ISSUE BRIEF

ENERGY SECURITY AND CLIMATE CHANGE

WORLD RESOURCES INSTITUTE

CSIS | CENTER FOR STRATEGIC & INTERNATIONAL STUDIES

Evaluating the Energy Security Implications of a Carbon-Constrained U.S. Economy

Britt Childs Staley, Sarah Ladislaw, Kate Zyla, and Jenna Goodward

Executive Summary

Technology plays an important role in determining how energy is produced, delivered, and consumed. In the future, it is expected to play an equally important role in enabling society to secure its energy system while reducing emissions of greenhouse gases (GHGs). But it is unclear what mix of technologies holds the greatest promise for simultaneously addressing climate change and energy security.

In this paper, the Center for Strategic and International Studies (CSIS) and the World Resources Institute (WRI) examine eight scenarios for technological development and energy use in the United States in 2035. All envision limiting the atmospheric concentration of carbon dioxide (CO_2) to 450 parts per million (ppm).

Applying an Energy Security Lens

The authors then assess how each scenario affects eleven factors closely associated with energy security:

- diversity of energy sources;
- diversity of suppliers;
- import levels;
- security of trade flows;
- geopolitics and economics;
- reliability;
- risk of nuclear proliferation;
- market/price volatility;
- affordability;
- energy intensity (energy used per unit of gross domestic product); and
- feasibility.

Lessons Learned

This approach, which we think of as envisioning carbon-constrained futures through an "Energy Security Lens," produced a number of insights that could inform U.S. policymakers as they consider technologies to address energy, climate, and economic priorities:

- Regardless of fuel and technology choices, some level of energy insecurity is inevitable, especially in the near term, as the United States transitions to a low-carbon energy system. Policymakers should explore ways to mitigate this insecurity during the transition.
- Meeting GHG reduction goals will be more costly with only today's technologies than with high penetration of more advanced low-carbon energy technologies. Policymakers should provide the sustained financial and institutional support necessary to advance all available low-carbon technologies, which can reduce costs and increase energy security over the longer term. This will provide the best chance for the emergence of a variety of technology options and quicken the transition to a secure low-carbon energy system.
- Global – not just domestic – deployment of advanced low-carbon energy technologies can minimize the costs and energy security risks of achieving climate change goals. The U.S. should support the adoption of advanced low-carbon technologies both at home and abroad.
- Common notions of "feasibility" (economic, technical, commercial, political) must be stretched. Policymakers should prepare the public to accept higher energy prices while making significant investments in low-carbon energy technologies

Center for Strategic and International Studies
1800 K Street, NW
Washington, DC 20006
Tel: 202-887-0200
www.csis.org

World Resources Institute
10 G Street, NE, Suite 800
Washington, DC 20002
Tel: 202-729-7600
www.wri.org

January 2009
Printed on recycled paper

and infrastructure. Clearly, such investments are necessary to ensure that viable alternatives are available when they are needed. However, energy and economic security concerns make it equally important that policymakers not take overly aggressive action that could jeopardize the existing fuel system until these alternatives can be deployed at scale.

- A non-carbon-constrained energy future also raises questions of feasibility and significant energy security concerns. A low-carbon future with advanced technology development, however, offers significant commercial and energy security benefits.

Introduction

Technology plays a key role in determining how energy is produced, delivered, and consumed. As a result, climate modelers have long considered how technology could be used to limit emissions of carbon dioxide and other global warming gases produced during energy generation. At the same time, security experts have analyzed how energy technologies might make the U.S. energy system less vulnerable to disruption. Few researchers, however, have considered simultaneously how the energy technology mix affects climate change and energy security – or the potential tradeoffs.

In this paper, the Center for Strategic and International Studies (CSIS) and the World Resources Institute (WRI) propose an "Energy Security Lens" as a tool for evaluating relative levels of energy security. The authors then examine carbon-constrained technology scenarios through this lens, with the following goals:

- To identify technologies that hold the greatest promise for reducing greenhouse gas emissions while addressing energy security concerns; and
- To draw policy lessons for promoting these technologies over the long term while managing energy security conflicts during the transition.

Defining an Energy Security Lens

CSIS and WRI noted in an earlier publication that it is difficult to define "energy security," and even more challenging to articulate meaningful security goals.[1] Here, the authors begin with a commonly cited definition of energy security as the availability of adequate, reliable, and affordable energy supplies.[2]

BOX 1 Energy Security: Definition and Metrics

Various institutions interested in global, regional, or national security have devised metrics to measure relative levels of energy security. This deep body of work often employs complex mathematical formulas and a sophisticated understanding of risk analysis, consumer behavior, and social science. These analyses typically focus on isolated energy security concerns, like oil import dependence or electric reliability, rather than a broader notion of energy security that also includes the links between factors. For instance, the Oil Security Metrics Model, developed by the Department of Energy's Oak Ridge National Laboratory, measures U.S. oil security in terms of monetary metrics (transfer of wealth, economic surplus losses, and macroeconomic disruption costs) and non-monetary metrics (political risk, strategic risk, and military costs). Another example is the Asia Pacific Energy Research Centre's 4 A's of energy security – availability, accessibility, acceptability, and affordability – and other energy security indicators (diversification of energy supply sources, net import dependency, non-carbon-based fuel portfolio, net oil import dependence, and Middle East import dependence).

Such models, while useful, are necessarily simplified representations of energy security and often fail to reflect the complex dynamics affecting the security of the energy system. They emphasize the predominant concerns of the day and favor indicators that are measurable, instead of those that are equally important but more difficult to quantify. This can yield conclusions and recommendations designed to alleviate one set of concerns without recognizing unintended consequences. On the other hand, the more comprehensive view proposed in this paper necessarily contains less precise metrics, and requires some level of subjectivity and uncertainty to evaluate non-measurable metrics and factors in relation to one another.

Although these terms are commonly used, they are subjective and inherently difficult to evaluate. For instance, it is hard to quantify relevant factors, such as geopolitical dynamics, that influence this definition. Similarly, it can be difficult to decide what a "better" energy security scenario looks like. For example, is reliable access to expensive energy more secure than unreliable access to cheap energy? The answer depends on a host of political, economic, and cultural factors impossible to capture in an abstract model.

In other efforts to measure energy security, researchers and policymakers have developed an array of analytical approaches (see Box 1). While these are useful tools, each is designed for a specific purpose and cannot fully account for the complexity necessary for evaluating the energy security implications of various technology scenarios.

