute a growing share to U.S. natural gas exports.[f]

2.1.2.6 Evolving Supply Estimates

Estimates of total available gas resources in the United States continue to change—mostly increasing in recent years but with some instances where resource estimates were lowered as a result of uncertainties surrounding unconventional gas resources.[g] Coupled with a future gas consumption trajectory that is highly reliant on interdependent sectoral possibilities, approximating the number of years of gas supply that the United States possesses is difficult (see text box in Section 2.1.3). While a review of historical resource estimates shows a general trend of increasing resources[41] due to technological improvements, among other reasons, the lack of consensus around unconventional gas resources and future consumption adds a significant factor of uncertainty to gas-related planning and decision making, particularly for long-lived infrastructure. Credible, objective analysis of potential scenarios of supply and demand profiles would help inform ongoing dialogues that grapple with the question of how many years of natural gas supply exist.

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[f] EIA's Annual Energy Outlook 2012 predicts that the United States will become a net exporter around 2022.

[g] EIA adjusted their estimate of technically recoverable resources from the Marcellus shale play from 827 tcf in their Annual Energy Outlook (AEO) 2011 publication to 482 tcf in the AEO 2012, a 40% decrease, largely as a result of new well productivity data and updated U.S. Geological Survey (USGS) assessments.

2.1.3 Looking Ahead

The rapid ascendency of shale gas has caught many in the energy sector by surprise, prompting a host of unexpected and significant departures from historical trends as energy markets readjust toward equilibrium in the near term. Looking ahead, the emergence of unconventional gas resources has also considerably altered the calculus of medium- and long-term energy options, with potentially major implications for the long-term evolution of the U.S. energy portfolio.

How Many Years of Natural Gas Supply?

Reported supply longevity of natural gas varies widely—from 80–250 years and depends on many factors.[h] While that metric could serve as a useful indicator for planning and policymaking purposes, it is important to understand some of the technical uncertainties embedded within this simple estimate.

Supply

Technically recoverable resources (TRR), an indicator of total available gas supply, include both proved reserves (technically and economically producible now) and unproved resources (technically but not necessarily economically producible). TRR estimates vary as a result of using new data or different assumptions for various factors, including:

- Geological assessments of oil and gas fields
- Field productivity based on observed and predicted well recovery rates
- Current and expected improvements to drilling and production technologies
- Current gas market prices and other economic conditions

The materialization in recent years of huge unconventional sources of natural gas, such as shale gas, tight gas, and coalbed methane, has added significant uncertainty to these estimates.[i] Industry experience with unconventional resources, particularly shale gas, has been too brief and inconsistently documented to permit confident estimation of resource field productivities. Other sources of natural gas, including methane hydrates and renewable natural gas (RNG) could play a large role in the future but are currently at very early stages of development.[j]

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[h] See, for example, *Potential Supply of Natural Gas in the United States*. (2012). Potential Gas Agency.; “FAQs: Natural gas.” International Energy Agency. Accessed September 7, 2012: http://www.iea.org/aboutus/faqs/gas/; “Issues in Focus #11: U.S. Crude Oil and Natural Gas Resource Uncertainty.” (2012). EIA, Annual Energy Outlook 2012.

[i] According to the National Petroleum Council’s (NPC’s) compilation and assessment of industry, government, and academic natural gas resource estimates, “the United States’ unconventional, remaining recoverable resource base is around 60 to 75% of the total remaining gas volumes in the United States” (National Petroleum Council. *Prudent Development: Realizing the Potential of North America’s Abundant Natural Gas and Oil Resources*. National Petroleum Council, 2011. Accessed August 29, 2012: http://www.npc.org/reports/rd.html).

[j] A recent study estimated that approximately 4.8 tcf of domestic RNG, a substitute for conventional natural gas that can be produced from biomass wastes, was potentially available (Mintz, M.; Wegrzyn, J. “Renewable Natural Gas: Current Status, Challenges and Issues.” Clean Cities Program, U.S. Department of Energy, 2009. Accessed August 30, 2012: http://www1.eere.energy.gov/cleancities/pdfs/renewable_nat ural_gas.pdf; National Petroleum Council. *Renewable Natural Gas for Transportation*. National Petroleum Council, 2012. Accessed August 31, 2012: http://www.npc.org/FTF_Topic_papers/26RNG.pdf). Early assessments of methane hydrates, ice-like lattices of water with natural gas trapped inside, indicate vast resource potential if able to be technically recovered (NETL. *Energy Resource Potential of Methane Hydrate*. National Energy Technology Laboratory, 2011. Accessed September 6, 2012: http://www.netl.doe.gov/technologies/oil-gas/publications/Hydrates/2011Reports/MH_Primer2011.pdf; Boswell, R. “Resource Potential of Methane Hydrate Coming into Focus.” *Journal of Petroleum Science & Engineering* (56:1-3), 2007; pp. 9-13).

Demand

Significant uncertainty also exists on the demand side. It is very likely that U.S. gas demand will change and grow in the coming years for several reasons, including:

- The United States is projected to become a net exporter of natural gas. The growing domestic supply is reducing the need for imports while low domestic prices have prompted interest in exporting substantial volumes of LNG.
- The electric power sector's consumption of natural gas is likely to continue increasing as further coal-to-gas fuel switching occurs and new natural gas plants continue to be built.
- Greater deployment of natural gas transportation technologies would increase the currently marginal gas consumption by the transportation sector.

If realized, these consumption possibilities may have considerable effects on future gas demand, with corresponding effects on the ultimate length of domestic gas supply. Additionally, these possibilities are interdependent on each other and will have unique impacts on overall gas market dynamics. Simple calculations of resources divided by production omit the non-trivial factor of market economics and prices in determining levels of supply and demand.

Conclusion

Clear and accurate estimates of natural gas resources are a vital foundation for policymakers, regulators, and industry stakeholders to develop successful long-term plans, policies, and investments. Significant uncertainties exist on both the supply and demand side. Much of this uncertainty will likely be reduced as unconventional gas production matures and industry trajectories crystallize. Until then, prudent risk and uncertainty analysis will help inform robust decision making.

2.2 History and Recent Developments of Renewable Energy

2.2.1 Introduction

Renewable energy has long held the promise of making significant contributions to the U.S. energy sector, but it has only been over the past five years or so that newer technologies like wind and solar PV have begun to concretely demonstrate some of that potential. Rapid growth in renewable energy deployment and consumption over the past decade has been achieved by a combination of technological improvements, policy incentives, and periodically high prices for conventional energy sources, although new challenges now face the sector.

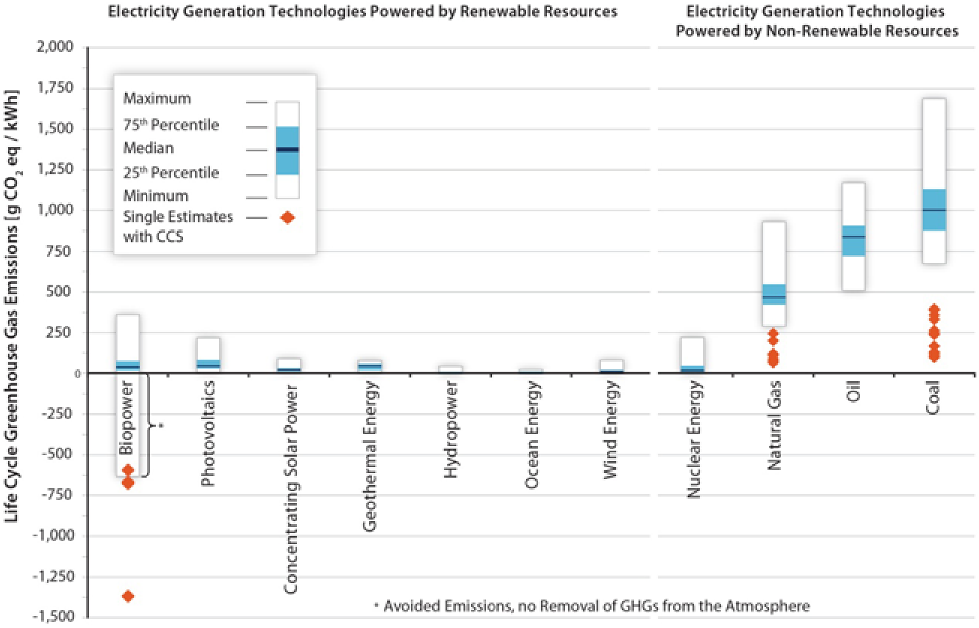
2.2.1.1 Characteristics of Renewable Energy

Renewable energy sources are diverse and have different types of benefits and challenges. Wind, solar, and ocean energy are plentiful and carry no fuel costs, although their often-higher capital costs can make financing difficult, especially if their energy output is variable or otherwise not dispatchable. Conventional geothermal, biomass, and hydroelectric energy also enjoy no fuel costs and are dispatchable, although the resource base is more limited and location specific. Most renewable energy sources have far fewer greenhouse gas emissions associated with their full life cycle compared to coal and petroleum (Figure 4) and, because they are often available domestically, can help improve aspects of energy security by offsetting reliance on imported fuels.[42] A growing body of work has been dedicated to understanding the challenges and costs of increasing integration of renewable energy into the existing energy infrastructure; these studies often conclude that challenges and costs are manageable up to certain levels of renewable penetration but may require changes in operation to traditional business and regulator practices.[43] Finally, most types of renewable energy have fewer conventional pollutants than traditional fossil fuels and generally require less consumable water to operate.[44]

2.2.2 Renewable Energy Market Activity and Drivers

Hydropower, the largest single source of renewable energy in the United States, has seen relatively stagnant growth since the 1970s, but wind, biofuels, and solar have grown rapidly over the past five years. Today, renewable energy exceeds nuclear in the U.S. energy supply (Figure 5).

Wind power and ethanol biofuels began growing rapidly in the early 2000s due to high oil and natural gas prices, technological advancements, deployment mandates (i.e., renewable portfolio standards), and fiscal incentives. When fossil fuel prices declined due to the global recession, wind, solar, and other forms of renewable energy continued to see strong growth due to incentives offered in the American Recovery and Reinvestment Act of 2009, traditional tax credits, and state-based renewable energy standards (also known as renewable portfolio standards, or RPSs). Some of the Recovery Act incentives have now expired and the future for renewable energy in general looks more challenging given the low growth in demand for electricity and potentially reduced tax incentives. In addition, low prices for natural gas can make it difficult for renewable energy project developers to sign power purchase agreements, often necessary for financing, and could force many sources of renewable energy to the sidelines until natural gas prices rise.



Count of Estimates	222(+4)	124	42	8	28	10	126	125	83(+7)	24	169(+12)
Count of References	52(+0)	26	13	6	11	5	49	32	36(+4)	10	50(+10)

Figure 4. Comparison of as-published life cycle greenhouse gas emission estimates for electricity generation technologies[45]

Note: The impacts of the land use changes are excluded from this analysis. Here, natural gas refers only to conventional sources.

