Clean Energy Investments in an Uncertain Future

by

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Bachelor of Science in Physics
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and the Department of Civil and Environmental Engineering
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ABSTRACT
The energy sector faces a multitude of challenges related to climate change and energy security. These challenges will likely prompt considerable changes in the coming decades, including significant investment and new market design. To help fulfill multiple goals and limit the necessary tradeoffs among them, industry and policymakers alike are looking to new technologies. However, uncertainty regarding the challenges, the solutions, and the behavior of the energy system, make it difficult to discern which investment is right for what time.

This thesis reviews the potential changes in today's energy system and examines the difficulties of addressing challenges that appear urgent yet elusive. An extensive literature review considers the problems of clean energy investment decision-making in modern energy systems, and evaluates the potential contributions of a real options approach and system dynamics. A case study on the market growth of Gas-to-Liquids technology provides more detail on the use of system dynamics to gauge market uncertainties.

Admitting to the lack of appropriate tools to objectively evaluate strategies for tackling today's energy challenges, this thesis helps answer why such questions as the appropriate timing investment are so difficult to answer, and contentious. Ultimately, it suggests a framework for considering the problem of clean energy investments under uncertainty. It considers a real options approach and system dynamics, despite their limitations, as a start for developing sophisticated tools to help grapple with investment uncertainties and to create thoughtful, strategic plans.

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Chapter 1: Preface and Overview

Rising concerns about energy security and climate change are prompting changes in energy systems worldwide. But how should stakeholders react? Which type of investments are appropriate, and at what times? Should stakeholders even attempt to change course given the uncertainties about the timing and impact of climate change and the uncertainty about the ability of various energy sources to meet our needs?

The original motivation for this thesis was to evaluate the advantages of early action to address energy and environment concerns such as climate change. However, a literature review of current challenges and approaches revealed that the question is difficult to objectively assess in a quantitative manner. Disputes in the policy arena and varied approaches by industry about the stringency and timing of action to address climate change intimate such troubles. Under the premise that new tools might improve upon current strategy, this thesis goes on to examine the benefits and limitations of a real options approach and system dynamics. It concludes that these tools may be a good start to addressing some of these issues and calls for more research on ways to apply them. Having found limited information on the current strategic-planning tools in use, it also suggests further research with industry and policymakers to learn more about the specific tools and processes they use to strategize their policies and investments.

The second chapter of this thesis begins with an overview of climate change and energy security and notes the approaches policymakers propose for addressing them. It highlights the overlap and tension among the multiple goals policymakers seek and observes the subsequent calls for investment in new technologies to limit potential tradeoffs. In addition, Chapter 1 reviews the concerns that industry has regarding balancing supply with demand in coming years, and their similar consideration of new technology as a way to meet projected challenges.

Chapter 3 details the challenges of making investments to address energy concerns. Specifically, it considers: How does one deal with a problem such as climate change that is full of uncertainties? And how can one make the 'right' investments to address such problems when the energy system is unpredictable and beyond the control of a single actor?

Chapter 4 discusses potential approaches to answering the question, what is the cost of delaying clean energy investments? It narrows the scope of the thesis to investments made by industry.

The theory of real options and the modeling approach of system dynamics are potentially useful tools to evaluate clean energy investment strategies. Chapter 5 reviews their limitations and advantages for helping develop a strategy towards clean energy investment strategy in the midst of uncertainty.

Chapter 6 reviews a case study of the use of system dynamics to analyze the potential market growth around Gas-to-Liquids (GTL) technology. Further work on the model could provide more insight about the use of system dynamics for understanding clean energy investment problems from a business perspective. Chapter 7 then concludes with a summary of previous chapters, and a note about further research.

Chapter 2: Energy Challenges, Approaches, and Trends

According to Chevron Texaco, the world is "witnessing a new energy equation driven by a number of factors," including increasing world demand, more challenging supplies, and a "complex geopolitical environment" (Chevron Texaco 2004). Exxon Mobil also believes significant changes are on the horizon, and that, "providing timely and adequate supplies is a large scale, long-term challenge" (Exxon Mobil 2004). As governments take action to address mounting concerns such as climate change and energy security, the energy industry is also preparing to operate in a new environment. Both government and industry are looking to new technologies to cope with supplying the growing demand that fuels economic growth, while addressing global energy concerns.

Changing Policy Environment

From regional electricity blackouts to price spikes in international oil markets, and from local air pollution to global climate change, the consequence of energy system performance is pervasive. As of late, energy security and climate change have reached the top of the agenda for many countries and corporations alike. Climate change has been the focus of recent international discussions such as the Gleneagles G8 Summit of 2005, and major oil and gas industries have discussed climate change concerns in their annual reports.[1] Government concerns over energy security and climate change are prompting changes in public policy which affect the environment in which the energy sector operates.

The discussions of climate change and energy security are familiar to many. To refresh the minds of readers and point to emerging policy trends, the following details the concerns, and policy approaches related to climate change and energy security.

Climate Change Definition

The United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as:

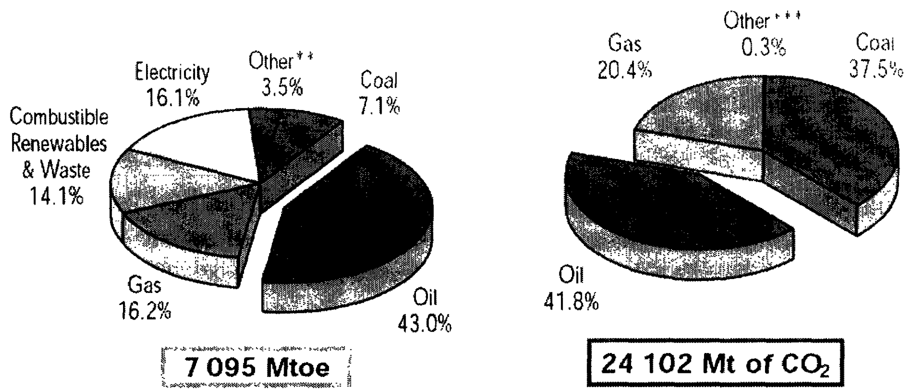
> *a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods*
> (United Nations 2005).

Scientists have studied questions related to greenhouse warming for a century. The institutional and socio-economic issues, however, have come in focus only the last couple of decades. Now the center of international debate via forums such as the UNFCCC or the Kyoto Protocol, the call to action to mitigate and adapt to climate change has taken on increasing urgency.

[1] For more detail, please see Chevron Texaco 2004, ExxonMobil 2004, Shell 2004 and G8 2005.

As the impacts of climate change are wide-ranging and potentially catastrophic, policymakers have a keen interest in mitigating climate change and its effects. The energy industry has a central role in mitigating climate change, as fossil fuels, which account for over half of total energy consumed worldwide, contribute the majority of global CO2 emissions. As the IPCC noted in its 2001 synthesis report for policymakers, "Emissions of CO2 due to fossil-fuel burning are virtually certain to be the dominant influence on the trend of atmospheric CO2 concentration during the 21st century" (IPCC 2001, 27).

Figure 1. World Total Energy Consumption and CO_2 Emissions by Fuel (2002)



Source: IEA 2005c, 28 and 44.

The following reviews potential effects caused by climate change as analyzed by scientific experts.