TABLE 1 Energy Security Lens: Summary of Key Factors

Factor	Definition and Relevance to Energy Security	Increased Security	Decreased Security	Metric Used in this Analysis
Diversity of Energy Sources	Over-reliance on any one fuel, even those that are renewable or domestically produced, increases the chance of widespread economic impact from a shortage or disruption.	• Diversified energy mix • Adequate extra supplies in case of disruption • Fuel switching capability	• Significant reliance on any one fuel or technology (economy-wide or within a sector) • Dramatic shift in global demand for one fuel or technology	• Percent contribution to fuel mix
Supplier Diversity	Over-reliance on any one supplier country or region can be an energy security risk if supplies from that region are disrupted.	• Wide range of suppliers and well-supplied market	• Over-reliance on fuels or technologies from any one supplier (or group of suppliers)	• Not measured because scenarios do not have production data. (See discussion on p. 9)
Level of Imports	Global trade in energy increases global energy security by providing resources for which there is no readily available alternative domestically. However, to the extent that energy imports are beyond the importing country's control, they are regarded as a potential source of insecurity.	• Majority of total energy needs (or any one fuel) comes from inside national borders • Wide range of suppliers and well-supplied market	• Majority of total energy needs (or any one fuel) comes from outside national borders • Domestic supply constraints	• Not measured due to lack of production data. However, level of consumption ofnatural gas, oil and overall energy use considered as a proxy for discussion
Security of Trade Flows	The security of trading corridors[a] is crucial to the security of imported energy. Reducing the volume of energy moving through these points could minimize their risks, as could increasing the number of trading corridors or improving their protection.	• Adequately protected trading corridors • Smaller volumes of energy goods traveling through choke points or additional transit corridors available	• Unprotected trading corridors • Larger volumes of energy goods traveling through choke points	• Not measured due to lack of production data. However, level of consumption of natural gas, oil and overall energy use considered as a proxy for discussion
Geopolitics and Economics	International economic and political factors can affect the leverage that producer nations have over consumer nations. These factors raise questions about how rising economies will secure sources of energy, form relationships with supplier countries, and manage their domestic energy use.	• Open investment and trading practices • Relative political and economic stability, security, and proper governance in energy-producing areas	• Closed investment in energy resources • Non-market activity governs energy trade and development • Political instability threatens energy production	• Not measured here (See discussion on p. 9)
Reliability	Aging, neglect, disruptions to physical infrastructure, and mismanagement can all have adverse impact on energy reliability, a fundamental characteristic of a secure energy system.	• Energy services are available most of the time	• Energy services are increasingly subject to disruption and interruption for longer periods of time	• Not measured here (See discussion on p. 9)
Risk of Nuclear Proliferation	Proliferation risk raises more traditional security concerns about the safety of widespread deployment of nuclear power and its connection to geopolitical leverage.	• Technologies less prone to proliferation • Waste management plans that reduce proliferation risk	• Increased conventional nuclear activity w/ insufficient proliferation or waste disposal plans	• Level of nuclear generation.
Market/Price Volatility	Price volatility discourages long-term investment due to the uncertainty of the long-term direction of the market and creates a barrier to providing adequate energy supply.	• Prices are predictable	• Prices are subject to swings and not predictable	• Not measured here (See discussion on p. 9)
Affordability	The relative affordability of energy is a critical component of energy security.	• Energy costs are a small share of expenditures	• Energy costs are a growing and large share of expenditures	• Aggregate deployment and operating costs of technology portfolio.

continued next page

TABLE 1 (continued)

Factor	Definition and Relevance to Energy Security	Increased Security	Decreased Security	Metric Used in this Analysis
Energy Intensity[b]	Demand reduction accompanied by strong levels of economic growth (overall energy intensity improvements) would insulate the economy from the negative effects of energy price fluctuations.	• Energy intensity (energy consumption relative to GDP) of the economy decreases	• Energy intensity of the economy increases (takes more energy to produce a given unit of GDP)	• Not measured due to lack of production data. However, level of consumption of natural gas, oil and overall energy use considered as a proxy for discussion.
Feasibility	Technology and energy supply growth plans that appear impossible or increasingly challenging to achieve call into question the ability to provide adequate, reliable energy supplies.	• Energy technology portfolio appears technologically and practically possible over commercially relevant timeframes	• Energy technology portfolio appears technologically and practically impossible over commercially relevant timeframes	• Difference between penetration levels shown in scenario and feasible penetration levels estimated by industry assessment.

Notes

a. Global energy markets are dependent upon a small number of fixed transport routes. According to the Energy Information Administration, "In 2007, total world oil production amounted to approximately 85 million barrels per day (bbl/d), and around one-half, or over 43 million bbl/d of oil was moved by tankers on fixed maritime routes." http://www.eia.doe.gov/emeu/cabs/World_Oil_Transit_Chokepoints/Background.html.

b. Energy intensity is a measure of the energy efficiency of a nation's economy. It is calculated as units of energy per unit of GDP.

In order to explore a more comprehensive view of energy security challenges, CSIS and WRI have developed an "Energy Security Lens," which elaborates on the commonly used definition of energy security as the availability of adequate, reliable and affordable supplies to include eleven factors that impact energy security (see Table 1; for a more complete discussion, see Annex II in online supplement).

These eleven factors were chosen by the authors as the most relevant among a host of factors commonly cited as either sources of concern or avenues for providing greater security.[3] The metric used by the authors to assess each factor is also listed.

Some of these factors represent direct threats to energy production and delivery, while others indicate more indirect strategic vulnerabilities. Readers may disagree about the relative importance of the factors, and these differences will affect the conclusions they reach by applying the Energy Security Lens. Still, the lens provides a systematic and transparent way of thinking about and discussing the energy security implications of technology choices.

Applying the Energy Security Lens

WRI and CSIS applied the Energy Security Lens to eight plausible carbon-constrained technology scenarios. Each scenario describes the U.S. energy mix under a carbon constraint in 2035, with varying levels of advancement in energy technologies. While the lens can be applied to any country or set of circumstances, the analysis presented in this brief focuses on U.S. energy security (see Box 2).

Rather than recreate a complex modeling exercise, the authors used existing scenarios produced by the Pacific Northwest National Laboratory (PNNL, see Box 3).[4] The scenarios reflect a range of possible future energy mixes for the United States,[5] all leading to a target atmospheric carbon dioxide (CO_2) concentration of 450 parts per million (ppm).[6] In each scenario, some technologies are considered to have achieved "advanced" development (i.e., decreased cost and increased performance relative to business-as-usual progress), while others are merely "reference," reflecting business-as-usual progress. A brief description of the scenarios used is provided in Table 2.

The authors assess the relative performance of each scenario in 2035 (see Box 4) by evaluating changes in each of the factors included in the Energy Security Lens. Detailed results for each of these scenarios are presented in Annex III in the online supplement. We note, however, that these particular scenarios merely illustrate an application of the Energy Security Lens; readers should not focus on the precise technology mixes, but rather on the lessons learned from applying the lens.

BOX 2 U.S. and the World

Addressing energy security and climate change requires participation from and cooperation with many other countries outside the United States.

Nearly all factors in the energy security lens deal directly with the actions among and between several nations. U.S. energy security will always be linked with the security and actions of other countries, so long as energy resources – as well as the materials to produce, convert, deliver, and use those resources – are bought and sold on a global market or traded among countries.