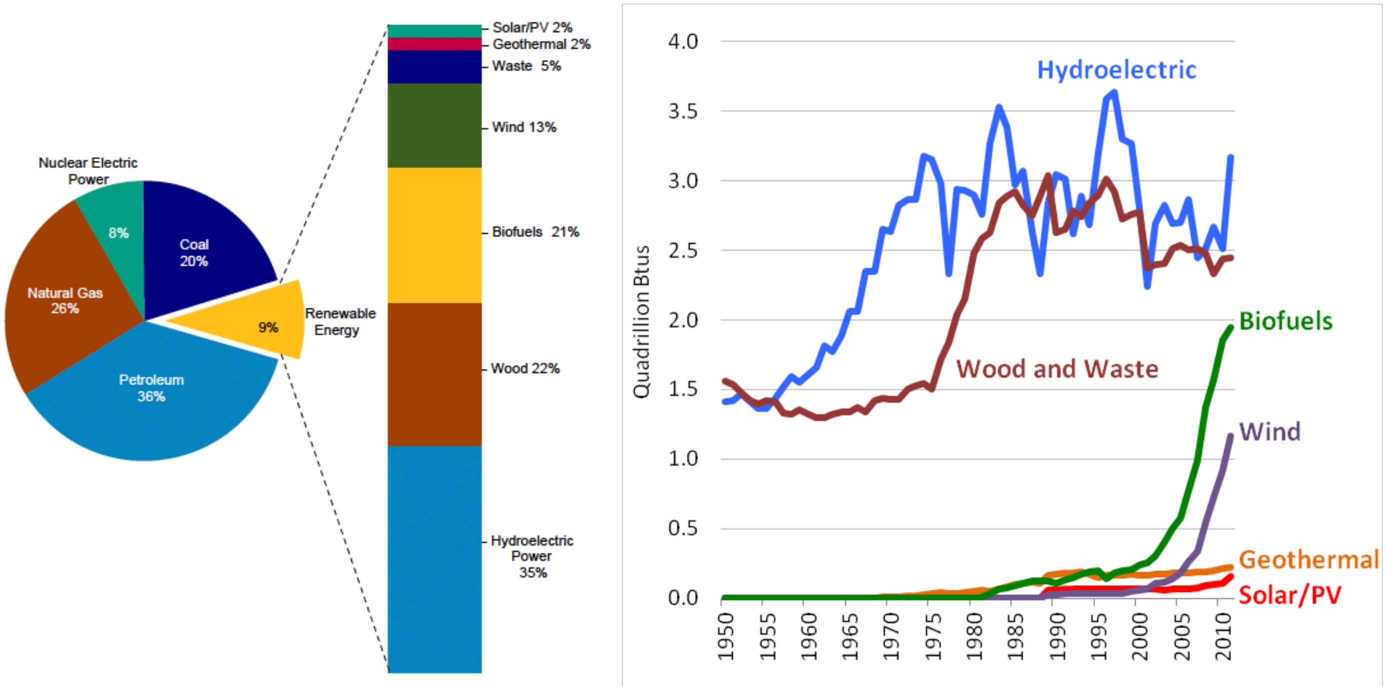


Figure 5. Renewable energy as share of total primary energy consumption in 2011 (left) and growth of renewable energy consumption, 1950–2011 (right)[46]

In the transportation sector, corn-based ethanol has been the fastest growing source of renewable energy over the past decade. Ethanol production has grown by more than seven-fold to 14 billion gallons in 2011, about 8% of the total U.S. highway vehicle fuel.[47] Ethanol use has been promoted by a combination of mandates and incentives, and now accounts for about 2% of primary U.S. energy supply. Without further developments in non-corn-based ethanol production, continued growth in domestic ethanol supply may be limited; production in 2012 has already declined due to the drought affecting many corn-growing regions of the United States.[48]

In the electric power sector wind has dominated other forms of renewable energy to date in terms of growth in generation and capacity installed. Solar PV, in particular, has been growing very rapidly even if it has started from a much smaller base. After nearly 2 GW of installed solar capacity in 2011, the United States could cross the 3 GW level in 2012.[49] State-level RPSs will continue to incent deployment of some renewable energy going forward, although many states are currently ahead of their deployment schedules and some are even debating scaling back their targets.[50]

2.2.3 Renewable Energy Costs

Many sources of renewable energy are still more expensive than non-renewable options, although full economic costs, values, and risks are often not represented in market prices across all energy production sectors. Some renewable energy costs are changing rapidly, while others are relatively stagnant. Over the past two decades, wind turbine costs have fluctuated considerably.[51] Perhaps more widely noted, solar PV module costs have declined by a reported 75% over the past four years,[52] making them increasingly competitive with the cost of average retail electricity service in different regions of the world. Figure 6 summarizes different levelized costs of energy service for renewable and non-renewable energy options. How these price dynamics change in the future will be influenced by many variables, an increasing number of which may be beyond the direct control of U.S. decision makers.

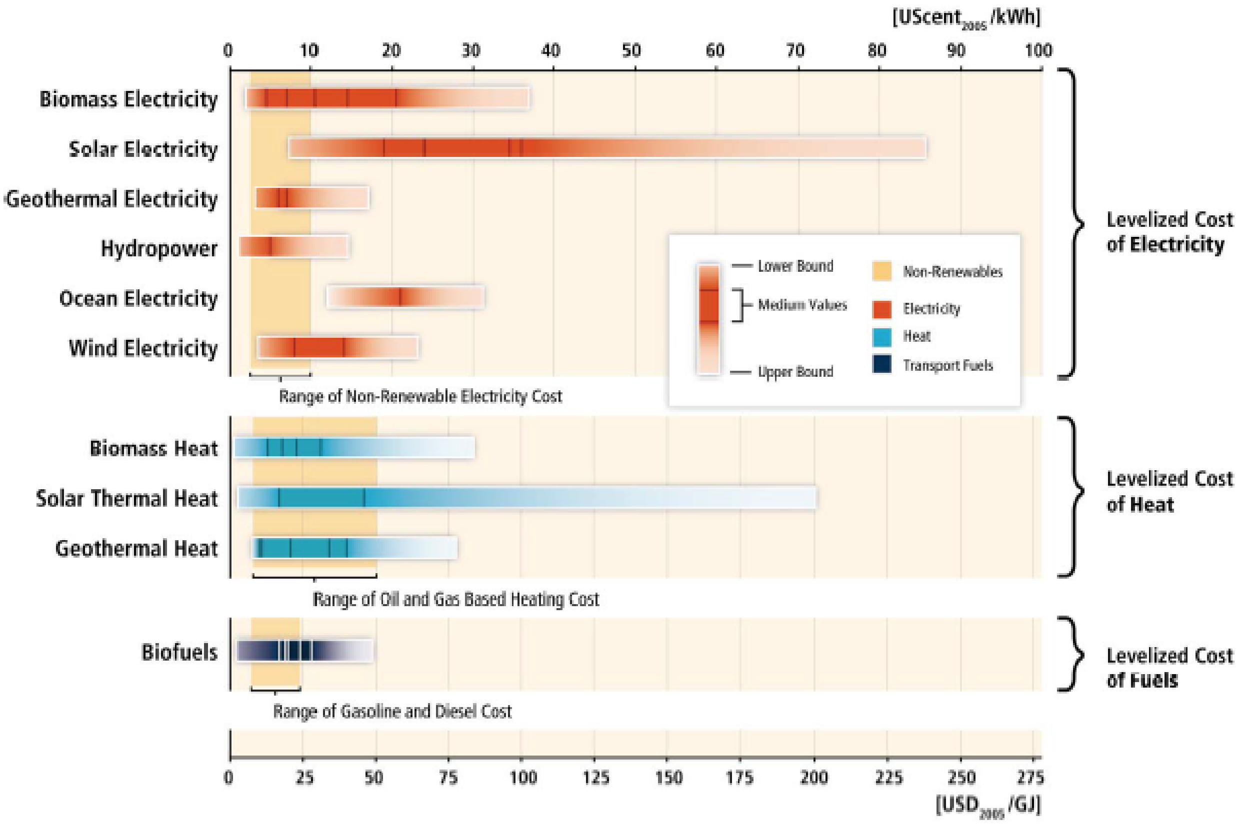


Figure 6. Range in recent levelized costs of energy for selected commercially available renewable energy electricity generating technologies in comparison to recent non-renewable energy costs[53]

3 U.S. Electric Power Sector

3.1 Background

The U.S. electric power sector is currently experiencing unprecedented change due to a combination of low-priced natural gas, stricter forthcoming environmental standards, and rapid growth of renewable energy. These changes have led to a swift decline in coal- and oil-fired generation and corresponding increases in natural gas and renewables (Figure 7). Coal-fired generation has declined from roughly 48% of annual net U.S. generation in 2008 to approximately 35% as of mid-2012.[54] This is arguably one of the most tumultuous periods of change in the power sector since World War II. It remains to be seen whether this shift from coal to natural gas and renewables will continue or reverse itself as natural gas prices fluctuate relative to coal and incentives for renewable energy expire.

Installed wind capacity in the United States grew by more than five times between 2005 and mid-2012 to approximately 50 gigawatts (GW).[55] Wind electricity generation grew by more than seven times over the same time period.[56] Solar energy generation grew by more than five times over the period, with the vast majority of that growth coming from solar PV capacity additions.[57] However, on an absolute level, wind and solar still represent modest contributions of total electricity generation, representing only 3.5% of total U.S. net generation in 2012.[58] The fleet of natural gas combined cycle plants has operated more regularly over the past few years, largely at the expense of coal plants, increasing in some independent system operator (ISO) regions dramatically. The weighted average capacity factor for combined cycle plants operating in the PJM Interconnection's service territory, for example, was more than double the level from 2008 during the first three months of 2012.[59]

One important set of dialogues that has accompanied the rise of natural gas has recently commenced on better coordinating the natural gas and electricity sectors. FERC is largely spearheading this effort between ISO/regional transmission operator (RTO) and natural gas transmission companies. The following section of this report explores that, and other power sector dynamics, in more detail.

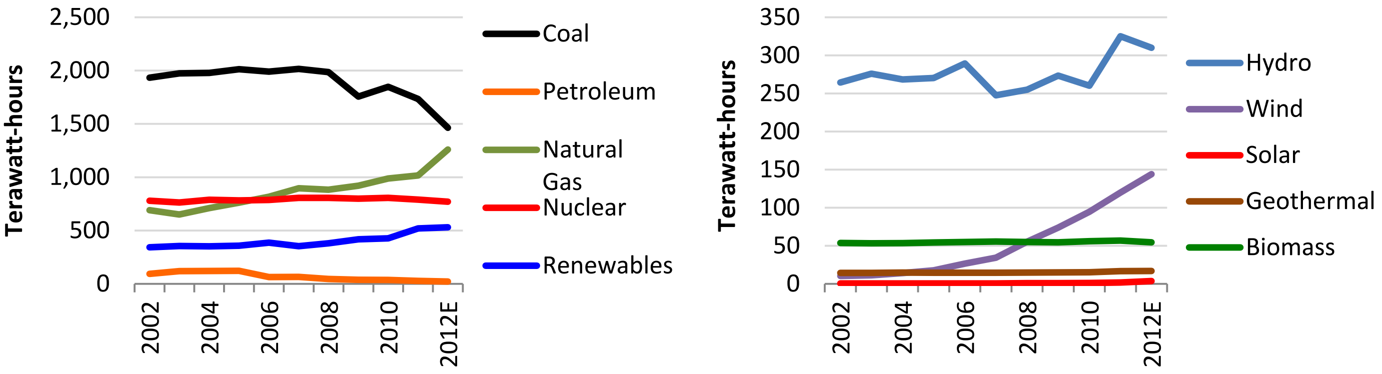


Figure 7. Annual U.S. net generation, 2002–July 2012 (left), and U.S. renewable energy generation, 2002–July 2012 (right)[60]

3.2 An Optimized Diverse Electricity Portfolio

Natural gas and renewable energy technologies enjoy many complementarities spanning economic, technical, environmental, and political considerations. These complementarities arise from their similarities, which include improved environmental performance compared to coal and oil and their ability to contribute to a robust U.S. economy, but it is from their dissimilarities that the biggest opportunities for mutually beneficial collaboration can be found.