Climate Change Impact

Since its establishment in 1988, the International Panel on Climate Change (IPCC) has assessed the scientific, technical, and socio-economic information regarding climate change.[2] According to its latest assessment, there is strong evidence that global warming is occurring and that human activities have contributed to the warming observed over the past fifty years. An increase in greenhouse gas emissions due to human activities has led to a higher concentration of greenhouse gases in the atmosphere. This, in turn, has led to a change in global average temperatures, as well as other climate changes. Measurements indicate a 31 ± 4 % increase in the atmospheric concentration of CO2 from 1750 to 2000, and an increase in global mean surface temperature of about 0.6 ± 0.2°C over the twentieth century (IPCC 2001). In addition, scientists have observed other effects consistent with the theory on global warming, such as changes in sea level and precipitation, and the retreat of glaciers. For example, scientists believe that over the 20th century, the global mean sea level has risen by about one to two millimeters per year.

[2] According to the Principles Governing IPCC Work as mandated by the United Nations Environmental Program and the World Meteorological Organization, "The role of the IPCC is to assess on a comprehensive, objective, open and transparent basis the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation." (IPCC 2003)

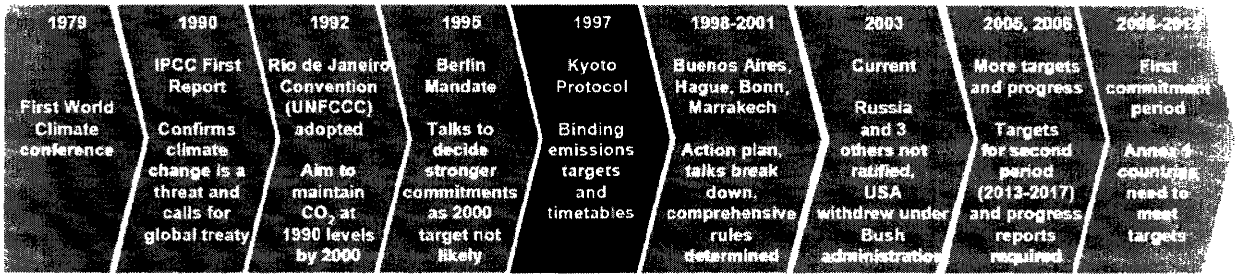
Though there are uncertainties about the size of increase, the IPCC projects that atmospheric carbon dioxide concentrations, global average surface temperature, and sea levels will continue to rise.

The projected change in climate will likely have varying impacts by region, some positive and negative. However, for most areas, the adverse impacts are likely to overwhelm the beneficial ones. Furthermore, should the rate and extent of climate change increase with greater cumulative emissions, the effect of negative impacts will likely dominate everywhere. Climate change scientists expect an increase in extreme weather events, and a change in climate variability. Scientists also note the possibility of an increase in flooding, and in some areas increased drought and fire. The above changes, along with regional changes in patterns of species and diseases could threaten human health, biodiversity and ecological productivity (IPCC 2001). Local socio-economic and environmental conditions, as well as actions taken to adapt to climate change, will affect the impact and extent of damage. However, the potentially irreversible damages due to climate change, such as the extinction of species and human settlements lost to flooding and extreme storms and the threat to human quality of life, make climate change a critical issue for policymakers. Though the above is not an exhaustive list of the potential impacts of climate change, and though there are great uncertainties about what the extent and location of potential impacts will be, it is clear that the risks of the socio-economic effects of climate change are high.

Approaches to Addressing Climate Change

154 nations and the European Community adopted the United Nations Framework Convention on Climate Change in 1992. It went into force in 1994 with 189 signatories. The UNFCCC was the first agreement of its kind, urging international action to limit greenhouse gas emissions (GHGs). Its ultimate objective is to stabilize the atmospheric concentration of GHGs "at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC 1992). However, the UNFCCC sets no mandatory target for what constitutes a dangerous GHG emissions concentration. The Kyoto Protocol, which went into force in February of 2005, sets mandatory limit on the GHGs of its signatories. This will require major adjustments to signatories' energy systems. Other international agreements and dialogues such as the UNFCCC and G8 Summits are prompting action outside of the Kyoto Protocol. World leaders at the Gleneagles G8 Summit, for example, vowed to make discussion and action on climate change a top priority, regardless of their Kyoto commitments (G8 2005). Apart from the mandatory or voluntary commitments to reduce GHG emissions, particular actions to do so are generally unspecified. However, several experts have promoted theoretical approaches and many countries have already taken action. While there are measures to address emissions associated with agriculture, land-use changes and forestry, and waste management, this paper will focus on energy-related policies.

Figure 2. Kyoto Timeline



Source: Goldman Sachs 2004, 39.

Three general strategies for reducing GHG emissions related to energy include: 1) increasing the use of energy sources alternative to fossil fuels; 2) reducing the carbon-intensity of production; and 3) raising the energy efficiency of supply and demand (Climate Change Secretariat 2004). Regardless of the approach taken, the goal of many government policies is to decouple emissions increases with economic growth while protecting the environment and ensuring energy security. Promoting energy efficiency is a common strategy among actors due to its potential for multiple benefits, including cost savings and demand management. However, developed and developing countries are making use of the several techniques available to mitigate GHG emissions in multiple sectors.

Common tools to address climate change include fiscal incentives and disincentives, market mechanisms, voluntary agreements, regulation and standards, research and development, and information and education. The focuses of these instruments span a broad range of energy areas. For example, several policymakers have used economic incentives to internalize the cost of carbon, and promote the use of alternatives. Such measures include carbon taxes, reduction in fossil fuel subsidies, and tax credits and accelerated depreciation for renewable energy sources and energy efficient products. Market mechanisms developed in and among countries include carbon emissions trading, such as the European Union Greenhouse Gas Emission Trading Scheme, and tradable renewable energy credits, as implemented in some states in the U.S. While many policies require mandatory action, voluntary and negotiated agreements are also in wide practice. These have ranged from agreements to reduce energy consumption, conduct energy audits, increase the efficiency of products, and engage in emissions trading. Regulations and standards are also in effect to coordinate new technologies as well as encourage prompt action. Policies in this area range from energy efficiency requirements and production targets for renewable energy, to coordinating interconnection standards for distributed generation or developing hydrogen safety standards. Research and development is also an important initiative used to develop and reduce the costs of such technologies as carbon sequestration. In addition, information and public awareness is important to promoting the necessary changes in industry and amongst consumers to mitigate climate change. Best practices and information sharing, public awareness campaigns, and product labeling are such notable measures (Climate Change Secretariat 2004 and IEA 2005b).

The above is not an exhaustive list but it illustrates the extent of activities being taken to mitigate climate change. Numerous countries, at different stages in economic development, are taking a range of actions. The focus of policy ranges from supply and demand and from fossils fuels to alternatives. For example, the Philippines has passed an Energy Plan to increase its renewable energy capacity, while France and Finland have increased their nuclear power generation capacity with upgrades and new investments. Some strategies involve "no regrets" measures,[3] while others assume a near-term cost with the intention of long-run benefits from climate change mitigation. Overall, countries are already making significant policy changes to their energy systems and a major transformation to energy systems worldwide is on the horizon.