Global cooperation is also necessary to address climate change goals. The model presented in this paper assumes that the United States is operating in concert with the rest of the world. Additional scenario runs (not presented here) that constrain or delay action by one or more countries outside the United States show that a lack of coordinated action drives up the overall cost of mitigation and, under certain scenarios, makes it impossible to meet stabilization goals. These results indicate that a coordinated global response is critical to managing energy security and reaching GHG reduction goals.

BOX 3 PNNL/CTTP Model

This analysis applies the energy security lens to a model and set of scenarios developed by the Pacific Northwest National Laboratory (PNNL) and used by the U.S. Department of Energy's Climate Change Technology Program (CCTP) to inform federal investments in energy technology research and development. PNNL has developed long-term assessments of advanced technology scenarios using MiniCAM, an integrated assessment model. The model provides information on the future global and regional energy mix through 2100 based on various carbon constraints (450-750 parts per million atmospheric CO_2 concentration) and baskets of technology assumptions. The assumptions for each scenario specify which technologies develop along reference (or business-as-usual) paths, and which reach advanced stages, presumably aided by research, development, and deployment policies. Those in advanced stages have better performance and are less costly, and therefore contribute in larger measure to greenhouse gas abatement efforts.

[Note: The scenarios presented in this brief represent a pre-publication version of PNNL's latest scenarios publication. Therefore the scenarios used in this document and the PNNL document are different. The PNNL report can be found at: http://www.pnl.gov/atmospheric/publications/]

Lessons from Applying the Energy Security Lens

Table 3 summarizes the performance of each of the technology scenarios relative to each other.[7] A green box indicates a scenario that performed better than the average of the scenarios for that factor. Scenarios get a "red light" in categories where they fare worse than the other scenarios. Yellow scenarios are close to the mean or average for a given factor, and factors with gray boxes are not evaluated in this table due to a lack of quantifiable metrics. They are discussed subjectively below, and the authors take them into account in the overall assessment. While not noted in this table, the analysis also shows that a scenario with reference technology assumptions but without carbon constraints is not a more energy secure outcome than the other scenarios.[8]

Diversity of Energy Sources for Power Generation

None of the scenarios shows a significant change in the overall diversity of the fuel mix in the electric power sector, although diversity does improve slightly in the Energy Efficiency and Renewables scenario. This scenario is more diverse primarily because 2% of the power sector fuel mix comes from oil and 28% comes from coal, while in the All Advanced scenario, 29% comes from coal, and there is no oil. By the numbers the Energy Efficiency and Renewables scenario is more diverse because of the contribution of another fuel source (oil) and the "reduced

TABLE 2 PNNL Technology Scenarios Evaluated (450 ppm CO_2 Constraint)

Technology Scenarios	Assumptions
Constrained Reference Case	"Reference" assumptions for all technologies (i.e., normal technological progress and no carbon capture and storage [CCS])
Energy Efficiency and Renewables Case	Advanced technology assumption for efficiency, renewables, and biomass; reference nuclear power and no CCS
Energy Efficiency Case	Advanced efficiency, no CCS, all else reference case
CCS Case	Advanced CCS, reference case nuclear power, and other technologies
Nuclear Case	Advanced nuclear power, no CCS, reference case for other technologies
Biomass and CCS Case	Advanced biomass and CCS, reference case for other technologies
Advanced Supply	Reference end-use technologies; all else advanced
All Advanced	Available CCS and advanced assumptions for all technologies

TABLE 3 **Summary of Lessons from Applying the Energy Security Lens: 2035**

Technology Scenarios	Energy Security Factors						
	Diversity of Fuels (power gen)	Diversity of Fuels (transport)	Feasibility	Proliferation	Affordability	Total Energy Demand	T Co
Constrained Reference Case							
Energy Efficiency and Renewables Case							
Energy Efficiency Case							
CCS Case							
Nuclear Case							
Biomass and CCS Case							
Advanced Supply							
All Advanced							

Note: See Annex I for Lens Table Methodology.

reliance" on coal. However, few analysts would consider reliance on oil (generally imported and expensive) instead of coal (domestic and inexpensive) to provide greater energy security. This example illustrates the importance of considering the energy security lens factors in concert, rather than focusing in on any one component.

Two scenarios show a significant shift from coal to nuclear power, but this change does not improve overall diversity, as the power sector is still dominated by a single fuel, nuclear instead of coal. These results are partly due to the limited timeframe for analysis; 25 to 30 years is not much time to realize technology improvements or make major adjustments to the nation's energy infrastructure. (Over a longer period to 2050, fuel diversity does improve dramatically in some scenarios.) Given that none of the scenarios dramatically improves energy diversity over the next few decades, it will be important to manage the specific security vulnerabilities of the technologies and fuels that are part of the mix, whether they are natural gas imports, nuclear proliferation, or the reliability and intermittency of renewables.

Diversity of Energy Sources for Transportation

None of the scenarios shows a substantial reduction of oil use in the transportation sector – oil contributes at least 76 percent of the sector's 2035 fuel mix in all scenarios, compared to 95 percent in 2008[9]– but the All Advanced, and Energy Efficiency, Energy Efficiency and Renewables cases offer the greatest relative level of fuel diversity.[10] In addition, there is little deployment of biofuels for transport in any of these scenarios (even the Biomass/CCS scenario), largely due to the increased GHG emissions from land-use changes that result from large-scale

performs better than other scenarios
performs about the same as other scenarios
performs worse than other scenarios
not quantifiable

Total Oil nsumption	Total NG Consumption	Price Volatility	Reliability	Geopolitics	
					Without advanced technology, meeting the carbon constraint yields undesirable energy security outcomes.
					Low-cost efficiency and renewables enable climate mitigation, while generally improving energy security.
					Taking advantage of advanced efficiency opportunities yields important energy security benefits.
					A single technology advancement (advanced CCS) provides significant cost-improvements over the reference case scenario, but increases vulnerability to supply-related security issues.
					Availability of advanced nuclear technologies but not CCS yields a power sector mix much like the 450 ppm reference case scenario.
					Even with advanced biomass, significant changes in energy mix are not seen.
					Advancing supply technologies but not efficiency raises more energy security concerns the scenario in which both are advanced.
					Availability of advanced technology facilitates managing energy security, while meeting a climate constraint.

biofuels production. (Scenarios with less aggressive carbon constraints do show increased use of biofuels.) None of the scenarios used in this exercise modeled a significant advance in batteries for on-board storage in plug-in hybrid vehicles or any other technology advances that could enable a significant shift to electricity for mobility.

The lack of significant changes in the liquid fuel mix reflects the fact that it is generally cheaper to reduce emissions from power generation than from transport,[11] and the model seeks the lowest-cost reductions. However, to the extent that policymakers see oil dependence as a key energy security concern, they may wish to implement policies to move the transportation sector away from oil more aggressively. This issue is explored more fully in Box 6 and will be addressed in a subsequent publication by the authors.