For electric power stakeholders with multiple assets under their purview, investment decisions on new electric power projects are based on the evaluation of many factors, including: project costs and financing, fuel supply availability, current and projected future market dynamics, local and federal energy policies, environmental regulations, and portfolio diversity. Embedded within each of these factors are varying types and magnitudes of risk, including: financing interest rates, fuel supply uncertainty and price volatility, and environmental compliance costs. Investments in new generation capacity have historically been made project-by-project on a primarily least-cost basis, which does not adequately incorporate risk as represented by the variance of expected future costs. This has led to the development of sub-optimal regional electricity portfolios with inefficiently higher levels of risk given portfolio costs.[61]

Traditional integrated resource planning (IRP) by utilities attempted to incorporate the concept and benefits of portfolio optimization as well as utilize non-supply resources such as demand-side management (DSM).[62] However, these strategies still focused primarily on minimizing the costs of a planned generation mix across a selection of possible future scenarios without sufficiently incorporating the economic cost of risks or valuing the minimization of these risks.[k,63] A simple example is fuel price volatility. Many IRP models assumed specific future fuel prices in their cost calculations, or considered a set of possible future prices, but did not incorporate the volatility of those prices. Large short-term (daily, weekly, or monthly) fluctuations in fuel prices introduce considerable generation and revenue variability not conveyed by the use of long-term average costs and revenues (see Figure 8 for an example). These types of portfolio risks were poorly accounted for in IRP models yet have major consequences for energy reliability. Today, IRP models have evolved along a variety of paths, particularly with respect to evaluating portfolio risks. Some utilities now employ scenario and sensitivity analysis, stochastic analysis, or a combination of both to better incorporate portfolio risk assessment into the planning process.[l]

Risk minimization is as important as cost minimization. Multiple benefits accrue from developing markets and policies conducive to building optimized portfolios with efficient levels of both risk and cost. More robust methods of portfolio evaluation and planning that incorporate explicit valuation of risks, such as mean-variance portfolio techniques, can help stakeholders

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[k] For an overview of state IRP programs, see Wilson, R.; Peterson, P. (2011). “A Brief Survey of State Integrated Resource Planning Rules and Requirements.” Prepared for the American Clean Skies Foundation. Cambridge, MA: Synapse Energy Economics, Inc.

[l] For a comparison of selected utilities’ IRP practices and approaches to risk assessment, see Aspen Environmental Group and Energy and Environmental Economics, Inc. (2008) “Survey of Utility Resource Planning and Procurement Practices for Application to Long-Term Procurement Planning in California - DRAFT.” Prepared for the California Public Utilities Commission.

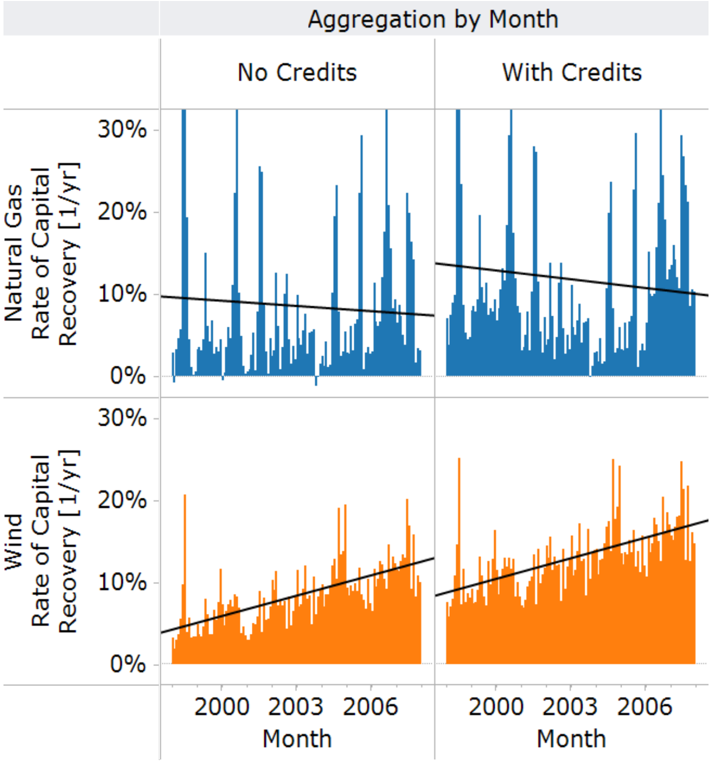

Figure 8. Simulated returns for natural gas combined cycle and wind generators using PJM RTO hourly power price and load data for 1999–2008

Note: "With credits" includes variable monthly capacity payments to natural gas generators and production tax credits to wind generators. The natural gas generators were assumed to operate mostly during peak periods while wind generators operated more evenly across the day. This accounts for some of the higher volatility of the natural gas returns, but another major source of volatility is the need for natural gas generators to dispatch only when the hourly power price exceeds their fuel and other variable operating costs in order to generate positive returns.

Source: Bush, B.; Jenkin, T.; Lipowicz, D.; Arent, D. J.; Cooke, R. (2012). *Variance Analysis of Wind and Natural Gas Generation under Different Market Structures: Some Observations*. NREL/TP-6A20-52790. Golden, CO: National Renewable Energy Laboratory.

create an electric power sector that is best prepared to adapt to the widest array of possible future outcomes at lowest risk and cost. This is particularly valuable given the long (20–60 years) lifespan of electric power generation and infrastructure assets as well as the experience over the last few decades of highly unexpected industry developments and rapidly changing market dynamics.

Natural gas and renewable energy investments have fairly different risk profiles and offer rather complementary portfolio options. Combined pursuit of both can significantly reduce overall portfolio risks in the electric power sector. A diverse electricity portfolio can be continuously adjusted and re-mixed to adapt to changing market conditions over the lifetime of portfolio assets.[64]

The following section highlights several major issues and their attendant risks facing natural gas and renewable energy investments that may be complementarily addressed by the other technology.[m] For this discussion, wind and solar energy are primarily used to represent renewable energy options as they have been the biggest sources of renewable electricity growth in the last decade. However, this discussion is also generally applicable to other renewable energy technologies.

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[m] These issues are only a subset of the full suite of considerations for these investments and likely also do not reflect all areas of possible complementarity.

3.2.1 Natural Gas Issues

3.2.1.1 Fuel Supply and Transportation

Issue: Domestic natural gas supply is on the rise due to shale gas; total supply estimates continue to be refined as the shale gas experience continues to unfold. Long-term fuel availability will greatly affect the profitability of new natural gas plants in the latter years of their service period.

Growing natural gas consumption by the electric power and other sectors increases the challenges associated with gas pipeline constraints, which can cause market-based price spikes[65] and necessitate investments in new infrastructure.[66] Additionally, the ability of current pipeline systems to handle changing gas consumption patterns in the power sector—from generally low utilization rates and sporadic peak demands to overall much higher and continuous utilization rates—are a source of reliability concern, particularly during peak seasonal demand periods.[67] Cost allocation approaches to funding new infrastructure and ensuring reliable pipeline service to natural gas generators are the subject of current dialogue.

Complementarity: Renewable energy generation, such as wind and solar, does not experience the same market-based fuel supply concerns as natural gas generation. “Fuel” supply is guaranteed from a cost standpoint with no exposure to or dependence on market dynamics. (However, there is significant resource variability and uncertainty risk.)

3.2.1.2 Fuel Price Volatility and Generating Costs

Issue: Natural gas prices have experienced significant historical volatility since the deregulation of gas prices in the late 1980s. This has been attributed to a number of factors, including higher levels of short-term purchasing, financial trading activity, large variations in seasonal demand, cross-sectoral demand interactions, and the diversity of market participants.[68] Gas price volatility translates to significant generating cost variance for natural gas plants.

There is much debate over the future level of gas price volatility, especially given the numerous potentialities of natural gas across sectors (e.g., export of LNG and use as transportation fuel). While recent near- to mid-term projections indicate a range of $4–$8/MMBtu out to 2035 (depending on supply and demand as well as economic growth),[69] price variability adds additional risk to future costs.

Complementarity: Like cost minimization, long-term cost certainty also has important economic value to an electricity portfolio.[70] Renewable energy technologies, such as wind and solar, have zero fuel costs and relatively fixed generating costs when adequately geographically distributed.[71] This cost stability reduces the variance of expected future costs, reducing overall portfolio risks.[72,n]

3.2.1.3 Renewable Portfolio Standards

Issue: Twenty-nine states and Washington, D.C., currently have mandatory RPS programs in place, while eight more have voluntary goals. The requirements vary widely but most rise to a

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[n] For a quantitative analysis of the value of reducing fuel price risk within a resource portfolio, see Bolinger, M.; Wiser, R.; Golove, W. (2002). *Quantifying the Value that Wind Power Provides as a Hedge against Volatile Natural Gas Prices*. LBNL-50484. Berkeley, CA: Lawrence Berkeley National Laboratory.

target percentage by 2020–2030. Some targets are fairly minor but others, like California's 33% renewables by 2020, represent substantial deployment of renewable energy generation.[o]

Stakeholders operating within state or utility RPS requirements with predominantly natural gas capacity may find themselves subject to compliance costs if renewable targets cannot be met, particularly if jurisdictions increase or advance their RPS targets down the road, a not unlikely possibility. Overinvestment in natural gas and underinvestment in renewables now could potentially impact future compliance.

Complementarity: Renewable energy projects eligible to meet RPS requirements are not subject to future cost uncertainty, as with little or no fuel costs and typically long-term power purchase agreements. Renewable generation may acquire additional revenue streams through the sale of renewable energy certificates (RECs) or similar monetization of environmental benefits.

The modularity of some renewable energy technologies (kilowatts to hundreds of megawatts) also provides valuable flexibility to deployment timelines of new capacity and can incrementally hedge risks from future policy uncertainty.[73] Natural gas investments, on the other hand, tend to be in larger increments (e.g., 500 MW and more) of new capacity.

3.2.1.4 Federal Environmental Regulations

Issue: Within the past three years, a number of EPA emission regulations affecting power plants, including carbon dioxide emission-limiting New Source Performance Standards (NSPS), the Cross-State Air Pollution Rule (CSAPR), and the Mercury and Air Toxics Standards (MATS),[p] have been proposed or finalized. While litigation and judicial review have delayed implementation and prompted reconsideration of several rules in recent months,[q] the broad industry expectation of these environmental regulations have accelerated the scheduled retirement of aging coal plants[74] and reinforced the belief that no new coal plants will be built in the future unless their emissions can be reduced by carbon capture and sequestration, an as yet unproven and costly technology.