Energy Security Definition

Energy security is also a concern for policymakers and industry. Though it is a separate issue from climate change, the two are both linked to energy resources, infrastructure, and usage. In fact, the definition of energy security has changed over time, and is even varied amongst its users today. Generally, it refers to the reliable and adequate supply of energy at affordable prices. More broadly, it entails the timely management of world energy resources. The following section highlights background significant to the issue, and notes the expansion of the meaning of energy security from oil and import risk to other types of energy and risks. It also discusses the integration of energy security with goals of economic growth and environmental protection.

In the 1970's, the prime focus of energy security was access to oil and limiting import risks. After the oil price shocks of 1973-1974, twenty-six nations took action to improve their energy security by signing the Agreement on an International Energy Program (IEP), which established the International Energy Agency (IEA). The main concern of the treaty was oil supply and affordability. Its objectives were to "promote secure oil supplies on reasonable and equitable terms," "take common effective measures to meet oil supply emergencies," "promote co-operative relations with oil producing countries and with other oil consuming countries", "play a more active role in relation to the oil industry," and reduce their dependence on imported oil (United Nations 1974).

With the growing importance of electricity to energy systems and the rise in natural gas use worldwide, energy security has evolved to encompass more than just oil and import risks. According to the IEA, "Today, the term includes other types of energy, and risks such as accidents, terrorism, under-investment in infrastructure and poorly designed markets, all of which might curtail adequate supplies of energy at affordable prices" (IEA 2002).

To facilitate the discussion of energy security, it helps to sort the issue by its two factors: 1) economic shortages due to market power and 2) actual shortages in supply. The former is predominantly concerned with the concentration in energy markets and the resulting price distortions, while the latter primarily relates to balancing supply and

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[3] 'No regrets' strategies refer to actions whose benefits are greater than their cost, regardless of climate change mitigation impact.

demand in time. An economic shortage is when the market price of energy is set as if energy were in short supply, when in actuality the supply is abundant (Greene and Ahmad 2005).

The Impact of Energy Security Failures

The majority of the world's proven oil reserves are geographically concentrated. Because of this concentration, competitive markets may easily be hindered. The Oil Embargo of 1973 proved just how much turmoil a key producer could create by limiting production. Today, the Organization of the Petroleum Exporting Countries (OPEC), an organization of eleven oil-exporting countries,[4] accounts for almost forty percent of the world's oil production and roughly two-thirds of the world's proven oil reserves (EIA 2005b). OPEC's large production capacity allows it to heavily influence world oil prices, which remains a concern for oil-importing nations.

Table 1. Oil Reserve Estimates by Geography

Rank	Country	Oil – Proved Reserves (bbl)	% of World Total	OPEC	Middle East
World	-	1.025 E 12	-	-	-
1	Saudi Arabia	2.617 E 11	26	√	X
2	Canada	1.789 E 11	17		
3	Iran	1.380 E 11	13	√	X
4	Iraq	1.125 E 11	11	√	X
5	United Arab Emirates	9.780 E 10	10	√	X
6	Kuwait	9.650 E 10	9	√	X
7	Venezuela	7.800 E 10	8	√	
8	Russia	6.900 E 10	7		
9	Libya	3.800 E 10	4	√	
10	Nigeria	3.400 E 10	3	√	X

Note: Estimates established in 2004, Except for Russia, 2003 and World, 2002.
Source: Data from (CIA 2005).

Price spikes due to manipulation of market power are a serious threat to the energy security of oil-dependent nations. For example, a 2005 report published by the Oak Ridge National Laboratories estimates that for the United States, the cost of oil dependence since the 1970's has accrued to $2.7-$4.7 trillion in constant 2000 dollars (Greene and Ahmad 2005). The same report characterizes these losses as due to: transfer of wealth, loss of potential GDP, and macroeconomic adjustment costs. The transfer of wealth refers to the direct payment of dollars for oil, while the potential loss of GDP refers to the loss in consumer and producer surplus by paying higher than competitive prices. The macroeconomic adjustment cost relates to the underemployment in capital

[4] OPEC Countries include: Algeria, Indonesia, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, United Arab Emirates, and Venezuela (EIA 2005b).

and labor due to slow adjustments in prices and wages from a price shock.[5] In addition to economic costs, a jump in oil prices can raise the cost of daily activities that rely on it, incurring social costs and affecting quality of life.

Even without market manipulation, however, price spikes due to shortages in oil supply can occur. Such disruptions are due to actual supply shortages versus the economic ones described above. For example, many transportation and production disruptions can occur, caused by factors such as social unrest or strikes. Though natural gas has never experienced similar supply disruptions, imbalances between supply and demand have caused price spikes before.

In fact, imbalance between supply and demand is a general energy security concern for all types of energy. As the industrialized nations increase their use of digital technologies, for example, electricity reliability is becoming an important factor in energy security. For example, a 2003 blackout in the U.S. left 50 million people without power for 36 hours, interrupted telecommunications, water, sewage services, costing approximately $6.4 billion in economic activity (ELCON 2004).

Underinvestment, technical failures, and political instability, amongst other factors, can disrupt the delicate balance between supply and demand, creating price shocks. Such shocks can affect quality of life, and incur significant economic costs. Efforts to address energy security require policies to address market imperfections or simply protect people from the serious consequence of disrupted energy supply.

Policies for Addressing Energy Security

Oil-importing countries can protect themselves against market manipulation by reducing the net price elasticity of demand for concentrated oil sources (Greene and Ahmad 2005). Several provisions outlined in the Agreement on IEP, which continue today, were intended to do just that.[6] Many also addressed disruptions due to real supply shortage, as opposed to economic shortages. Additional steps, such as improving investment conditions, specifically address market flaws to keep supply and demand in better balance. The following outlines policies to promote energy security, according to their focus area, many of which are relevant beyond oil security. Generally, these include demand response, supply investment, reserve creation, diversity in fuel type and source, and increasing transparency and information. Overall, increasing the flexibility in supply and demand can increase the quick response and recovery from shortages and breakdowns.

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[5] High energy prices increase input costs as energy is a component of all production and services. A resulting increase in inflation can lower demand and create anticipation of higher interest rates, reducing investment. A price shock that throws an economy out of equilibrium can result in underemployment of both capital and labor, if rigidities in the market keep prices and wages from adjusting quickly.

[6] Such measures included: development of emergency reserves, fostering dialogue amongst producer and consumer countries, creation of an international information system, development of long-term cooperative efforts to promote energy conservation, the accelerated development of alternative energy sources, and research and development (United Nations, 1974).

Institutional preparation is one tactic to prepare for the long-run. Dialogue with producer countries is intended to foster an understanding between players in the market. Emergency strategies to allocate scarce supplies where they are needed are critical to ensuring quick and seamless short-term responses to disruptions. Demand response is another critical tactic to react to energy disruptions. Investment in energy efficiency of consumption can be a powerful tool. Reserve supplies, such as the Strategic Petroleum Reserve for oil or spinning reserves for electric power, can tide over critical demand in the short-run. Information systems that monitor energy markets can be a way to warn of imminent imbalances between supply and demand. Increasing the reliability and timeliness of data can make warning systems more effective. Investment is a critical task to ensuring energy security. Encouraging a favorable investment climate to ensure adequate infrastructure and capacity is a basic requirement for any energy market. Diversifying investments by location and fuel type, and developing cost-competitive substitutes, can reduce the impact of price changes in a fuel source.