Feasibility

Feasibility is an evaluation of the likelihood of (or ability to achieve) the technology deployment levels indicated in the scenarios. In this analysis, feasibility is measured relative to an industry-informed assessment by the Electric Power Research Institute (EPRI) of maximum deployment potential.[12] To put these assessments in context, even a scenario without any GHG constraints pushes the limits of industry's assessment of feasibility in some categories (see Box 5). This indicates that aggressive development of energy technologies will be necessary regardless of climate policy.

When compared with EPRI's assessment, all of the scenarios raise serious concerns about the feasibility of aggressively deploying advanced technologies other than coal and nuclear power. All of the scenarios show less coal (including coal with

BOX 4 A Question of Timing: Why 2035?

For the purpose of this brief, energy security is assessed in each scenario for the year 2035. From a technology deployment standpoint, this is a short time horizon, as it will take much longer for many of the truly transformative technology improvements and infrastructure changes to take place. The authors do not attempt to assess the later stages of each scenario — although many of them show much greater change across many of the energy security factors in later years — as energy security concerns tend to be based on nearer-term dynamics, and anything beyond 2035 is too far in the future to evaluate energy security. The time lag for a substantial technology shift emphasizes the importance of managing the transition to a low-carbon energy future. During politically and commercially relevant timeframes (out to 2035), policymakers will have to manage the energy security concerns of an energy mix that looks much like the current one.

CCS), more natural gas, more hydropower, and more non-hydro renewables than EPRI's assessment indicates is possible with aggressive development. Of the scenarios only the Nuclear case exceeds EPRI's predictions for nuclear power deployment between now and 2030.[13] In several cases, the scenarios show twice the level of non-hydro renewable capacity considered possible by industry. Additional feasibility considerations for a variety of technologies are difficult to represent in these models, such as the ease of grid integration and competition for water and land use.

Nuclear Proliferation Risk

The risk of proliferation of nuclear materials is linked to the overall level of nuclear energy use, rather than percentage of energy mix. Nuclear power production increases substantially in all scenarios (and most dramatically in the advanced Nuclear case). This suggests a need to address the potential security implications of increased nuclear power in any low-carbon future energy system.

Affordability

The cost of deploying each of the scenarios varies widely, from $500 billion to $1.2 trillion in 2035 (see Annex IV in the online supplement).[14] The most affordable scenario is one in which aggressive technology improvements occur across the board, including renewables, energy efficiency, CCS, and nuclear power (All Advanced). The least affordable scenario is the one in which CCS is not developed, nuclear power is held at today's levels, and only reference improvements take place for other technologies (Constrained Reference).

These results are largely a function of the model's assumptions, as technological advancements are generally defined as reductions in price. Still, the finding reinforces the message that investing in a wide variety of technological advancements today has the potential to yield significant cost savings over the longer term. In addition, these mitigation costs must be considered in the context of the cost of inaction on climate change, which by some estimates could be at least 5% and perhaps as high as 20% of global GDP.[15]

BOX 5 The Infeasibility of the Business-as-Usual Forecast

Recent energy market trends suggest that the world is on an unsustainable and undesirable trajectory. These trends include: tight supplies and the elimination of excess capacity, persistent and growing demand, infrastructure and capabilities limitations, heightened geopolitical and investment risks, higher prices, and growing concern over climate change. At the same time, absent a major strategic shift in policy, U.S. influence in global energy markets will continue to erode due to the emergence of new global players. The global financial crisis has disrupted the high price and accelerated demand trends of the last several years, providing temporary relief to consumers, but the underlying unsustainable trends are likely to prevail over the long run.[a]

PNNL's unconstrained (without a carbon constraint) business-as-usual scenario (see Annex III in the online supplement) shows a world with greater reliance on the same composition of fuels currently used today but on a much broader scale, and a continuation of current GHG emission trends. This scenario raises the same feasibility concerns as the advanced technology scenarios that reduce GHG emissions while also adding generation capacity, but with greater energy security concerns and without addressing climate change. Business as usual, therefore, is not a solution to either the energy security or climate change challenge.

[a] International Energy Agency, 2008. *World Energy Outlook*.

Energy Intensity

Since reliance on any fuel comes with security risks, lowering overall energy demand is a strategic advantage. Energy demand, however, should be decoupled from economic growth (see Box 4). Energy intensity (energy use per GDP) is therefore a more meaningful metric than demand, but in the absence of GDP projections for this analysis, the authors have assessed total demand as a proxy for energy intensity.

The CCS scenario shows greater energy demand than the others due to several factors. These include the additional energy consumed in CO_2 capture, the exclusion of advanced efficiency technologies from the scenario, and the lack of price-driven demand reduction due to the relative inexpensiveness of CCS in this scenario. The Advanced Supply case (reflecting advancements in everything but end-use technologies) also indicates a high overall energy demand relative to the scenario in which all technologies are advanced. Some effect of either a carbon price or efficiency improvements can be seen across the board: oil consumption in transportation is reduced by a range of .04–1.3 million barrels per day (4–11 percent of the unconstrained projection) in 2035 in all scenarios.

The following factors are important aspects of the lens, but were not quantifiable with the data available:

Supplier Diversity, Level of Imports, and Trade Flows

It is difficult to determine how the scenarios would affect levels of fuel supply imports, supply sources, and trade flows. This is because the model only indicates how much supply is available globally, not where it comes from. The scenarios do, however, provide insights into the demand for globally traded fuels like oil, natural gas, and coal. All of the scenarios show a slight reduction in global oil demand relative to projections without a carbon constraint (5–21% reduction). Likewise, the scenarios show reduced natural gas demand (9–19% reduction) and coal demand (47–67% reduction), compared to an unconstrained scenario. Given the global market for oil and the increasingly connected market for gas, a reduction in overall global demand would improve security of supply for all consumers, including those in the United States.

Market/Price Volatility

Price volatility, which has been increasing in world oil markets over the last year, creates uncertainty that discourages investment. In some ways, participating in global commodity markets, such as the oil market, makes countries more vulnerable to the effects of volatility; however, the security advantages afforded by a global and well-functioning market have historically outweighed this risk. Policymakers and companies continually look for ways to reduce market volatility by providing adequate supply, and promoting free market principles and greater transparency. Unfortunately, long-term models, such as the one explored in this paper, cannot capture the smaller time scale (days, weeks, or months) over which volatility can be especially problematic.

Reliability

Reliable energy systems have the ability to provide consistent energy supply to meet demand. Reliability is typically reflected in terms of outages or interruptions over a period of time, conditions not provided in these scenarios. All scenarios require significant infrastructure changes to integrate new technologies into the energy mix, and to ensure that energy is available to meet demand. The Energy Efficiency and Renewables case may be particularly challenging, given that the diffuse and intermittent nature of renewable generation is problematic for grid stability in the absence of energy storage solutions.