Today's highly efficient natural gas plant technology easily meets the environmental standards proposed by these regulations and thus have been the predominant generation replacement choice. This has provided substantial short-term opportunities to reduce the country's carbon dioxide and other criteria pollutant emissions without additional cost or policies.[75] However, the emissions reduction benefit of natural gas will eventually plateau as long-term emission thresholds become increasingly stringent. Tightening emission regulations and the possibility of future low-carbon policies during the 30+-year lifespan of natural gas plants are an area of considerable uncertainty and, subsequently, additional latter-period profitability risk.

Complementarity: In the near-term, the environmental benefit of both natural gas and renewable energy compared to the current generation mix provides a common platform from which to

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[o] For more details on state RPS programs, see the Database of State Incentives for Renewables & Efficiency (www.dsireusa.org).

[p] The NSPS rules would only apply to new power plants, whereas CSAPR and MATS would apply to both new and existing power plants.

[q] CSAPR was rejected by the U.S. Court of Appeals for the District of Columbia in August 2012. The prior Clean Air Interstate Rule (CAIR) will remain in place while EPA reviews the court's decision.

garner support for both options.[76] In the long-term, renewable energy investments will not be subject to future cost risk of environmental compliance measures and instead may find additional revenue streams from their environmental benefits should low-carbon policies be implemented.

3.2.2 Renewable Energy Issues

3.2.2.1 Cost-Competitiveness

Issue: After natural gas, wind has been the second-largest contributor of new capacity, with particularly strong growth in the past five years.[77] However, only the most favorable wind sites, coupled with supportive state and federal policies, can compete with natural gas on a purely levelized cost basis.[r] Less favorable wind sites, solar, and other renewable energy technologies remain costlier or selectively competitive until continued learning curve efficiency gains and cost reductions are made. Relative inexperience and difficulties with siting and permitting also add costs. The limited cost-competitiveness of renewable energy technologies in the near-term deters greater levels of deployment. In addition, the relatively high capital cost of renewable projects could risk being deemed imprudent by regulators evaluating from a least-cost perspective and insufficiently valuing the mitigation of long-term operating cost variability.

Complementarity: Natural gas plants have low upfront costs, with fuel costs and associated price risks largely passed on to consumers (when deemed prudent by regulators) in well-established fuel adjustment clauses (FAC) and purchased gas adjustment (PGA) mechanisms.[s] Low natural gas prices lower overall levelized costs of energy and will continue to do so in the short term.

3.2.2.2 Uncertain State and Federal Incentives

Issue: The recent surge in new wind capacity has resulted from a package of supportive policies and incentives, including the federal production tax credit (PTC), investment tax credit (ITC), the Recovery Act's Section 1603 Treasury grant program,[t] state RPS programs, and decreasing technology costs.

The PTC, in particular, has been instrumental in driving record year-on-year increases in new wind capacity but is set to expire at the end of this year. The impending expiration has already had effects on the industry with virtually no new wind turbine orders for delivery in 2013.[78] Continued growth of wind capacity and the nascent U.S. wind manufacturing industry will depend on continued policy support until cost-competiveness is attained. In August 2012, the Senate Finance Committee approved a temporary tax extender package that extends the PTC and ITC for one year; however, final congressional action remains to be taken. In the meantime, this continuing policy uncertainty affects the industry's ability to make long-term investments and secure favorable financing.

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[r] The levelized cost of energy methodology is a simple and useful tool for comparing various energy options; however, it can be misleading in its inability to incorporate important factors that cannot be easily quantified.

[s] While regulatory prudence reviews provide a mechanism to engender responsible fuel supply procurement, they do not completely remove the asymmetry of risk burdens between utilities and consumers that FACs and PGAs create.

[t] For an outlook of U.S. renewable energy financing in 2012, see Sharif, D.; Grace, A.; Di Capua, M. (2011). "The Return – and Returns – of Tax Equity for U.S. Renewable Projects." Commissioned by the Reznick Group. New York, NY: Bloomberg New Energy Finance. Additional literature on renewable energy financing can be found at http://financere.nrel.gov/finance/publications.

Several state legislatures have proposed bills to repeal or shrink state RPS programs within the last couple years. While these efforts have largely been symbolic with little traction,[79] future challenges to RPS programs could arise and similarly impair renewable energy industry development.

Complementarity: Given its long history of government support[u] and the established state of the fossil-based economy, natural gas plants do not require major new policy or incentive supports to achieve cost-competitiveness. Long-term investments in natural gas plants do not hinge upon the continuing renewal of local or federal incentives (however, as discussed above, environmental policies introduce significant policy-related investment risks).

3.2.2.3 Resource Variability and Dispatchability

Issue: While variable renewable generation, such as wind and solar without energy storage, do not incur fuel supply risks in the way that conventional power plants do, they do experience dynamic resource variability along the minute-to-minute, hour-by-hour, and longer timescales. From the utility and regulator reliability planning perspective, wind and solar only provide low capacity value, which decreases with increasing penetration on the system.[80] This capacity can only be dispatched within the limits of resource availability.

Complementarity: Natural gas can be dispatched flexibly, which offers more capacity for system reliability. The quick ramping ability of natural gas generators makes them ideal for complementing variable renewable generation. This flexibility may generate additional value as new ancillary service products are designed to accommodate increasing levels of variable generation on the grid (see next section on collaborative market re-design) and new regional capacity or other ancillary services markets are developed to meet future reliability needs. A balanced electricity portfolio of both natural gas and renewable energy assets can adjust generation shares based on continuous optimization of resource availability, fuel costs, and emission requirements.

3.2.2.4 Transmission Planning and Costs

Issue: Large investments in transmission will be required to harness areas with the greatest renewable energy potential, such as the high wind potential central regions of the United States, which are mostly far from load centers. Despite widespread acknowledgment of the general need for an expanded and more reliable U.S. electricity grid, even without large amounts of variable renewable energy generation, transmission remains a contentious issue with slow-moving progress on resolving planning, permitting, and cost allocation concerns.

Complementarity: Notable overlaps between natural gas production regions and high wind energy potential regions suggest the possibility of new transmission projects jointly proposed and supported by new wind and natural gas projects to be sited close to each other. This pooling of efforts can accelerate implementation of proposed transmission investments and can also help ensure that new transmission is planned to optimize both natural gas and renewable energy assets.

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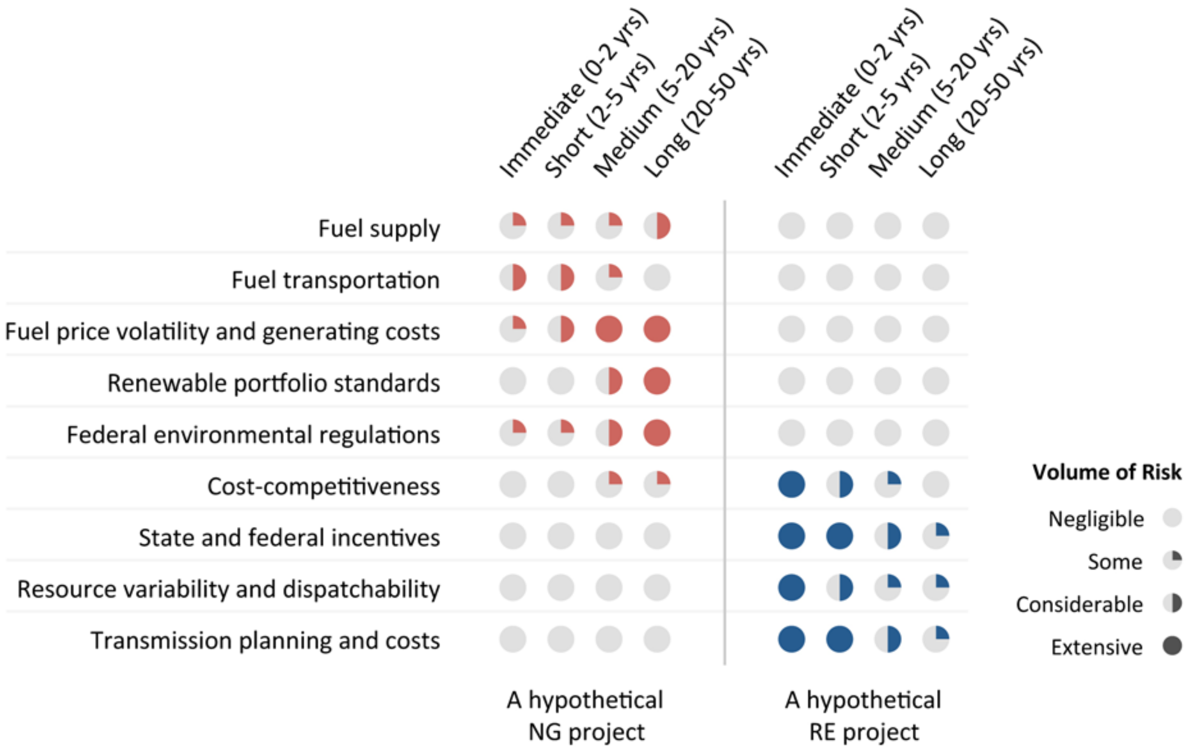
[u] Domestic oil and gas industries have received tax incentives since the early 1900s and continue to today. For a historical review of U.S. energy tax policies, see Sherlock, M.F. (2011). *Energy Tax Policy: Historical Perspectives on and Current Status of Energy Tax Expenditures*. Washington, DC: Congressional Research Service.

3.2.3 Temporal Framework

Because the occurrence of risks along an investment's lifetime varies significantly by issue and technology, it is also important to consider these risks within a temporal framework. Figure 9 provides a generalized illustrative assessment of the magnitude and timescale of the major issues discussed. A more rigorous quantitative application of this framework in the analysis of specific power project options could help inform stakeholder investment decisions.



	A hypothetical NG project				A hypothetical RE project			
	Immediate (0-2 yrs)	Short (2-5 yrs)	Medium (5-20 yrs)	Long (20-50 yrs)	Immediate (0-2 yrs)	Short (2-5 yrs)	Medium (5-20 yrs)	Long (20-50 yrs)
Fuel supply	◔	◔	◔	◑	○	○	○	○
Fuel transportation	◑	◑	◔	○	○	○	○	○
Fuel price volatility and generating costs	◔	◑	●	●	○	○	○	○
Renewable portfolio standards	○	○	◑	●	○	○	○	○
Federal environmental regulations	◔	◔	◑	●	○	○	○	○
Cost-competitiveness	○	○	◔	◔	●	◑	◔	○
State and federal incentives	○	○	○	○	●	●	◑	◔
Resource variability and dispatchability	○	○	○	○	●	◑	◔	◔
Transmission planning and costs	○	○	○	○	●	●	◑	◔

Volume of Risk

Negligible	○
Some	◔
Considerable	◑
Extensive	●

Figure 9. Illustrative framework for evaluating investment options by risk source, magnitude, and timescale[81]

3.3 Collaborative Market Re-Design

Rapidly changing energy industry paradigms and deeper experience with new technologies have evoked a need for re-designed market structures and business practices suited to current needs. Much has changed within the last decade to make historical practices maladapted to today's need for highly flexible operations and expected future growth trajectories.

Shale gas has brought unprecedented changes to the gas industry, prompting increased efforts by regulators and stakeholders to foster efficient market-based gas operations. In August 2012, FERC hosted five regional conferences on gas-electric coordination to better understand the issues faced by gas and electricity stakeholders and how they might help address these issues through new regulations or recommendations.