Overall, energy security is a significant concern for many countries. Policies to improve energy security seek to affect investment and improve the operation of market. This potentially creates significant changes for participants in the energy markets. A quote from an IEA document on energy security nicely summarizes:

> *The principal method for assuring dependable supplies is fostering adequate resource development by a diverse group of suppliers through the creation of efficient markets, undistorted pricing, secure frameworks for investment and transparent relations between consumers and suppliers. This is backed up by emergency response measures* (IEA 2002, 3).

Policy Overlap and Tensions

Though energy security and climate change are distinct issues, they are intimately related because of their mutual concern with energy use and supply. A sophisticated view of energy systems acknowledges the impact that it has on multiple socio-economic and environmental goals. Over the years, countries have begun to take an 'integrated approach' to energy, harmonizing their agendas with broad-looking policies. The Comminiqué from the Gleneagles G8 Summit highlights this trend:

> *We will act with resolve and urgency now to meet our shared and multiple objectives of reducing greenhouse gas emissions, improving global environment, enhancing energy security and cutting air pollution in conjunction with our vigorous efforts to reduce poverty* (G8 2005).

A look at national energy policies, and the IEA's Shared Goals adopted in 1993, reinforces the evidence.[7] However, as much harmony as some policies have managed, necessary tradeoff amongst goals are likely to be inevitable. Additional international development commitments add to the challenge of balancing multiple objectives. The following considers the overlap in approaches to climate change and energy security, noting the sustainability goals of countries taking integrated approaches. In addition, it

[7] Please see Appendix I for a copy of the IEA Shared Goals.

examines the challenges to achieving multiple goals. Finally, it discusses the differences in strategies to highlight the impending tradeoffs.

Synergies of Integrated Approaches

The general strategy for mitigating climate change, at its most basic, is to increase the use of alternative energy sources, reduce the carbon-intensity of production, and increase energy efficiency. In addition, energy security seeks to balance supply and demand such that supplies are adequate, reliable, and cost-effective. Many options can help meet these multiple objectives and balance the needs for energy security, environmental protection, and economic development. Carbon capture and storage technology, for example, could permit the continued use of fossil fuels while cutting their GHG emissions. Because fossil fuels currently account for the largest share of energy consumption in the world, their continued use is a significant factor in maintaining the use of affordable supply. As noted earlier, increased use of other less carbon-intensive energy sources can also reduce emissions while enhancing energy security. Domestic low-carbon sources such as nuclear power, renewables, and natural gas, for example can reduce import dependence and diversify demand. In addition, energy efficiency of supply and consumption can increase energy intensity, lowering operation costs and emissions for the same output.

International development agencies are also looking to integrate approaches for economic development and the environment. The United Nations' Millennium Development Goals, adopted in 2000 by the General Assembly, for example, seeks to simultaneously reduce poverty, and improve health, education, and environment among other things.[8] To balance economic development, security, and environmental goals, many of such initiatives are looking to approaches similar as those described above. The World Bank, for example, is poised to increase its annual lending commitments for energy efficiency and renewable energy projects by 20% per year, from 2005 to 2010 (World Bank Group 2004).

Development Goals

Development initiatives are strongly tied to energy as the access to reliable energy sources can improve quality of life and increase economic productivity. Benefits range from improving sanitation, education, and working conditions to providing relief from chores, access to information, and increasing mobility. The environmental, health, and economic aspects of energy usage make it a key part of international development initiatives. As the IEA notes:

> *Energy is a prerequisite to economic development. The prosperity that economic development brings, in turn, stimulates demand for more and better energy services* (IEA 2005d, 35).

While total and per capita energy consumption in developing countries is lower than that of industrialized nations, per capital energy consumption is likely to rise with economic development. Population growth will likely also contribute to a rise in developing countries' total energy consumption. A rise in energy consumption causes serious

[8] For more a more detailed description of the goals, please visit http://www.un.org/millenniumgoals/

concern about an increase in GHG emissions. Compatibility between the two goals of energy security and climate change reduction will depend on the availability and attractiveness of non-carbon-intensive energy sources, and the priorities of developing nations. Fossil fuels, however, tend to be available and more economically attractive than other options. China, for example, was already the world's second largest emitter of greenhouse gases in 2000 (Marland et al 2005), and its fossil fuel consumption continues to rise (BP 2005). The potential for future economic growth along with a heavy reliance on fossil fuels means developing countries could significantly contribute to global GHG emissions. The following EIA statistic highlights, though somewhat exaggerates, the cause for concern. If the world emitted carbon at the same per capita levels as industrialized countries, total carbon dioxide emissions in 2001 would have been 3.5 times greater than they were (EIA 2004b).[9] The effort to reduce poverty and permit economic expansion, while curbing emissions is a tenuous one.

The availability and use of cost-competitive alternative sources and energy efficiency could relieve this tension. However, the technologies are generally either not yet available or have not yet been adopted.

> *A concerted global effort to drive down the costs of low carbon technologies would allow continued poverty reduction without excessive increases in greenhouse gas emissions in the medium or long term. We are, however, a long way from this reality* (UK 2004, 25).

While it is not clear if government initiatives to prompt energy expansion in development countries will succeed,[10] the desire to promote economic growth while curbing emissions may be a significant tension if the technologies considered are not considered cost-effective by developing nations. The choice and timing of technology investment is at the crux of the problem. Whether countries will wait for technologies to progress or continue with the best available resources as soon as possible, regardless of carbon content, remains to be seen.

[9] Per capita energy consumption in developing countries is actually significantly lower than developed countries (EIA 2004b).

[10] Many of the world's poorest countries have yet to start the cycle of energy infrastructure development and economic growth.

Table 2. Policy Goal Descriptions, Overlaps, & Tensions

<table>
<tr><td colspan="3">ISSUES</td></tr>
<tr><td>Climate Change
Reduce GHG Emissions Associated with Energy Demand and Supply</td><td>Energy Security
Provide Reliable & Adequate Supply of Energy at Affordable Prices</td><td>Development
Improve Health, Education, and Environment</td></tr>
<tr><td>• Promote Alternative Energy Sources
• Increase Energy Efficiency
• Reduce Carbon Intensity of Fossil Fuels</td><td>• Facilitate Demand Response
• Inc & Diversify Supply Investments
• Reduce Import Dependence
• Prepare Emergency Responses</td><td>• Develop Energy Infrastructure to Improve Quality and Capacity
• Identify and Promote Energy Uses to Aid Economic Growth Goals</td></tr>
<tr><td colspan="3">OVERLAPS</td></tr>
<tr><td colspan="3">• Energy Efficiency: reduces consumption for the same output, thus lowering operation costs and emissions
• Renewable Energy: domestic, cost-effective alternatives to fossils can cut emissions and reduce import reliance
• Carbon Capture and Sequestration: permits continued use of fossils to meet supply needs while limiting emissions
• Technology Transfer: reduce fossil fuel consumption in developing countries and limit emissions or potential competition over fossil fuels.</td></tr>
<tr><td colspan="3">TENSIONS</td></tr>
<tr><td colspan="3"><u>Challenges</u>
• Develop supply in time to meet growing demand, while mitigating the environmental consequences of production and consumption.
• Providing the energy necessary for developing countries to grow their economies and meet their basic needs, while limiting resulting emissions and avoiding competition over potential supply shortages.