Advancements in infrastructure technologies will improve the reliability of each of the scenarios and will support a move to more diverse energy supplies. However, new generations of transmission and distribution ("smart grid") technologies will raise new concerns about digital security and data protection, much like the security issues associated with the Internet.[16]

Geopolitics

The geopolitical dynamics of energy revolve around the countries that control energy resources, the countries that need those resources, and the countries through which energy distribution infrastructure passes. It is difficult, given various energy mixes, to identify what leverage producer nations will have over consumer nations, and what relative gains in economic strength mean in political terms. Each scenario examined could be affected by geopolitical factors. This is because all scenarios continue to show a significant role for oil, which is thought of as the key political vulnerability for the United States. The scenarios also indicate a significant role for natural gas, a fuel with the potential to raise the same global trade concerns as oil. Moreover, the reality of a global marketplace is that most of the materials used to build the technologies modeled in these scenarios come from outside the United States, exposing the U.S. to some degree of global geopolitical concern regardless of the energy technologies chosen.[17]

Relative Performance of Scenarios

The most promising scenario from the perspective of energy security (i.e., with the most green areas in Table 3) is the Energy Efficiency and Renewables scenario. Other standouts include the All Advanced and the Energy Efficiency cases. It is important to note that the Energy Efficiency and Renewables scenario outperforms the All Advanced and the Energy Efficiency scenarios primarily because it leads on diversity of fuels for power generation. As discussed on page 5, this greater diversity is due to the presence of oil in the power sector fuel mix, which does not improve energy security. The Energy Efficiency and Renewables scenario also raises concerns about the reliability and stability of the electricity grid (described above) that are not quantifiable in this analysis.

All three leading scenarios reduce oil dependence in the transportation sector, a key geopolitical concern, in ways the others do not. The All Advanced scenario is among the best at providing diversity in the transportation sector and reducing oil consumption. It may not be surprising that the All Advanced scenario – with significant technological advancements and cost reductions in the greatest number of different technologies – is also the least expensive overall. However, this scenario reflects progress on multiple technologies (e.g., wind, solar, geothermal, and a suite of energy efficiency technologies, including appliances and building materials, etc), so it is perhaps not analogous to scenarios that move a single technology applications, like CCS or nuclear power, to an advanced stage.

Of the scenarios that rely on advancements in single technologies, the Nuclear scenario fares very poorly while the CCS scenario fares much better, indicating that much can be gained for energy security (as well as cost savings) by pursuing CCS technology. The Constrained Reference case also performs poorly, demonstrating that technology advancements can improve energy security in ways beyond simply reducing costs.

Findings and Conclusions

Viewing carbon-constrained technology scenarios through the Energy Security Lens reveals several themes relevant for policymakers. These themes, along with recommendations for those seeking to address climate change and energy security in U.S. policy, are outlined below. In addition, the analysis identifies two topics that merit further exploration: the emerging role of natural gas as a near-term lower-carbon alternative to coal and the role of oil in the transportation sector (see Box 6). These topics are considered in more detail in separate publications.

- **The Inevitable Energy Security Challenges**

  Just as some level of climate change is unavoidable, so is some level of energy insecurity, especially in the near term. Policymakers should explore ways to mitigate these security impacts during the transition to a secure, low-carbon future.

  Many of the PNNL technology scenarios, as viewed through our Energy Security Lens, have the potential to improve U.S. energy security. However, no one scenario completely removes the continued need to manage various energy security concerns. Even the All Advanced scenario leaves the United States vulnerable to some of the same energy security concerns we have today.

- **The Importance of Advancing Clean Energy Technology**

  Technology advancements are necessary for meeting GHG reduction goals, while providing adequate, affordable and reliable energy supplies. Policymakers should provide the financial and institutional support needed to reach the "advanced" stage of all available low-carbon energy technologies, particularly renewable energy and energy efficiency technologies.

  The world must develop and deploy a variety of energy technologies if it is to stabilize atmospheric GHG concentrations and provide adequate supplies of affordable and reliable energy. The needed technology advancements and cost reductions will not be achieved without adequate support. Implementing a price on carbon will create an incentive to expand all low-carbon technologies. Policymakers must also eliminate non-financial barriers to each of the technologies in the scenarios. Given that the All Advanced technology scenario yields several positive outcomes for GHG mitigation and energy security, policymakers should do all they can to address challenges facing each of the following technologies:

  Carbon Capture and Storage

  The scenarios show that employing CCS will allow the use of coal, gas, and oil much longer into the future, dramatically reducing the overall cost of GHG emissions abatement relative to the other scenarios. The ultimate level of CCS deployment is much higher in the absence of other technology improvements, such as nuclear, greater efficiency, and renewables. However, expectations for CCS are high: in the CCS case, CO_2 storage must ramp up twice as fast between 2020 and 2035 as in the All Advanced case. A multi-stakeholder process led by WRI[18] recently published guidelines for U.S. support of CCS.

  Renewable Energy

  Policies to push renewable energy (e.g., a renewable portfolio standard for power generation) can encourage greater fuel diversity on a shorter time frame than is predicted by current models, as well as provide other energy security benefits.

BOX 6 The Natural Gas Bridge and the Role of Oil in Transport

Two subjects for further research emerged from the application of the security lens: the role of natural gas and the future of the transportation sector. The authors draw preliminary observations below, but plan to conduct further research to explore these issues in greater detail, because of their critical importance to both energy security and climate change.

Natural gas is a valuable short-term emission reduction strategy, but not a long-term solution to climate change or energy security concerns.

It is possible that natural gas will become the near-term fuel of choice for power generation under a carbon-constrained economy. The U.S. Department of Energy's Energy Information Administration (EIA) analyzed several scenarios for compliance with the Climate Security Act of 2007 proposed by Senators Lieberman and Warner. The EIA analysis indicated that under the emissions cap proscribed, natural gas consumption could increase greatly if other low-carbon compliance technologies are limited to their current rates of deployment.[a]

However, the PNNL scenarios indicate that in order to achieve an aggressive stabilization target, natural gas will need to be almost entirely removed (or have its emissions sequestered) from the energy mix in the long term. In addition, a reliance on natural gas raises some of the same energy security concerns (e.g., limited supply, high prices, and dependence on a small number of suppliers) as oil. Unconventional gas resources are being heralded as an abundant future supply of gas that will alleviate gas competition concerns, but their GHG emissions implications are unclear.[b] It is also not clear that industry is poised to develop natural gas resources or able to dispatch natural gas-fire power plants at the scale or pace indicated in some near-term energy mix scenarios.[c]

The authors' additional research explores whether significant shifts to natural gas in the near-term could complicate efforts to achieve long-term climate and energy security goals.