The growth of variable renewable energy generation in regional electricity networks has led to a flurry of novel industry and regulatory approaches to handling higher levels of variable generation. The experience of these approaches, some successful and some not, and the subsequent analyses of their results have brought to light areas of operational and market inefficiencies. They have also produced a variety of recommended technical, structural, and economic solutions to improve the assimilation of variable generation at lowest cost with market efficiency.[v]

The section below highlights six major market design issues facing natural gas and renewable energy electricity generators:

1. **Harmonization of day-ahead natural gas and electricity scheduling logistics.** Significant misalignments exist in the scheduling and procurement of day-ahead and intra-day natural gas and electricity generation.[82] In several electricity regions, natural gas generators need to procure gas supplies before receiving electricity schedules from electricity system operators, resulting in excess fuel supply risks. Optimization of electricity and gas scheduling timelines can minimize the existing inefficiencies across the two markets and reduce system and operating costs.
2. **Flexible natural gas pipeline service options.** Pipeline transportation service options were originally developed to meet the needs of historical gas purchasers, mainly gas utilities [i.e., local distribution companies (LDC)].[83] These options were not well-suited to the fluctuating and less predictable supply requirements of gas electricity generators. Gas generators today rely on a mix of firm and interruptible pipeline service, third-party delivery service, and daily released pipeline capacity from LDCs.[84] While this patchwork approach has functioned reasonably well so far, the recent upsurge in gas generation has exposed greater electricity reliability concerns caused by gas pipeline constraints and relying on interruptible service.[85] Incidents of gas curtailments to electricity generators, such as the occurrence in New England in January 2004 due to unusually cold weather,[86] are evidence of this growing challenge. New pipeline service options, particularly for flexible and short-term firm capacity, and improved rules for more efficient and real-time pipeline capacity release may be needed to meet gas generators' highly dynamic needs and ensure adequate levels of electricity reliability.[87] Currently, some pipeline operators provide customized service options to meet specific generator needs[88]; however, the lack of standardization and illiquidity of flexible pipeline services may create inefficiencies and additional costs to procurement of pipeline capacity.
3. **Implementation of natural gas pipeline expansion and local gas storage facilities.** The growing use of gas for electricity has also created the need for more pipeline capacity. However, pipeline operators have historically relied on long-term (20-year) fixed supply contracts with gas purchasers to demonstrate project necessity to regulators and acquire the revenue certainty needed to finance the large investments required for new pipelines.[89] Natural gas electricity generators, who comprise a growing portion of pipeline demand but rely on highly dynamic regional electricity markets[w] to determine when and at what price they will be dispatched, are unwilling to sign long-term fixed supply contracts.[90] In turn, pipeline operators are unable to undertake the pipeline

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[v] For an in-depth discussion of operational and institutional challenges of integrating high levels of renewable energy, see Milligan, M.; Ela, E.; Hein, J.; Schneider, T.; Brinkman, G.; Denholm, P. (2012). *Exploration of High-Penetration Renewable Electricity Futures. Vol. 4 of Renewable Electricity Futures Study*. NREL/TP-6A20-52409-4. Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/analysis/re_futures/

[w] In areas operated by RTOs and ISOs.

capacity expansions needed to maintain service reliability. This has largely been the result of regulatory requirements on cost recovery that were developed for the prior industry paradigm of LDCs as the primary type of gas customer.[91] Therefore, new regulatory frameworks and methods of contracting and initiating pipeline expansion projects may need to be developed. Additionally, fair and reasonable allocation of infrastructure expansion costs across pipeline customer groups needs to be determined.[92]

4. **Valuation of flexibility.** The economic value of generator flexibility in existing electricity markets has largely derived from the ability of these generators to meet historical needs for flexibility, primarily to cover fairly predictable daily load profiles and contingency events and meet system reliability standards. The ability of existing generators to provide the flexibility required by variable renewable generation is inadequately valued by current market structures and products. For example, natural gas combined cycle (CC) and combustion turbine (CT) plants provide varying degrees of ramping flexibility to accommodate fluctuations in net load,[93] and both are more flexible with lower cycling costs than coal plants.[94] Several arenas in which this type of flexibility could be more explicitly valued include: ancillary service markets with the creation of a new category of "flexibility" reserves,[95] newly developing regional capacity markets whose aims are to incentivize new capacity to meet future demand,[96] reliability planning models to differentiate the capabilities of existing flexible and inflexible resources,[x] and the ongoing endeavor to accurately value energy storage technologies.[97]
5. **Electricity dispatch timing.** Regional electricity markets with hourly dispatch schedules are unable to utilize lower-cost flexible generators *within each hour* to meet large but relatively slow ramping needs arising from fluctuations in variable generation.[98] Instead, all within-hour ramping is met primarily by expensive regulation reserves, which were meant to stabilize much smaller rapid fluctuations in generation and frequency. This results in inefficiently higher integration costs. Sub-hourly (5- to 15-minute) economic dispatch has been shown to allow existing lower-cost resources to meet a greater portion of the ramping needs caused by variable generation, minimizing the use of expensive regulation reserves for that purpose.[y] Regions that currently use hourly dispatch schedules, such as the Western region[z] (excluding California) and Southeast region of the United States, can improve their ability to cost-effectively integrate variable generation by moving toward faster dispatch schedules.

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[x] For example, the flexibility of natural gas capacity compared to coal or nuclear capacity is not reflected in energy reliability models used by the Midwest Independent System Operator (MISO) [*Technical Conference on Coordination between Natural Gas and Electricity Markets for the Central Region*; August 6, 2012, St. Louis, Missouri. Federal Energy Regulatory Commission (FERC)].

[y] Analysis of sub-hourly market data has shown that price signals from sub-hourly electricity markets provide generation to meet sub-hourly fluctuation at little to no extra cost compared to hourly prices. While sub-hourly prices may fluctuate greatly, on average the price is very close to the hourly energy price. This analysis suggests that this type of load-following generation response can be acquired at little cost using existing resources (Milligan, M.; Kirby, B.; Beuning, S. *Potential Reductions in Variability with Alternative Approaches to Balancing Area Cooperation with High Penetrations of Variable Generation*. NREL/MP-550-48427. Golden, CO: National Renewable Energy Laboratory, 2010; 78 pp.).

[z] For an analysis of the operational feasibility of integrating 35% wind and solar in the Western region, see NREL. (2012). *Western Wind and Solar Integration Study*. NREL/SR-550-47434. Work performed by GE Energy, Schenectady, NY. Golden, CO: National Renewable Energy Laboratory.

6. **Balancing electricity generation and load over larger geographic areas.** The intra-day, intra-hour variability and uncertainty of variable renewable generation as well as load are reduced when consolidated over larger geographic areas.[99] This results in smaller overall fluctuations in demand and supply, which reduces the need for relatively expensive operating reserves to smooth these fluctuations. This decreases variable generation integration and load balancing costs. A variety of physical and virtual methods of consolidating balancing areas have been analyzed.[100] Regions with small balancing areas can reduce normal load balancing costs as well as better integrate variable generation through pooling mechanisms with neighboring balancing areas, assuming adequate transmission capacity.

Clearly, significant changes to gas and electricity markets and operations can help the energy industry adapt to the twin drivers of shale gas and renewable energy. Many of the changes needed in the electricity market have implications for both natural gas and renewable energy generators along with other electric power stakeholders: The drive to more accurately value flexibility across electricity institutions will directly benefit natural gas generators, while movements to co-optimize gas and electricity markets will have operational impacts on renewable energy generators. Therefore, proactive engagement among the gas and renewable energy industries and other electric power stakeholders to collaboratively resolve the diverse set of issues described above can enable the efficient technical, economic, and environmental utilization of both natural gas and renewable energy in the near, medium, and long term.

3.4 Concluding Remarks

Natural gas and renewable energy technologies offer very different and complementary attributes to consider within a portfolio and integrated systems approaches. These complementarities span the economic, technical, environmental, and institutional. The long-term evolution and structure of the electricity sector depends on the multilayered and compounded uncertainties present within the range of possible industry developments and energy pathways. Further understanding and quantitative analysis of the ability of a diverse electricity portfolio to maximize the benefits and minimize the risks of each portfolio option can help inform stakeholder decisions and allow the development of a solid foundation from which to handle uncertain futures.

The dramatic rise of shale gas and growing experience with renewable energy integration have led to deep and still-evolving changes to market structures, physical systems, business practices, and regulatory policies. Both natural gas and renewable energy may play important future roles in the electric power sector. In this critical period of industry adaptation to new energy paradigms, active engagement and partnership between the natural gas and renewable energy sectors can lead to efficient well-designed electricity markets better situated to achieving the long-term energy goals of energy security and climate change mitigation.

4 U.S. Transportation Sector

Renewable and natural gas fuels have significant potential to reduce petroleum dependence and emissions in the transportation sector.[aa] Yet, to date, they have had limited market penetration. The following section seeks to illuminate various alternative transportation fuel pathways, and serve as a primer for discussion on transportation energy futures.

4.1 Petroleum Lock-In

Historically, petroleum products in the form of motor gasoline and distillate fuel oil (diesel) have dominated the U.S. transportation sector. Table 2 shows fuel usage by select on-road transportation modes for the year 2010. Petroleum products made up approximately 92% of sector-wide energy usage in 2010 and dominated all modes of ground transportation considered in this report.[101]

Table 2. 2010 U.S. Transportation Sector On-Road Fuel Usage (Energy Basis) by Mode

		Petroleum			Non-Petroleum				
	Share of Total Sector Energy Use	Gasoline[bb]	Diesel	Petroleum Total[cc]	Electricity	Natural Gas	Blended Ethanol[dd]	Biodiesel[ee]	Non-Petroleum Total
All Uses	100%[a]	57.0%	20.1%	92.3%[b]	0.1%	2.5%[c]	4.3%	0.9%	7.7%
Light-Duty Vehicles	58.2%	92.5%	0.3%	92.9%	0.002%	0.1%	7.0%	0.01%	7.1%
Commercial Light Trucks	2.0%	56.8%	37.4%	94.2%	0.0%	0.0%	4.3%	1.5%	5.8%
Freight Trucks	17.5%	6.8%	88.5%	95.7%	0.0%	0.2%	0.5%	3.6%	4.3%
Buses (all types)	0.9%	8.9%	83.5%	92.5%	0.0%	3.4%	0.7%	3.4%	7.5%

[a] Other transportation uses such as rail, aviation, shipping, and military use are not shown.

[b] This percentage also includes jet fuel, residential fuel oil, aviation gasoline, liquefied petroleum gases, and lubricants.

[c] Only 0.1% is from compressed or liquefied natural gas for transportation fuel, with the remaining 2.4% used for pipeline fuel natural gas.

The oil industry has evolved to serve the vast needs of the United States and the world and has generally demonstrated the ability to meet market demand and respond to price signals. The question remains, however, what will the cost of oil be? Dependence on petroleum has serious implications for economic growth, energy security, climate change, and as a result, foreign policy. In the context of increasingly globalizing energy markets, U.S. energy security can be enhanced by minimizing exposure to fuel price volatility and reducing risk of abrupt supply

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[aa] Transportation accounts for 71% of U.S. petroleum use and 33% of GHG emissions.