<u>Tradeoff</u>
• Shift to new technologies if and only when they meet the same performance criteria and become cost-competitive with current applications, and risk the consequence of continued emissions, OR
• Motivate earlier change to address climate change by internalizing the cost of carbon before the new and old technologies converge, and bear the potential costs to economic growth and energy security.</td></tr>
</table>

The Difficulty of Integrated Approaches

While many of the suggested integrated approaches are feasible ways to meet multiple objectives, many of them face short- to mid-term challenges. Fossil fuels have supplied the majority of global energy consumption for decades. They currently tend to be less expensive than alternative sources. As a 2004 UK policy document notes:

> *The tension between ever increasing dependence on fossil energy and the urgent need to reduce world greenhouse gas emissions presents a major challenge for policy makers considering long term energy security* (UK 2004, 14).

Though fossils have reliability and safety concerns, so do their alternatives. Many are familiar with the environmental and security concerns of nuclear power. Most renewable sources currently provide limited capacity, are difficult to integrate with traditional power sources due to their intermittency, or have costs that affect their adequate supply at cost-competitive prices. Hydrogen, an innovative energy carrier that may some day be produced by carbon-free methods, would likely increase GHG emissions in the short-term because its conversion process is inefficient and non-fossil production is too pricey. Furthermore, safety issues need to be resolved. Much more development is needed to address the above concerns with fossil fuel alternatives.

In addition, fossil-enabling technologies are also expensive and have safety concerns. Carbon capture and sequestration, for example, is still deemed too expensive in many cases, and there is concern about its long-term reliability and environmental side-effects. Natural gas is a less carbon-intense source than oil. While advanced liquid natural gas (LNG) technologies have reduced the cost of transport, the market is still developing.[11]

Many policymakers are looking to advanced technologies and research and development to solve these issues. IEA noted the important role of new technologies when they developed their Share Goals in 1993.

> *Continued research, development and market deployment of new and improved energy technologies make a critical contribution to achieving the objectives outlined above. Energy technology policies should complement broader energy policies. International co-operation in the development and dissemination of energy technologies, including industry participation and co-operation with non-Member countries, should be encouraged* (IEA Ministers 1993).

Summary

Despite very different origins of the challenges with energy security and climate change, emerging policies to address them have a significant overlap. This is not that surprising, however, given that several of the earliest policies to address energy security and environmental concerns were 'no regrets' strategies.[12] Many countries have also recognized the interconnection between energy and other national goals, and are aiming to take integrated approaches. However, in these same plans, countries seem to rely on technological developments to widen their options and meet multiple policy goals while limiting the tradeoffs among them. World leaders at the G8 Evian Summit of 2003, for example, promoted international collaboration on the research and development of new energy technologies to provide energy security and mitigate climate change (G8 2003).

The fact that many new technologies are not cost competitive with conventional applications creates a tension amongst these potentially divergent goals. Countries want to assist development goals, for example, but would like to slow demand enough so supply can keep up. Rapid growth rates mean potential competition over resources

[11] More detail about the growth of natural gas markets follow below.

[12] 'No regrets' strategies refer to actions whose benefits are greater than their cost, regardless of climate change mitigation impact.

scarce in the short- to mid-term. Concerns over climate change add another constraint on the goal of economic growth. The energy system is large and complex, and poses many challenges to governments. Many governments would like to see a global free market supporting their energy needs. However, they are also increasingly concerned about market externalities such as climate change and energy security, and are shifting and developing new policies to shape the market to meet its needs.

Energy System Trends and Industry

Apart from a changing political environment in response to climate change and energy security concerns, energy systems will have to cope with changes in supply and demand. Demand is growing, and industry and energy experts project that it will continue at a rapid rate. Supply is also changing. Markets are becoming increasingly global and longer distances in travel are required. In addition, industry is looking to develop fields in new regions and of new types. Meeting rapid demand growth with adequate supply is a challenge for industry, which is looking to new investments and technologies to help.

Demand

A surge in demand from developing countries like China and India has prompted concern about the potential for future rapid demand growth. The IEA projects that if current trends hold, energy demand will increase sixty percent by 2030 (IEA 2005d). Exxon and Shell, among other energy companies, are preparing to meet what they call a significant challenge. ExxonMobil noted in a 2004 report, "Developing reliable, affordable supplies to meet this energy demand will be an enormous challenge" (ExxonMobil 2004a).

Population growth and concerted efforts to improve access to energy and expand economies contribute to the expectation that demand will rise at unprecedented rates. World population growth has been rapid over the years, and will likely continue to rise for the foreseeable future. According to the US Central Intelligence Agency (CIA): "The planet's population continues to explode: from 1 billion in 1820, to 2 billion in 1930, 3 billion in 1960, 4 billion in 1974, 5 billion in 1988, and 6 billion in 2000" (CIA 2005).

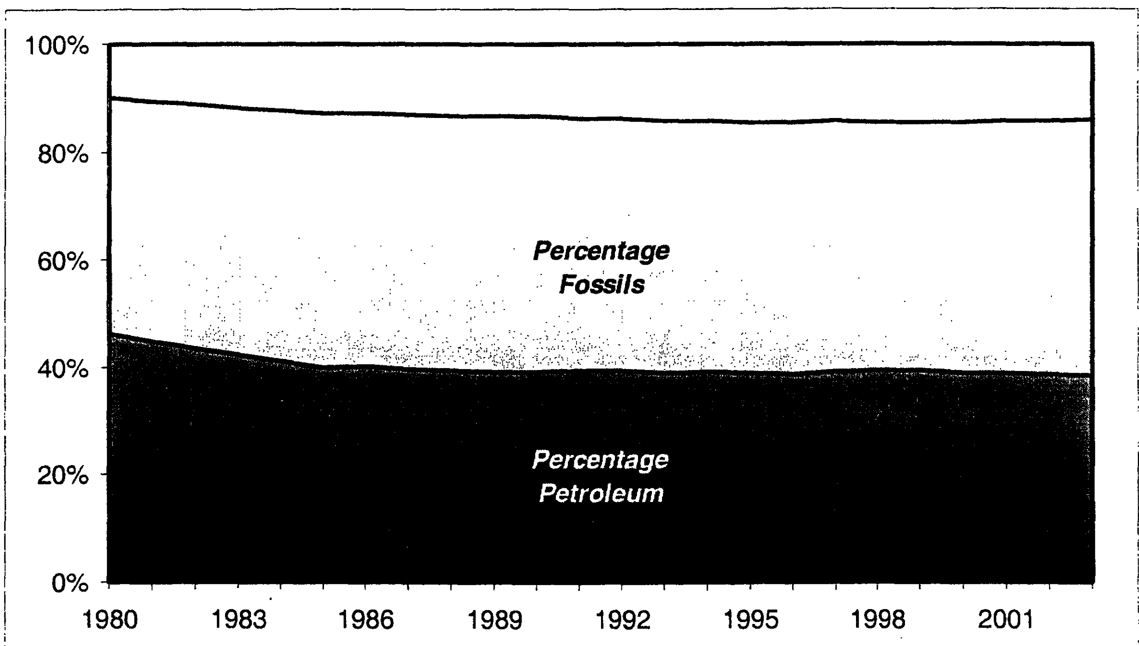
In addition, several developing parts of the world have recently experienced sharp economic growth. According to a 2004 US Energy Information Agency (EIA) report, the gross domestic product (GDP) of developing countries in Asia nearly quadrupled between 1980 and 2001, outpacing the rest of the world.[13] In addition, CIA World Factbook numbers on economic output give a sense of the economic growth in some developing countries. Though global output rose by 4.9% in 2004, the output of China, Russia, and India rose by 9.1%, 6.7%, and 6.2%, respectively (CIA 2005).