Even significant efforts to reduce GHG emissions may not shift the transportation sector significantly from its reliance on oil.

Oil dependence is a major U.S. and global energy security issue today, due to the over-reliance on oil for transportation use and the concentration of conventional oil supplies in a handful of regions. The PNNL modeling exercise indicates that a fundamental move away from oil may not be necessary to achieve climate goals if substantial emission reductions can be cost-effectively achieved through the electric power sector. In fact, the role of higher-carbon unconventional oil grows in some of the carbon-constrained scenarios. Oil's share in overall energy use decreases in each scenario, but the transportation sector remains reliant on oil for about 75–80 percent of its energy needs.

This raises the question of how much climate policy will improve energy security in the transportation sector, since a least-marginal-cost approach to climate mitigation does not address one of the key political concerns regarding energy security: oil dependence. Reduced reliance on oil as a fuel source may actually have some of the most synergistic benefits for both energy security and climate change by both reducing reliance on imported oil and reducing emissions.

The authors' further work explores arguments for and against transforming the transportation sector and explores potential advantages of linking transportation to the electricity generation system through technologies such as plug-in hybrid electric vehicles.

Notes

a. U.S. Department of Energy, Energy Information Administration, *Energy Market and Economic Impacts of S. 2191, the Lieberman-Warner Climate Security Act of 2007* (Washington, DC: DOE, 2008). Available at http://www.eia.doe.gov/oiaf/servicerpt/s2191/index.html. Accessed August 12, 2008.

b. See, for instance, U.S. Department of Energy research on methane hydrates, highlighted in the National Energy Technology Laboratory's methane hydrate newsletter *Fire in the Ice*, available online at http://www.netl.doe.gov/technologies/oil-gas/FutureSupply/MethaneHydrates/newsletter/newsletter.htm.

c. North American Electric Reliability Corporation, *Special Report: Electric industry Concerns on the Reliability Impacts of the Climate Change Initiatives* (November 2008) and Victor Niemeyer, "Climate Policy: The Cost of Compliance," *EPRI Winter Journal 2008*, Electric Power Research Institute (2008).

However, widespread deployment of renewable power will also require greater access to the electricity grid, improvements to the grid itself, and large-scale energy storage to address intermittency.[19] Investment in and incentives for these upgrades will be as important as support for renewable energy technologies themselves.

Energy Efficiency

Reduced overall energy consumption benefits consumers and significantly improves energy security over a scenario in which only supply-side technologies are encouraged. Advanced efficiency improvements for transport are particularly effective for improving energy security by reducing reliance on oil. Energy efficiency and demand-side management are available today and should be promoted aggressively.

Nuclear Power

While the scenario showing only nuclear power in the advanced stage raised numerous energy security concerns, nuclear energy plays a large role in all of the emission-constrained technology scenarios. Current obstacles to widespread nuclear deployment include difficulties ensuring the security of nuclear facilities, lack of a long-term solution for waste management, the need for long-term risk protection against liability, the cost and shortages of materials and labor, and nuclear proliferation concerns.

A resurgence of interest in civilian nuclear power and perceived shortcomings of the international Nuclear Non-Proliferation Treaty raise significant concerns about how to safeguard against the spread of nuclear arms, nuclear-weapon usable material, and fuel-cycle facilities in these future scenarios. The non-proliferation community recognizes that many factors influence proliferation, including the technical difficulty of fissile material extraction, cost, time, fissile material type, potential for safeguarding and detection of tampering, and physical protection.[20] These serious issues must be addressed in the near term if the United States is to participate in a nuclear renaissance.

Research, Development, and Demonstration Funding

Federal funding on research, development, and demonstration (RD&D) can compensate for the disincentive private firms face in conducting basic research or demonstration (namely the difficulty of capturing all the benefits from their investments).[21] RD&D efforts have suffered from inconsistent and insufficient levels of funding. In the past, different administrations and legislators have shown preferences for different technologies, causing budgets to rise and fall according to changing priorities. Successful technology development requires a stable and sustained commitment to funding over many decades. RD&D investment decisions are also plagued by disagreement on approach and process. A system that increased the stability of funding and institutional research processes could achieve the technology advancements envisioned in these scenarios much more successfully

- **The Need for Global Action**

  Aggressive global action will be necessary, and multilateral collaboration on technology deployment will be critical, to achieving mitigation targets while keeping costs down and providing greater security.

  The PNNL scenarios and many other modeling exercises illustrate that globally coordinated action is the least-cost pathway to GHG emission reductions.[22] U.S. technology development and deployment alone cannot achieve the global emission reductions needed, nor can it provide the lowest-cost reductions.[23] The Energy Security Lens suggests that globally coordinated action and cooperation are also essential for maintaining adequate levels of energy security, because domestic security sometimes relies explicitly on the actions of other countries. Moreover, key developing countries share many of the same energy security concerns, and are eager to find solutions that target both energy security and GHG emission reduction goals. Therefore, the United States should pursue both domestic and international policies that support the deployment of advanced technologies throughout the world.

- **Re-visiting Current Perceptions of Feasibility**

  Addressing energy security and climate challenges requires strong political will. Policymakers and industry must revisit their notions of "feasibility," while pushing for the most efficient and effective GHG reductions possible.

  In many ways, feasibility and cost issues are at the heart of the tensions between the energy security and climate change communities. Climate stabilization is theoretically feasible but will be difficult to achieve, given long capital investment and project development cycles, a shortage of materials and skilled personnel, and escalating costs of projects. These challenges call into question the pace, scale, and cost of the changes that models indicate will be necessary to reach stabilization. If policies push too hard, and the technology advancements on which they are relying do not materialize in the desired time frame, energy shortages, high energy costs, and decreased political support for emissions mitigation may result. If policies are not stringent enough, the market will find quick fixes (like fuel switching) which will be inadequate for achieving long-term climate goals.

  However, the same investment and project development challenges constrain our ability to meet the needed increases in energy supply even without attempts to reduce GHG emissions, a path that introduces the dramatic and costly consequences of climate change as well. In addition, new capital, infrastructure, production, and even new human resources can come online quickly if political will is strong and the appropriate market signals, including a cost for carbon and other complementary policies, are in place.

Viewing future technology scenarios through the Energy Security Lens makes it clear that while emission constraints can be met with only reference technology advancements, this is not a desirable outcome from an energy security or cost perspective. To address both climate and energy security simultaneously, the United States will need the technologies depicted in the "advanced" PNNL scenarios, along with policies to develop and deploy them. However, even with substantial technology advancements, there will still be energy security concerns to manage, both during and after the transition to a low-carbon economy.