[bb] Assumes 95% of all gallons of gasoline consumed in the United States are blended with ethanol at an E10 (10% by volume) level. Assumes energy density of pure gasoline is 114,000 Btu/gal, and energy density of pure ethanol is 81,800 Btu/gal (*2012 Ethanol Industry Outlook.* Renewable Fuels Association, 2012. Accessed August 30, 2012: http://ethanolrfa.3c dn.net/d4ad995ffb7ae8fbfe_1vm62ypzd.pdf).

[cc] Includes liquefied petroleum gases, not shown in the table.

[dd] Assumes ethanol is blended with 95% of consumed motor gasoline gallons at an E10 level. Includes EIA estimates of E85 usage as well.

[ee] Assuming 2 billion gallons of pure biodiesel was produced with an energy density of 118,300 Btu/gallon.

disruptions. This can be accomplished by fostering diversity among which fuel types are able to be utilized, and where they are sourced from. While domestic shale oil production has increased in recent years to provide an added diversity, the capability of the transportation sector to more flexibly utilize alternative sources of fuel would provide another type of hedge against volatility. Increasing penetrations of biofuels and plug-in electric vehicles will likely contribute to accomplishing this. Abundant low-cost natural gas also presents opportunities to do so.

4.2 Alternative Transportation Options

This section will review the following alternative transportation options:

- Ethanol
- Alternative blended fuels
- Drop-in biofuels
- Plug-in electric and plug-in hybrid electric vehicles
- Hydrogen-fueled vehicles
- Natural gas vehicles.

4.2.1 Ethanol

Among renewable fuels, corn starch ethanol has had the highest penetration in the transportation sector, due to blending tax credits, import tariffs, and the Renewable Fuel Standard (RFS) (see Section 4.3.2). More than 95% of the 134 billion gallons of gasoline consumed in the United States in 2011 were blended with ethanol, typically at the E10 (10% ethanol) level.[ff],[102] E10 can be used with existing vehicle engines and gasoline distribution infrastructure, and certain vehicles can safely accommodate higher blends such as E15. Because E10 and E15 blends are currently upper bounds for most vehicles, there is a limited amount of market penetration ethanol can have without changes to fleet mix and distribution infrastructure. The 8 million flex-fuel vehicles in the United States can operate on gasoline with blends of up to 85% ethanol (E85),[103] though infrastructure to distribute blends above E10 is limited.[104] In general, pro-ethanol policies face controversy, with critics saying subsidies are too costly, unfair, or unnecessary[gg] and supporters claiming improved energy security, lower greenhouse gas (GHG) emissions, and increased rural incomes and employment.[105]

Natural gas is a common input to both corn and ethanol production processes and, as a result, their prices depend in part on the price of natural gas. Corn is typically grown using fertilizer, and natural gas is a key feedstock to producing fertilizer; in fact, it accounts for up to 90% of total fertilizer production costs.[106] It is often used to produce heat for a number of process steps necessary to convert corn to ethanol.

Cellulosic ethanol can be derived from a range of abundant biomass resources, mitigating many of the potential macroeconomic and environmental consequences associated with corn ethanol.

[ff] Due to its lower energy density, ethanol-blended gasoline results in lower fuel economy.

[gg] Some have argued that the ethanol industry would have been profitable far earlier than 2011 without subsidization, some claiming as early as 2006 (Hurt, C; Tyner, W.; Doering, O. *Economics of Ethanol.* Purdue University, 2006. Accessed August 30, 2012).

Its production is currently more expensive than corn ethanol, even with a $1.01/gal subsidy (set to expire at the end of 2012); however, it has lower lifecycle GHG emissions.[hh] The EPA reduced early year production mandates (2010–2012) from the RFS for cellulose-derived biofuels due to a lack of production; many technological and economic hurdles still exist for these biofuels.[107]

4.2.2 Alternative Blended Fuels

A variety of fuels are being developed that require petroleum blending and/or changes to infrastructure to be widely utilized; these fuels are most economically produced using hydrocarbon feedstocks but can also be sourced renewably. *Biodiesel*, produced by converting food oils and fats, can be blended at up to 20% with petroleum diesel in newer engines without any required engine modifications;[108] the United States currently produces approximately 2 billion gallons per year; renewable biodiesel technologies are being actively pursued.[109] *Methano*l can be blended in manners similar to ethanol; if produced by conversion of hydrocarbons like natural gas or coal, it has very low production costs.[110] *Butanol* is another alternative that blends well with gasoline and ethanol; it is produced most economically from natural gas but can also be sourced renewably.[111] *Dimethyl ether* (DME) is a potential alternative to diesel fuel; it can be produced from cellulosic and hydrocarbon feedstocks and has significant emissions advantages over gasoline, even when sourced from hydrocarbon feedstocks.[112] In general, more research is needed to understand the impacts and implications of these fuels.[113]

4.2.3 Drop-In Biofuels

Drop-in biofuels are designed to be consumed alone or at high levels of gasoline blending without any changes to engines. Many potential pathways are being explored, including conversion of renewable synthesis gas, sugars, and algal oils, though none have been economically demonstrated in the United States. Federally funded research efforts are focused on drop-in biofuels intended to replace aviation and trucking fuels because electrification is not feasible for those applications.[114]

4.2.4 Plug-In Electric and Plug-In Hybrid-Electric Vehicles

Plug-in electric vehicles (PEV) and plug-in hybrid electric vehicles (PHEV) are becoming technically and economically viable options for light duty transport. In recent years, vehicle electrification efforts have enjoyed significant federal support. The Obama administration has called for 1 million electric vehicles to be on the road by 2015 and has provided extensive tax credits and stimulus grants to help accomplish that goal. The most significant impediments to market penetration are the cost, limited range, and long recharge times of battery technology.[115]

Advanced battery technology, manufacturing techniques, and supply chains are still in their infancy. As a result, upfront costs for these vehicles are quite high, with the cost being largely attributable to the cost of the battery packs. While battery cost data is confidential, Ford Motor Company's CEO Alan Mulally was recently quoted to have said battery packs for the PEV Ford Focus Electric cost "around $12,000 to $15,000," or 30%–38% of the retail price of the $39,200 vehicle.[116] Fuel costs, on the other hand, are significantly lower for electric vehicles than gasoline vehicles.

[hh] The RFS mandates that qualifying cellulosic ethanol must reduce life cycle GHG emissions by at least 60% relative to gasoline.

Table 3. Vehicle Prices, Fuel Costs, and Ranges for Four Light Duty Vehicles[117]

	2012 Chevrolet Malibu	**2012 Chevrolet Volt**	**2012 Ford Focus Sedan**	**2012 Ford Focus Electric**
Technology Type	Gasoline Engine	PHEV	Gasoline Engine	PEV
Net Retail Price [$][a]	$21,995	$31,645	$16,500	$31,700
Annual Fuel Costs [$][b]	$1,591	$573	$1,391	$435
Vehicle Range [miles]	432	35/344[118]	384	76

[a] Price after available federal tax credits. State and local tax credits may be available.

[b] Assuming 12,000 miles per year (50% highway driving), gasoline costs at $3.50 per gallon, and electricity purchases made in the Denver metropolitan area.

PEV batteries typically take several hours to recharge using a 120 V or 240 V outlet. Charging often takes place overnight so vehicles have enough stored energy to complete a morning commute. Under residential time-of-use rate plans available in certain regions, nighttime electricity is available at a lower rate than daytime electricity, further increasing the potential fuel cost savings for vehicle owners. Overnight charging also offers a synergy with wind power in many areas of the country; wind generally has higher outputs overnight and can be curtailed due to a lack of load if there is high wind penetration. Widespread overnight charging of electric vehicle batteries could help to reduce wind curtailments and create more revenue for wind turbine operators.[119]

The emissions benefits of electric vehicles vary depending on the generation mix of electricity used to power it, as well as the amount of gasoline fuel used (if a PHEV). A recent study estimates that the emissions rate for a battery-powered vehicle can vary by more than a factor of three, depending on the location of charge. The range of carbon intensity of electricity in the country corresponds to carbon emissions rates on par with gasoline fuel efficiencies between 31 and 115 miles per gallon (MPG), respectively. This results in emissions reductions between 11% and 75% relative to a 27-MPG car.[120] As power-sector emissions are reduced due to fuel-switching from coal to natural gas, the average emissions benefits of electrified vehicles will increase.

4.2.5 Hydrogen-Fueled Vehicles

Hydrogen is currently being explored for applications in light-duty passenger vehicles, via direct/blended combustion in internal combustion engines (ICE) and in fuel cells. Either pathway emits only water vapor as a byproduct, reducing emissions of GHGs, criteria pollutants, and hazardous air pollutants. Also, it can be produced from a wide variety of domestic energy resources, reducing dependence on foreign oil and increasing energy security in the transportation sector.

Natural gas–hydrogen blends such as Hythane™ (20% H_2 by volume) or "HCNG" (30% H_2 by volume) can meet strict emissions standards in bi-fuel vehicles while avoiding the need to use expensive catalytic converters to reduce nitrogen oxides and carbon monoxide. A lack of commercially available bi-fuel approved vehicles, large infrastructure costs, and short vehicle ranges will be significant barriers to market penetration. There are not currently any commercially available vehicles that utilize this fuel type; only demonstration fleets exist.[121] Using natural gas or mixed blend fuels may serve as a technological and commercial stepping stone to a hydrogen future, as certain features of hydrogen and natural gas distribution are similar, including refueling technology, fuel storage, station siting, and the training of technicians and vehicle operators.[122]

Because of their extremely high energy efficiencies and low emissions, fuel cell electric vehicles (FCEV) are undergoing extensive research and development efforts. In an FCEV, hydrogen is used to create electricity for a high efficiency electric motor. The hydrogen can either be stored on board the vehicle in a manner similar to liquefied or compressed natural gas, or a feedstock such as natural gas or ethanol can be converted on-board via fuel processors.[123] Hydrogen has significantly lower energy density than traditional petroleum products, so the storage weight, space, and safety issues associated with hydrogen fuel are similar to that of CNG and LNG.

While the potential benefits of FCEVs are significant, so are the barriers to market penetration. As with other vehicle technologies in their infancy, FCEVs are expected to be quite expensive. Hyundai plans to manufacture 1,000 FCEVs in 2013 for a sticker price of $88,550 and aims to sell them for under $50,000 by 2015.[124] With expensive price tags and limited availability of vehicles and refueling infrastructure, FCEVs will have many hurdles to overcome.

4.2.6 Natural Gas Vehicles

Of the over 250 million vehicles in the United States,[125] an estimated 120,000 (0.05%) were fueled by direct combustion of natural gas in 2011.[126] The United States ranks 17th in the world for total number of NGVs in its vehicle fleet and 39th on a per capita basis.[127] NGVs have higher upfront costs and lower fuel costs and emissions than their petroleum-fueled counterparts. Natural gas fuels have lower energy densities than petroleum fuels and are stored in tanks that take up more space and weight than traditional fuel tanks, resulting in lower vehicle ranges. Alternative fuel storage methods, including low-pressure solid matrix adsorption and novel storage locations (e.g., inside door panels) are being explored to address range issues. Currently, NGVs lack the refueling infrastructure required for large-scale consumer adoption. Growth in infrastructure investments and consumer adoption are inter-dependent, posing a “chicken-or-egg” problem that plagues many new vehicle technologies. Bi-fuel natural gas–gasoline vehicles may help to serve as bridge technology toward wider NGV adoption.