[13]Note: Developing Asia includes: Afghanistan; American Samoa; Bangladesh; Burma; Solomon Islands; Bhutan; Brunei; Cambodia; Sri Lanka; China; Cook Islands; Fiji; French Polynesia; Guam; Hong Kong; Hawaiian Trade Zone; Indonesia; India; U.S. Pacific Islands; Korea, North; Kiribati; Korea, South; Laos; Macau; Mongolia; Maldives; Malaysia; New Caledonia; Niue; Vanuatu; Nepal; Nauru; Pakistan; Papua New Guinea; Philippines; Samoa; Singapore; Thailand; Tonga; Taiwan; Vietnam; Wake Island (EIA 2004b).

Fossil fuels have been the predominant provider of energy throughout the world, though it has fallen somewhat over time (please see Figure 3). Energy companies expect that increased demand for energy will most likely be met, at least initially, by fossil fuels because of their ease of use and low cost. For example, the predominant fuels for transportation, around the world, are petroleum-based. Though per capita sales of motor vehicles in developing countries remain low, it is on the rise in rapidly growing regions like China and India. According to the EIA, "... more cars were sold in China in 2001 than in four of seven G-7 countries. This has large implications for world energy use and carbon dioxide emissions trends." In addition, fossil fuels accounted for 60% of electricity generation in OECD countries. Non-OECD countries are even more dependent on fossil fuels for electricity generation (EIA 2004b).

While developing countries tend to consumer at lower per capita rates than industrialized nations, economic growth in developing countries and population growth worldwide increase expectations that fossil fuel consumption around the world will rise. This expectation has significant implications for suppliers. According to a 2004 ExxonMobil report, industry will need to add about 80% of today's production in 10 years, in order to meet demand.[14]

Figure 3. The Share of Fossil Fuels in World Energy Consumption (1980-2003)



Source: Calculated with Energy Information Agency 2005 data (EIA 2005a, tables 1-4).

[14] ExxonMobil, "A Report on Energy Trends, Greenhouse Gas Emissions, and Alternative Energy." February, 2004 Exxon Mobil Report

Supply

While forecasts are limited in their ability to predict the future, they often represent trends and can often spur activity.[15] In the short-term, companies are looking to promote energy efficiency in both supply and demand to extend the lives of existing resources. In the long-term, however, the energy industry is looking to increase production of fossil fuels to meet the expected demand growth. Many are already preparing to develop new resources as well. For example, ExxonMobil's Senior Vice President, Rex Tillerson, noted his company's increased investment in resource development over the years, during a presentation at the Goldman Sachs' 2004 Global Energy Conference:

> *Capital investment has tripled since the merger (1999). This increase in resource development activity is providing the replacement for production volumes lost to normal field decline in our existing producing areas, as well as the source for volume growth in the future* (Tillerson 2004).

Fossil fuels continue to be the preferred area of investment for energy companies, regardless of their view of its long-term profitability in a carbon-constrained world. Royal Dutch Shell plc has the most invested in renewables as compared to other major energy companies. However, current investments are minor when compared to overall operations. The predominant argument for stronger investment in fossils as compared to renewables this is that supply from renewables could not feasibly meet demand. In a 2004 report, Shell noted, "the continued reliance on fossil fuels is mainly because other energy sources will not be available on a large enough scale over the next 20 years" (Shell 2004, 12). Exxon Mobil, in a 2004 report, explained their preference for R&D over investment was due to the insufficient return on investment (Exxon Mobil, 2004a).

Trends and Challenges

The continued production of fossil fuels to meet supply, however, poses its own challenges for the long-term. First, the scale of investments to meet demand growth is unprecedented. In addition, many energy companies expect to shift production from conventional resources to non-conventional. For example, during the same presentation as noted above, ExxonMobil Senior Vice President noted:

> *In 2003, conventional resource developments represented 80% of our volumes. ... But, volume from emerging and development technologies more than double by contribution in 2010, with substantial growth in deepwater, arctic, and LNG* (Tillerson 2004).

Finally, several of the areas where new production is planned, is in new areas under different political regimes and with harsh physical environments. Both trends to shift the physical and the geographic profiles of fossil fuel production pose new challenges. Harsh environments require technological breakthroughs to ensure stable supply at adequate costs, and non-conventional resources require novel approaches for extraction. ExxonMobil is relying on new technologies to be able to extend their production:

[15] For more discussion on forecasts, please see Chapter 2

New technologies will likely continue to extend the recoverable resource base, making additional – but currently uneconomical – conventional and unconventional resources commercially attractive (Tillerson 2004).