Annex 1. Lens Table Methodology for Quantifiable Metrics

WRI and CSIS applied the energy security lens to the PNNL/CCTP model scenarios in order to assess which climate stabilization scenarios and therefore which suite(s) of technologies are most beneficial from an energy security standpoint. Comparing the scenario results to the unconstrained reference baseline (BAU), none of the scenarios stood out as particularly different. For instance, every scenario was slightly better than BAU in terms of transportation fuel diversity, and slightly worse than BAU in terms of proliferation risk due to increased nuclear consumption over BAU in every scenario. Therefore, instead of comparing the scenarios to a baseline, WRI and CSIS ranked the scenarios relative to each other, and color-coded the results. Scenarios get a "red light" in categories where they are worse for energy security than most of the rest of the scenarios or a "green light" when they are better. Scenarios get a "yellow light" when they are about average, or right in the middle of all of the scenarios in the category.

The methodology used to separate the scenarios into red, yellow, and green lights is fairly straightforward, using standard deviation. Within each lens category, the authors calculated the standard deviation for the scenario data points. Any data points that fall within one standard deviation of the mean are assigned yellow. Any data points that are outside of one standard deviation, above and below, get red and green.

For example, in the "cost" category, the mean of the scenario data points is 0.75. The standard deviation is 0.26.

Therefore:

(red)	> (mean+SD)	> 1.01	Constrained Ref; Nuclear
(yellow)	(mean-SD) <x< (mean+SD)	0.49<x<1.01	Energy Efficiency and Renewables; EE; Bio/CCS; CCS; Supply; All Adv
(green)	<(mean-SD)	< 0.49	none

The authors applied the same methodology for assigning red, yellow, green for all of the categories. The metrics used for the scenario data points are as follows:

Proliferation: absolute amount of nuclear in the scenarios.

Overall energy consumption, natural gas, and oil consumption: absolute level of energy demand, gas/oil consumption in the scenarios.

Feasibility: the authors used EPRI's PRISM analysis, a bottom-up review of technology performance capabilities and deployment potential for comparison against the CCTP/PNNL results. The authors calculated the differences between the PNNL numbers and EPRI's numbers, by fuel type: liquids, gas, coal, coal w/CCS, nuclear, hydro, and non-hydro renewables. They then compared the results within each fuel type, and used the same methodology described above to categorize the scenarios. For instance, looking at natural gas, the authors calculated the difference between EPRI's analysis and each of PNNL's scenarios, subtracting EPRI's analysis of what is feasible from PNNL's analysis of what is required, in order to estimate the "feasibility gap". Those scenarios with a "feasibility gap" greater than one standard deviation from the mean of these feasibility gap data points are red: constrained and reference nuclear. Those with a gap lower than one standard deviation, only CCS score a green. This same methodology was applied across the fuel types.

Diversity of Fuels (both power and transport): the authors used the fuel mix data, and calculated the variance of these data to estimate the level of fuel diversity. Since variance is a measure of dispersion – in other words, the degree to which the data points are clustered around the mean – if a fuel mix is "diverse" – then the percent contributions from each technology will all be close together or clustered around the mean (e.g., 20% contribution from five different resources is more diverse than 90% from one source and 10% from another). Therefore, the scenarios with low variance are more diverse. Then using the same methodology described above, the authors assigned red, yellow, and green to the scenarios, with red being those scenarios that have a level of dispersion above one standard deviation of the mean level of dispersion.

For Annex II-IV, please see the online supplement available at www.wri.org/climate or www.csis.org/energy.

About the Authors

Britt Childs Staley is an Associate with the World Resources Institute's international climate policy team. Her research primarily focuses on clean technology deployment, including regulatory and investment frameworks to facilitate market penetration of new energy technologies. She holds a bachelor's degree in international politics from Georgetown University's Walsh School of Foreign Service.

Sarah Ladislaw is a Fellow in the Energy and National Security Program at the Center for Strategic and International Studies, where she concentrates on the geopolitical implications of energy production and use, energy security, energy technology, and climate change. Before joining CSIS in January 2007, Ladislaw worked in the U.S. Department of Energy's Office of Policy and International Affairs.

Kathryn Zyla is a Senior Associate in the Climate and Energy Program at the World Resources Institute, where she focuses on emissions markets, design of U.S. federal climate policy, and the intersection of climate change and energy security. Before joining WRI, Ms. Zyla served as a Senior Research Fellow for Domestic Policy at the Pew Center on Global Climate Change. She holds a master's degree in environmental management from Yale University and a bachelor's degree in engineering from Swarthmore College.

Jenna Goodward is a Research Analyst in the Climate and Energy Program at the World Resources Institute. Her work focuses on international climate policy and the expansion of markets for clean energy technology, particularly in developing countries. She holds a bachelor's degree from Scripps College in Environmental Economics & Politics.

Acknowledgments

The authors gratefully acknowledge the help and guidance of their colleagues throughout the production of this brief, particularly Debbie Boger, Rob Bradley, Jennifer Layke, Janet Ranganathan, and Jonathan Pershing at WRI and David Pumphrey, Frank Verrastro and Matthew Frank at CSIS.

This report benefited enormously from a thorough peer-review process. The thoughtful comments and suggestions of Tara Billingsley, Jason Bordoff, Karin Borgerson, Joseph Foti, Revis James, Lawrence Jones, Alex Perera, and Graham Pugh greatly improved this manuscript. A special thanks to Leon Clarke and Graham Pugh for their assistance with interpreting and incorporating the climate models jointly developed by the Pacific Northwest National Laboratory and the Climate Change Technology Program at the U.S. Department of Energy. Any remaining errors and omissions are, of course, the responsibility of the authors. For editing and design we thank David Malakoff, Allison Sobel, and Maggie Powell, and for production support, we thank Hyacinth Billings, of WRI, and Jennifer Bovair at CSIS.

This series is made possible through the generous support of the Doris Duke Charitable Foundation, the Connect US Fund of the Tides Foundation, and the Energy Foundation.

Notes

1. S. Ladislaw, K. Zyla, and B. Childs, *Managing the Transition to a Secure, Low-Carbon Energy Future* (Washington, DC: Center for Strategic and International Studies and World Resources Institute, 2008).
2. Other organizations that have used this or similar definitions for energy security include: the International Energy Agency, the European Commission, the Energy and Natural Resources Committee of the United States Senate, along with many others.
3. Many other energy security studies either focus on one or more of these factors or choose to divide factors into categories. For additional reading about energy security definitions and factors see: *Energy Security and Climate Policy – Assessing Interactions*, OECD/IEA 2007; Samantha Olz, Ralph Sims, and Nikolai Kirchner, *Contribution of Renewables to Energy Security*, International Energy Agency Information Paper, OECD/IEA 2007 http://www.iea.org/textbase/papers/2007/so_contribution.pdf ; Greene, David L. and Leiby, Paul N., *The Oil Security Metrics Model: A Tool for Evaluating the Prospective Oil Security Benefits of DOE's Energy Efficiency and Renewable Energy R&D Programs*, Oak Ridge National Laboratory, May 2006; A Quest for Energy Security in the 21st Century, Asia Pacific Energy Research Centre, 2007, and *The Economic of Energy Security*, Douglas R. Bohi, Michael A. Toman, Margaret A. Walls, Springer Publishing, 1996.