The majority of NGVs in the United States are powered using CNG. As of mid-2012, there were 1,065 CNG fueling stations in the United States, about half of which are open to the public.[128] Private and municipal fleets often rely on their own private fueling stations. Home refueling is also an option for CNG vehicles,[ii] which may help to alleviate consumer concerns over the lack of ubiquitous CNG refueling stations. However, current technology requires 5–8 hours for in-

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[ii] As of 2001, 63% of U.S. households used natural gas and could presumably use in-home refueling equipment (Werpy, M.R.; Santini, D.; Burnham, A.; Mintz, M. “White Paper on Natural Gas Vehicles: Status, Barriers and Opportunities.” Clean Cities Program, U.S. Department of Energy, 2009. Accessed August 30, 2012: http://www1.eere.energy.gov/cleancities/pdfs/clean_cities_workshop_natural_gas.pdf).

home refueling and costs upwards of $4,500 to purchase and install, though some companies are attempting to bring this cost down to $500.[jj]

There are approximately 3,200 LNG vehicles on the road today in the United States, utilizing 54 fueling stations, about half of which are public. Many of these vehicles are long-haul, heavy duty freight trucks with longer ranges than CNG vehicles but still shorter than diesel-fueled freight trucks. High mileage and low LNG gallon diesel-equivalent (GDE) costs can result in significant fuel cost savings over the lifetime of a freight truck. LNG suppliers typically offer long-term fuel price contracts, guaranteeing fuel costs for the lifetime of a truck (up to five years), regardless of LNG market price fluctuations. The process of conversion from natural gas to LNG removes water, carbon, and sulfur, resulting in fewer emissions upon combustion than CNG. However, from a life cycle standpoint, carbon emissions are slightly higher than CNG due to the energy intensive liquefaction process.[129] For both technologies, the utilization of biomethane from landfill gas or anaerobic digesters, as opposed to conventional natural gas, yields significant life cycle emissions reductions.[kk]

4.3 Relevant Transportation Policies

4.3.1 Fuel Economy Standards

The current Corporate Average Fuel Economy (CAFE) requirement for small to mid-size passenger vehicles is 36 MPG. The Obama administration recently came to an agreement with automakers to increase fuel efficiency to a fleet-wide average of 54.5 MPG for cars and light-duty trucks by 2025.[130] Carmakers use an air conditioner refrigerant leak reduction credit as a partial means of compliance, so the fleet-wide fuel efficiency target is closer to 49 MPG. On August 28, 2012, in an effort to promote and incentivize the penetration of certain "game-changing" vehicle technologies, the EPA and Department of Transportation released a ruling that grants electric, fuel cell, and CNG vehicle sales an increased CAFE compliance multiplier factor of 1.6–2 times their normal values in fleet-wide average fuel economy calculations for model years 2017 to 2022.[131]

4.3.2 Biofuel Production and Blending Incentives

Federal policies for biofuels include blending tax credits, import tariffs, minimum renewable fuel usage requirements, loan and loan guarantee programs, and research funding. The RFS has been particularly impactful, creating a guaranteed market for producers by requiring 36 billion gallons of renewable fuel to enter the national transportation fuel supply in the year 2022 with annual requirements ramping up to the target year. The requirement caps eligible corn-starch-based ethanol production at 15 billion gallons, leaving the remaining 21 billion gallons to be supplied by cellulosic biofuels, biomass-based biodiesel, and other advanced biofuels, with a minimum mandate for cellulosic biofuels of 16 billion gallons by 2022.[132]

[jj] General Electric Co. is utilizing an ARPA-E grant to develop in-home refueling equipment at a targeted cost of $500 ("Trucks Do It, Fleets Do It, Let's Pump Natural Gas." General Electric Reports. Accessed August 30, 2012: http://www.gereports.com/trucks-do-it-fleets-do-it-lets-pump-natural-gas/).

[kk] LNG and CNG vehicles using traditional natural gas have life cycle emissions reductions of 12% and 28%, respectively, compared to diesel. If landfill gas is used, reductions are estimated to be 77% and 88%, respectively ("Table 6: Carbon Intensity Lookup Table for Gasoline and Fuels that Substitute for Gasoline." California Air Resources Board, 2010. Accessed August 30, 2012: http://www.arb.ca.gov/fuels/lcfs/121409lcfs_lutables.pdf).

4.3.3 Battery Electric Vehicle Production Incentives

Government support for PHEVs and PEVs include tax credits (up to $7,500 per vehicle purchased), the federal loan guarantee program for battery and vehicle manufacturing facilities, and Recovery Act stimulus grants.[133] Depending on the location of purchase and intended use, local, regional, and state-level incentives may be available also.

4.3.4 Hydrogen Fuel Cell Vehicle Research Funding and Production Incentives

FCEVs receive R&D funding from the federal government. Areas of research include hydrogen production and delivery, storage, fuel cell technology, safety codes and standards, and advanced manufacturing techniques. Tax credits are available for hydrogen production and fuel blending, infrastructure projects, and FCEV purchases.[134]

4.3.5 Natural Gas Vehicles and Infrastructure Incentives

Federal support is currently quite limited, but the Obama administration has indicated its support for a tax credit to incentivize NGV purchases.[135] Local and state-level incentives do exist, many of which are quite substantial and include infrastructure grants, vehicle purchase rebates and tax credits, and loan programs.[136] At least 15 states currently authorize special tariffs for natural gas sold by LDCs as CNG transportation fuel. In a few of these states, LDCs are allowed to rate base and recover their capital costs for installing CNG fueling equipment.

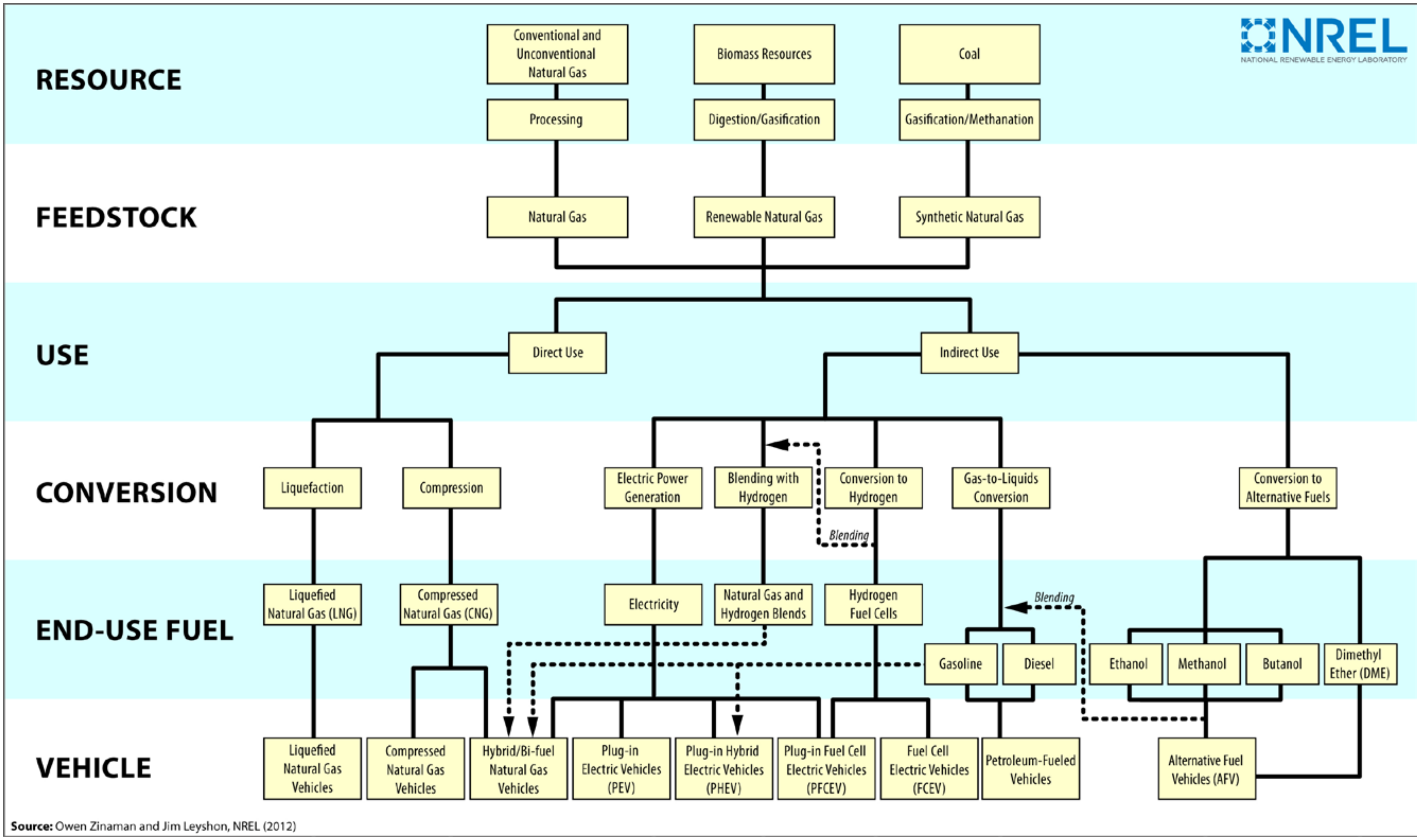
4.4 Natural Gas Pathways in the Transportation Sector

Abundant, low-cost natural gas presents opportunities to accelerate market penetration of not only CNG and LNG fuels, but also alternative fuels. The various potential pathways for utilization all have unique characteristics, barriers to deployment, and implications for the economy at large. Figure 10 is a simplified visual framework for the potential resources, pathways, and end-uses of natural gas in the transportation sector.

4.4.1 Direct Use

CNG or LNG can be burned directly in NGVs or in bi-fuel vehicles able to utilize both CNG and gasoline. In the realm of LDVs, the only commercially available dedicated natural gas car is the Honda Civic GX NG[ll]. However, many major car companies, including Ford and Chevrolet, are releasing pickup trucks with bi-fuel gasoline–CNG engines in their 2013 fleets.[137] These trucks are designed to use the inexpensive CNG first before using gasoline. While an incremental cost of $11,000 over its gasoline-only counterpart may deter consumers, the flexibility to use gasoline, the spread between CNG and gasoline costs, and the potential for inexpensive at-home refueling may shift the decision of some potential buyers. Increased adoption could lead to lower incremental costs due to gained economies of scale. Bi-fuel gasoline–natural gas vehicles may serve as a bridge technology to ease consumer adoption issues, encourage refueling infrastructure build out, and facilitate a larger penetration of light-duty NGVs.

[ll] Some light-duty NGV owners undergo aftermarket retrofitting.



Source: Owen Zinaman and Jim Leyshon, NREL (2012)

Figure 10. Natural gas pathways in the transportation sector

For medium and heavy duty fleets with predictable, periodic driving patterns, immediate opportunities exist for significant fuel cost savings if routes can utilize the existing, limited refueling infrastructure. If a natural gas vehicle uses sufficiently large quantities of fuel, fuel cost savings can accrue quickly enough that even a risk-averse investor may find a switch to natural gas attractive. Also, depending on the vehicle operator, construction of refueling infrastructure may be an economic option, using their own vehicles as an "anchor" fleet. Many organizations that invest in a natural gas refueling station do so with an anchor fleet in mind or even under contract in order to help ensure demand for their product beyond a less-certain demand from public use.