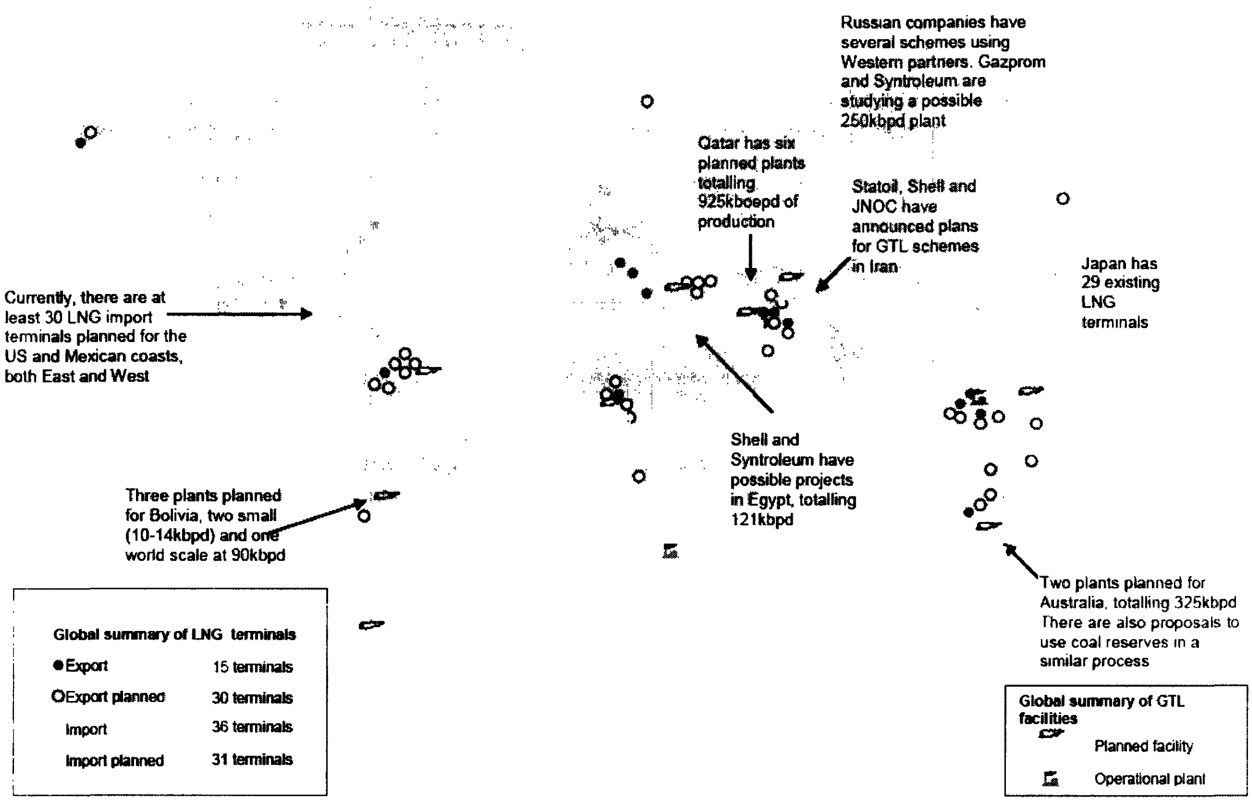
The Growth of Natural Gas

The natural gas market has been growing as of late, and companies are keen to make investments in this area. Technological breakthroughs have increased access and lowered production and distribution costs. In addition, its flexibility of fuel uses, such as for transportation or power generation, its abundance in reserves, and its lower carbon-intensity of combustion[16] make it a very attractive energy source. Increased growth in natural gas demand and long distances between demand and supplies contribute to people's expectations that natural gas will grow into a global market.

Currently, natural gas markets are isolated. However, changes in pricing mechanisms such as shorter contracts, have increased flexibility and encouraged global trade (EIA 2004a and EIA 2003). Global natural gas consumption has increased significantly in recent years. In 2004, consumption grew by 3.3 percent, as compared to 2.3% average in the past 10 years (BP 2005). International trade of natural gas has increased too. According to an EIA report on LNG, pipeline exports of natural gas grew forty-six percent from 1995 to 2002. In addition, trade in LNG increased by sixty-two percent. While markets have much further to go to fully liberalize, companies are already making investments, especially in the area of LNG. In 2003, fifty-five of the world's 151 LNG tankers were under construction (EIA 2003). A 2004 report by Goldman Sachs estimates that recent plans announced by the industry could double current global capacity in LNG by 2007 (Goldman Sachs 2004). Figure 4 displays a map of LNG and Gas-to-Liquids (GTL) investment projects. GTL technology, a proven technology that converts natural gas to low-sulfur diesel fuel could also accelerate the consumption of natural gas.

[16] Natural gas emits twenty-five percent fewer carbon emissions than oil, and fifty-percent less than coal (Goldman Sachs 2004, 16).

Figure 4. LNG & GTL Investment Projects



Source: Goldman Sachs 2004, 93.

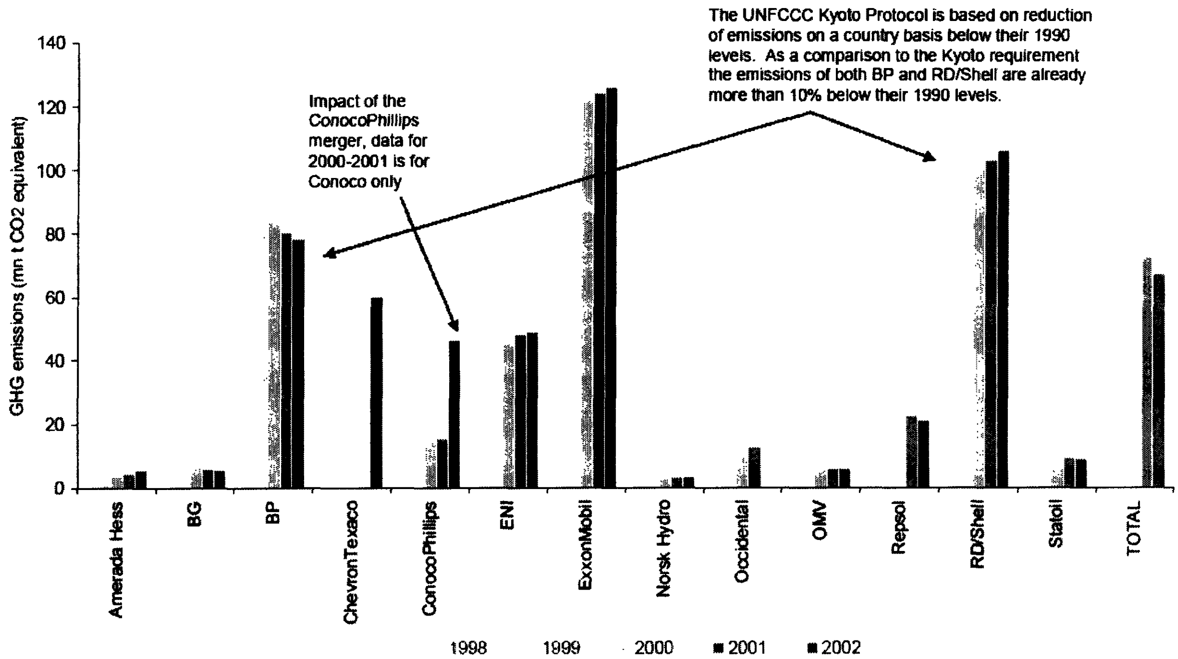
The Problem of Climate Change

Increasing supply in time to meet demand is challenging on its own. However, the added constraint of minimizing GHG emissions makes it a daunting task. The issue of climate change affects the energy industry in several ways. An increase in harsh weather conditions in certain areas could affect the cost and reliability of production and distribution. An increase in volatile weather conditions in the Gulf of Mexico has already impacted drilling operations (Goldman Sachs 2004).

Regardless of physical damages, government attempts to internalize the cost of carbon emissions, could dramatically affect demand profiles or supply costs. The GHG emissions associated with energy companies are significant (please see Figure 5), and cutting them could be costly. The Carbon Disclosure Project estimates that the costs of Oil and Gas Industry to cut its emission by 10% below 2001 levels could range from 0.4% to 2.5% of annual cash flow (Goldman Sachs 2004, 50).[17] In addition, as energy production represents only 10% of total GHG emissions, steps throughout the supply chain must be made to reduce emissions in the long-run (Goldman Sachs 2004, 41).

[17] Note: The cost of carbon reductions depends on many factors, including the market price of emissions.