4. As with all models, these scenarios are not meant to represent predictions or view of the future, but rather provide a tool for exploring possible outcomes resulting from a set of assumptions. The focus of this analysis is not to endorse a particular scenario as the best future, but rather to use the scenarios to explore the lessons learned from analyzing the energy security implications of potential energy mixes in a carbon-constrained economy.
5. The model reflects global technology advancements and emission constraints, although results shown here are for the U.S. energy system. Technology assumptions of scenarios are available on pages 3.3.-3.28 of PNNL's "New Technology Scenarios for Greenhouse Gas Emissions."
6. It is commonly believed that global average temperature increases must stay within 2 degrees Celsius (°C) in order to avoid the most severe consequences of climate change (IPCC, 2007. *Fourth Assessment Report*). For the purposes of this exercise, the authors chose the most carbon-constrained scenarios from PNNL (450 ppm CO_2, or approximately 550 ppm CO_2 equivalent). According to the Intergovernmental Panel on Climate Change, this target would correspond to a global average temperature increase of around 3 °C above pre-industrial levels.
7. The authors used a methodology based on standard deviation to classify scenarios as red, yellow, or green. A detailed description of this methodology is contained in Annex I.
8. This brief did not compare the scenarios to a 2008 baseline or to an unconstrained BAU scenario, because the goal is to compare the energy security implications of technology and fuel choices under a carbon constraint.
9. Calculated using 2008 data from the Energy Information Administration's Annual Energy Outlook 2009 Early Release. Available at http://www.eia.doe.gov/oiaf/aeo/supplement/sup_tran.xls.
10. As with the electricity sector, scenarios show transportation becoming more diverse later in the century than within the time frame considered here.
11. L. Clarke *et al, CO_2 Emissions Mitigation and Technological Advance: An Analysis of Advanced Technology Scenarios for Greenhouse Gas Mitigation*, Pacific Northwest National Laboratory, (December 2008), p. 5.18. Available at http://www.pnl.gov/science/pdf/PNNL18075.pdf.
12. To assess feasibility, the authors compared modeled technologylevels to an Electric Power Research Institute (EPRI) assessment of the capacity that could be built in 2030. (Electric Power Research Institute. *The Power to Reduce CO_2 Emissions: The Full Portfolio*. August, 2007.) The authors seek to assess the gap between what the scenarios indicate is required and what the EPRI analysis indicates is feasible. The EPRI "PRISM" analysis generated an estimate of the maximum deployment potential by 2030 for several clean energy technologies, based solely on technical feasibility. We utilize it as an expert opinion against which we benchmark the technology deployment levels in PNNL's technology scenarios and score their feasibility accordingly. EPRI's analysis was generated through a "bottom-up" review of technology performance capabilities and deployment potential, informed by the organization's expertise and consultations with its industry members. Some technological progress would be required to reach these levels, but EPRI includes only the potential that could be achieved given a supportive policy environment and feasible R&D progress (no technological breakthroughs are required). It is important to note that since EPRI's analysis only goes to 2030, meaningful comparison with technology penetration levels in EPRI's 2030 scenarios required interpolating PNNL's results for 2030 and comparing those to EPRI's estimates.
13. Even in the PNNL cases with advanced CCS assumptions, the amount of coal with CCS never reaches the potential shown by EPRI. However, the PNNL scenarios do show CCS deployment associated with oil, biomass, and natural gas, where EPRI does not. This could partly explain why the PNNL cases have more natural gas in many cases than the EPRI scenarios.
14. U.S. cumulative costs undiscounted.
15. Nicholas Stern, *The Economics of Climate Change: The Stern Review,* Cabinet Office—H.M.Treasury (Cambridge, England: Cambridge University Press, 2006).
16. National Energy Technology Laboratory, *Resists Attack, Appendix A3: A Systems View of the Modern Grid* (2007). Available at http://www.netl.doe.gov/moderngrid/docs/Resists%20Attack_Final%20_v2_0.pdf.
17. European Wind Energy Association, "Supply Chain: The Race to Meet Demand," *Wind Directions* (January/February 2007). B. Shah, *Solar Cell Supply Chain*, JP Morgan (January 7, 2008).
18. Sarah M. Forbes, Preeti Verma, Thomas E. Curry, and Dr. S. Julio Friedmann, *Guidelines for Carbon Dioxide Capture, Transport, and Storage* (Washington, DC: World Resources Institute, 2008). Available at http://pdf.wri.org/ccs_guidelines.pdf.
19. Electric Power Research Institute, *Green Grid: Energy Savings and Carbon Emissions Reductions Enabled by a Smart Grid* (2008).
20. David Hill, Idaho National Laboratory, "Generation IV International Forum." Presentation at the NATO-Russia Advanced Research Workshop, Carnegie Moscow Center, March 27-28, 2008. Available at http://www.sipri.org/contents/expcon/mccprolresistance.html. Accessed July 22, 2008.
21. Richard G. Newell, "Climate Technology Research, Development, and Demonstration: Funding Sources, Institutions, and Instruments," *Assessing U.S. Climate Policy Options*, Resources for the Future (2007), pp.118-132.
22. L. Clarke *et al, CO_2 Emissions Mitigation and Technological Advance: An Analysis of Advanced Technology Scenarios for Greenhouse Gas Mitigation*, Pacific Northwest National Laboratory, (December 2008). Available at http://www.pnl.gov/science/pdf/PNNL18075.pdf.
23. L. Clarke *et al, CO_2 Emissions Mitigation and Technological Advance: An Analysis of Advanced Technology Scenarios for Greenhouse Gas Mitigation*, Pacific Northwest National Laboratory, (December 2008). Available at http://www.pnl.gov/science/pdf/PNNL18075.pdf.

The **World Resources Institute** is an environmental think tank that goes beyond research to find practical ways to protect the earth and improve people's lives. Our mission is to move human society to live in ways that protect Earth's environment and its capacity to provide for the needs and aspirations of current and future generations.

At a time of new global opportunities and challenges, the **Center for Strategic and International Studies** (CSIS) provides strategic insights and policy solutions to decisionmakers in government, international institutions, the private sector, and civil society. A bipartisan, nonprofit organization headquartered in Washington, DC, CSIS conducts research and analysis and develops policy initiatives that look into the future and anticipate change. Founded by David M. Abshire and Admiral Arleigh Burke at the height of the Cold War, CSIS was dedicated to finding ways for America to sustain its prominence and prosperity as a force for good in the world. Since 1962, CSIS has grown to become one of the world's preeminent international policy institutions, with more than 220 full-time staff and a large network of affiliated scholars focused on defense and security, regional stability, and transnational challenges ranging from energy and climate to global development and economic integration.

ISBN 978-1-56973-711-8