With LNG prices as low as $1.70 per GDE in April 2012,[138] the economics and operational feasibility of LNG for heavy-duty long-haul trucking are now quite favorable to fleet operators. New long-haul vehicles typically drive 100,000+ miles per year in their first few years; with diesel prices around $3.80 per gallon[139] (and expected to average around $3.91 per gallon for the next five years), significant cost savings can be accrued to pay back the added cost of the LNG truck, which can range between $40,000 and $75,000.[140] Heavy-duty LNG vehicles have ranges of approximately 400 miles and drive routes that are known to fleet operators and predictable to potential gas suppliers looking to enter the market, requiring a small number of strategically placed stations along shipping corridors.[141] Royal Dutch Shell and Clean Energy Fuels Inc. have recognized this as a potentially profitable opportunity and are in the process of constructing LNG and CNG fueling stations along major interstate trucking corridors. Both companies plan to offer long-term fuel contracts to truck fleets, shielding fleet operators from fluctuating market prices and guaranteeing fuel costs that are lower than diesel fuel costs[mm] for the lifetime of the truck, which can be up to five years.[142,143] Yet, even if stations are available, more frequent refueling is necessary due to lower ranges. This can be undesirable to fleet operators, as they prefer their drivers to travel a full shift before stopping to refuel. Also, the size of natural gas tanks can impinge on the driver's sleeping space or require other space compromises.

There are also immediate opportunities for certain medium and heavy-duty commercial fleets, such as transit buses[nn] or delivery/refuse trucks, to convert to natural gas fuels. In May 2012, Waste Management announced that 80% of its refuse truck purchases during the next five years will be fueled by natural gas, stating that its projected fuel savings will pay back the additional cost of the NGV in just over one year.[144] Like long-haul trucking, fuel risk can be mitigated by using financial instruments or securing long-term contracts with natural gas providers. Many operators have routes that are local, periodic, and already undergo some form of logistical planning. Strategically placed private refueling stations can be built and integrated into route planning to realize significant cost savings. Also, if these fleet operators already own sites that are used as logistical hubs and/or refueling stations, they would be natural locations for natural gas refueling infrastructure. Technology to compress, dry, and filter pipeline natural gas to create CNG on a small scale is inexpensive relative to LNG and is likely the more attractive immediate option to operators. However, small modular liquefaction facilities are in various stages of

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[mm] Shell guarantees that LNG fuel will be at least 30% cheaper than diesel for the lifetime of the truck.

[nn] There were an estimated 846,051 buses operating in the United States in 2010 ("Table 1-11: Number of U.S. Aircraft, Vehicles, Vessels, and Other Conveyances." Research and Innovative Technology Administration, U.S. Department of Transportation, 2012. Accessed August 30, 2012: http://www.bts.gov /publications/national_transportation_statistics/html/table_01_11.html).

development and could be placed closer to sale (e.g., a natural gas refueling station) to reduce LNG transportation costs.

The direct utilization of natural gas in certain applications may provide opportunities for significant fuel cost savings and help reduce dependence on petroleum products. Similar to the experience of oil companies in the early 1900s, natural gas producers may have to venture into downstream retail markets to help develop nascent markets for their product. The potential build-out of natural gas refueling infrastructure, even if only along trucking corridors, will help encourage wider NGV adoption and encourage the diversification of fuel usage in the transportation sector. Also, bi-fuel vehicles, which can use either natural gas or gasoline, may serve as a transitional technology by affording consumers more range and refueling flexibility while providing significant fuel cost savings when natural gas is available.

4.4.2 Indirect Use

4.4.2.1 Conversion to Hydrogen

Hydrogen can be produced from a variety of feedstocks, including natural gas. In a steam reforming process, natural gas and high temperature steam react to form a synthesis gas (also known as "syngas") consisting of carbon monoxide and hydrogen; the carbon monoxide is then further reacted with steam to produce additional hydrogen. Life cycle emissions for steam reforming can be reduced if thermal inputs come from low carbon sources[oo] or if renewable natural gas is used as a feedstock. Estimates of well-to-wheels (WTW) emissions and petroleum usage for mid-size FCEVs, as well as gasoline and natural gas vehicles, are shown in Table 4.

Table 4. Well-to-Wheels GHG Emissions and Petroleum Use for Various Vehicles and Fuels[145]

Vehicle/Fuel Source	WTW GHG Emissions [grams CO_2-equivalent/mile]
Gasoline Vehicle (34 MPG)	340
Natural Gas Vehicle (34 MPGe)	270
FCEV – Natural Gas H_2	200
FCEV – Biomass Gasification H_2	37
FCEV – Nuclear High Temperature or Low-carbon Electrolysis H_2	42

The estimated emissions and petroleum savings of FCEVs using hydrogen from natural gas are significant when compared to gasoline vehicles. Natural gas can serve as an economical feedstock for hydrogen fuel and may be able to serve as a bridge to meet hydrogen demand as the economics of water electrolysis technology improve, allowing for further emissions reductions.

4.4.2.2 Electricity Generation

Natural gas can be burned in a gas CT or CC facility to generate electricity. This electricity can then be sent across electrical transmission and distribution infrastructure, along with generation

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[oo] Concentrated solar power and advanced high temperature nuclear reactors are potential candidates to provide high-temperature steam and low-carbon electricity for both steam reforming and electrolysis production techniques.

from other sources, to be used in PEVs and PHEVs. Natural gas power is among the least expensive generation options, which helps to reduce fuel costs for electric vehicles. As mentioned in Part III, the highly dispatchable nature of natural gas generation allows for higher penetrations of renewable generation, which in the long term may help to lower the life cycle emissions of battery vehicles. Separately, natural gas electricity can be used to provide heat and electricity for hydrogen production via water electrolysis.

4.4.2.3 Gas-to-Liquids Conversion

The gas-to-liquids (GTL) process is a chemical conversion process that transforms hydrocarbons such as natural gas or gasified coal into syngas, and thereafter into hydrocarbon liquid fuels such as gasoline, diesel, naphtha, or jet fuel. The obvious advantage of this pathway is the ability to utilize the extensive, well-developed markets and distribution networks for petroleum products. GTL fuels are also essentially sulfur free and have much lower emissions of nitrogen, carbon monoxides, and particulate matter. Yet life cycle GHG emissions for petroleum products are estimated to be approximately 25% higher than conventional oil.[146] GTL can be used to monetize inexpensive "stranded" gas resources that would otherwise not be able to be taken to market.[147]

No single break-even point for crude oil and/or gas prices exist to make a GTL project profitable; production costs vary significantly based on the location and capital cost of the plant, project financing, and gas and crude oil prices.[148] High oil prices and low natural gas prices have shifted the outlook of this technology, and various commercial-scale projects are now underway.[pp] Yet uncertainty in oil and natural gas prices, as well as high upfront capital costs, make the technology a gamble that many companies may find too risky.

4.4.2.4 Conversion to Alcohols

Technology also exists to convert natural gas into alternative fuels, such as ethanol, methanol, or butanol. These fuels can then be blended into petroleum products or used in alternative fuel vehicles. Today, butanol, methanol, and DME are most economically produced from natural gas, though they can also come from a variety of renewable feedstocks. Should any of these become a more common transportation fuel, natural gas may be able to serve as a bridge feedstock to further increase market penetration while renewable production techniques improve and gain economies of scale.

4.5 Concluding Remarks

This section examined several pathways by which natural gas and renewables can contribute individually and jointly in fueling the transportation needs of Americans. While the barriers to market penetration can be significant, there are both immediate opportunities and long-term prospects for significantly reducing emissions and petroleum use in the transportation sector. Over the past decade, the blending of biofuels with petroleum has been a key pathway to

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[pp] Very few GTL facilities exist today. Royal Dutch Shell operates facilities in Qatar and Malaysia. The South African company Sasol operates a single facility in Qatar, with plans to build facilities in Uzbekistan, Canada, the United States Gulf Coast, and Nigeria ("Pearl GTL – An Overview." Royal Dutch Shell. Accessed August 30, 2012: http://www.shell.com/home/content/aboutshell/our_strategy/major_projects_2/pearl/overview/; "GTL Projects." Sasol Corporation. Accessed August 30, 2012: http://www.sasol.com/sasol_internet/frontend/navigation.jsp?navid=21300011&rootid=2).

accomplishing this goal. Future pathways may reflect broader diversification through the use of natural gas (both directly and indirectly); sustainably derived, next generation bio-based fuels; and electric vehicles. The market entry points and value propositions for existing and future alternative fuel options are all unique and may vary regionally based on localized mobility needs and existing available infrastructure. Generally, more research and analysis is needed to understand the impacts and implications of these petroleum alternatives.

Multiple technology solutions may meet the evolving, complex energy needs of the U.S. transportation sector. As emerging technologies and fuels evolve, a prudent risk-adjusted strategy can facilitate technological breakthroughs and allow the development of a diverse and mature array of transportation energy solutions. Collaboration towards a set of messages that support diversification and optimal use of U.S. resources may offer new opportunities to address the environmental, energy security, and economic challenges faced today and in the future.

Petroleum is the only transportation fuel in the United States that has a fully developed retail refueling infrastructure; all other fuels' infrastructures suffer from some inadequacy. Many also face technological hurdles to commercialization. Natural gas is linked to many of these pathways as a primary energy source or key input; its current abundance could help accelerate timeframes of certain technologies. In the immediate future, natural gas will continue to serve as a key input to corn and ethanol production and help to provide low-cost electricity to fuel battery electric vehicles. Electric vehicles have had limited market penetration thus far, but economies of scale, decreasing battery costs, and improved technology may help to change this. Also, the price spread between natural gas and petroleum presents unique opportunities for each vehicle class to use natural gas fuels. While refueling infrastructure is limited for NGVs, multiple companies have expressed intent to construct either public for-profit refueling stations or private stations for company fleets. In-home refueling, CNG–gasoline vehicles, and modular liquefaction facilities may help to encourage consumer adoption as well. In the longer term, natural gas can also serve as a conduit to a broader hydrogen future. Should more natural gas refueling infrastructure be constructed, many of technical and logistical lessons of this undertaking may be transferrable to a hydrogen economy. Additionally, natural gas currently serves as the most economic feedstock for hydrogen production; it can provide low-cost hydrogen fuel and encourage investment in infrastructure that will one day allow renewably sourced hydrogen to play a larger role.

There are clearly opportunities in the near term where private parties may be able to accrue substantial cost savings by using natural gas as vehicle fuel. Stakeholders looking to facilitate higher NGV deployment may be able to look abroad for guidance on this undertaking. In extended timeframes, there is another set of opportunities that will require larger, longer-term investments and potentially public policy/funding to move forward. For these investments, supply estimates, as well as price impacts from demand in other sectors, become factors worthy of strong consideration.

Ongoing research may help elucidate answers to questions related to the evolution of the U.S. transportation sector:

- How large a role can natural gas have in a robust U.S. transportation sector, particularly given competing demands throughout the U.S. economy? What technology pathways are most promising?

- What role might alternative policies play? What metrics would drive policy decisions? Is public investment in refueling infrastructure necessary and/or appropriate?
- How will increased use of natural gas in the transportation sector affect the larger economy? This includes natural gas prices and market dynamics, the price of related fuels such as ethanol or hydrogen, utilization levels in other sectors, and global trade.
- Are there opportunities now or in the future for strategic collaboration between natural gas and renewable fuel companies to guide a transition to desired pathways?

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