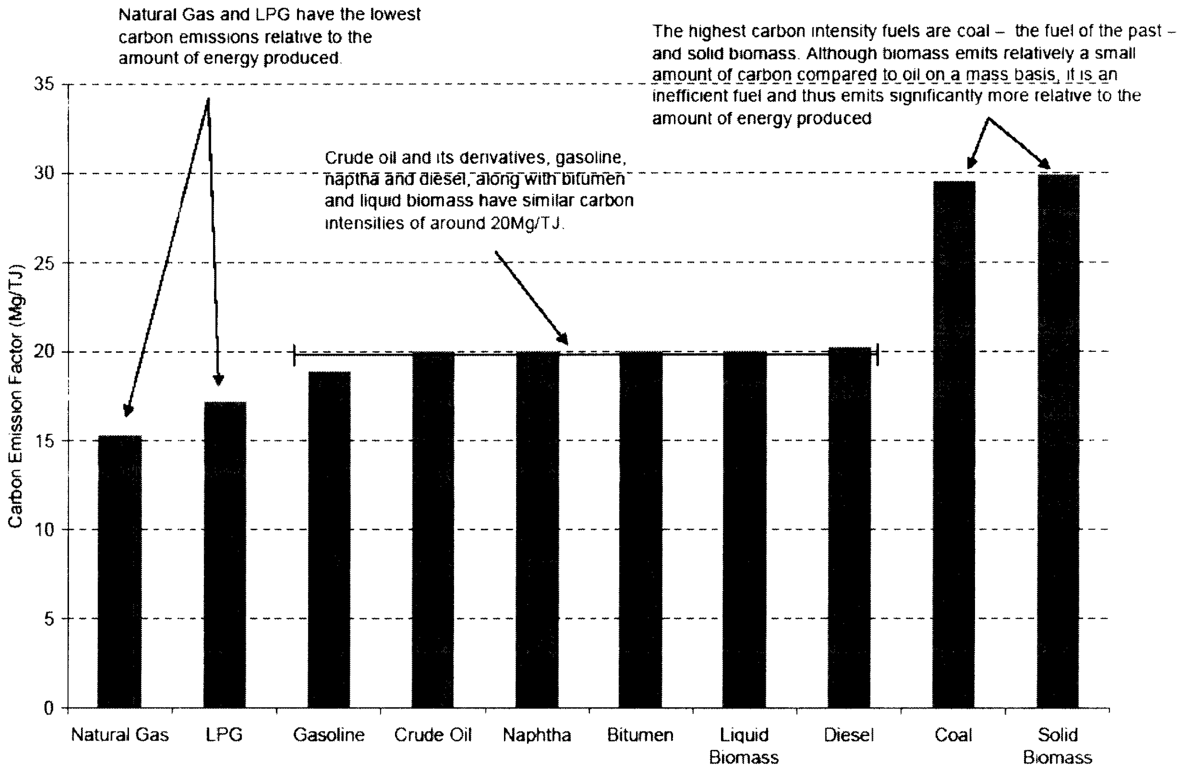
Figure 5. Absolute Emissions of Major Oil & Natural Gas Companies



Source: Goldman Sachs 2004, 48.

While energy companies are looking to meet growing demand with fossil fuels, the carbon-intensive nature of their production, distribution and, use is problematic (please see Figure 6). The trend towards an increase in non-conventional sources may contribute to the problem. Heavy oils, for example, provide significant amounts of recoverable reserve, and may help to geographically diversify sources. Canada and Venezuela's recoverable heavy oil reserves, for example, are similar in size to Saudi Arabia's conventional reserves (Holditch 2003). However, they are very carbon-intensive. The above, though not an exhaustive assessment, illustrates the potential tension that future reserves may pose.

Figure 6. Carbon Emissions Factors



Source: Goldman Sachs 2004, 85.

The challenge of increasing supply in a timely manner to meet demand is significant. However, impending efforts to internalize the cost of carbon may make the current approach that industry is taking, more difficult. Furthermore, the uncertainty of when such a change may occur makes investment tricky. Industry may soon find itself in the middle of political tensions over the desire to both meet energy security goals while mitigating the causes of climate change.

Summary

While energy experts and industry alike believe that energy reserves are sufficient to meet demand in the coming decades, both note that securely meeting demand in a timely, cost-effective manner will likely be a long-term challenge. According to Chevron, "Energy will be one of the defining issues of this century, and one thing is clear: the era of easy oil is over."[18]

Energy companies are bracing themselves for massive investment to increase supply, and are looking to new technologies to help. Many have started efforts to increase efficiency, boost production, and develop new techniques to extend current resources and access new ones. Fossil fuels expansion, especially in natural gas, is currently the focus of their efforts, and they are relying on technology to help meet long-term needs. Overall, the market is experiencing serious change, including a shifting geographic and physical

[18] Chevron, 2005, Will You Join Us Campaign. Information available online at http://www.willyoujoinus.com/

composition for fossils, potentially a more global market. While there is a trend towards an increasingly diverse mix of increased renewables, natural gas, and alternative petroleum sources, traditional fossil fuels currently dominate the mix.

The challenge for meeting demand may be difficult in its own right. However, concerns over climate change may significantly impact demand profiles, and thus the return on investments. Its impact is already noticeable, with the increase in demand and supply of natural gas. As Shell noted in its 2004 report on sustainability:

> *... both meeting the energy supply challenge and first slowing, and then eventually reversing, the rise in carbon emissions will remain a major challenge for energy producers and users alike* (Shell 2004, 9).

Similar to policymakers, industry is also looking for technologies to help them meet the challenges they face in a changing world of energy.

Conclusion

The energy system is complex, far-reaching, and poses many challenges to governments and industry alike. Issues of climate change, energy security, and economic development have been of growing concern for policymakers worldwide. Because policies to address each overlap, they cannot be thought of in isolation. In light of this, many policymakers seek integrated approaches. However, there are also likely tradeoffs among goals. For example, providing the energy necessary for developing countries to grow their economies and meet their basic needs, while limiting resulting emissions and avoiding competition over potential supply shortages, will be a challenge. Policymakers are thus looking to technological advances in fossil fuel and renewable energy production, distribution, and use to limit these tradeoffs and unify goals.

In addition, the energy market is experiencing significant change, including a shifting geographic and physical composition of fossil fuel resources and a potentially more global competitive market. While there is a trend towards an increasingly diverse mix of increased renewables, natural gas, and alternative petroleum sources, traditional fossil fuels currently dominate the mix and may continue to do so for the foreseeable future.

As such, energy companies are bracing themselves for massive changes, including a need to invest to increase supply. The challenge for meeting demand may be difficult in its own right. However, concerns over climate change may significantly impact demand profiles, and thus the return on investments. Like policymakers, they too are looking to new technologies to help.

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Chapter 3: The Difficulty of Investment

Introduction

Changes in the energy system are on the horizon, and some of the investments to fulfill that change are already being made. However, several aspects of the energy system make investments challenging. Any investment faces risk, such as operational or market risk, due to technical and socio-economic factors. However, uncertainties make decisive action difficult, from both a public policy and private investment perspective.

This chapter examines the difficulty of making clean energy investments in a changing energy system. It briefly highlights some usual risks that deter investment and are significant to energy, those related to price and regulation. It also elaborates on some of the uncertainties regarding energy security and climate change that can affect investment environments. Furthermore, it discusses the tradeoffs that must be made in the face of uncertainty, provides a brief summary on problems of valuing costs and benefits of actions, and outlines theories and examples of disputes over the correct course of action. Uncertainties make it difficult to justify actions, let alone develop appropriate strategies. Examples of divergent corporate strategies also highlight the difficulty of addressing energy challenges. Finally, the chapter concludes with an examination of why traditional strategy of building to the forecast is unsatisfactory.

Energy security and climate change are shrouded by large uncertainties, and unforeseen events can lead to startling and catastrophic events. Addressing the potential threats of climate change and energy security rely on long-term planning. However, uncertainties make the costs and benefits of action unclear. This in turn affects stakeholders' ability to justify action and develop solutions that optimize present and future returns. Traditional strategies, like building to the forecast, are no longer effective so creating and coping with changes is so difficult.

Investment Risks

Private investment is an important component of the global energy system. Most of the non-OPEC countries have private oil sectors (EIA 2005), and a rush of deregulation in electricity and natural gas markets around the globe has increased the role of the private investment in these areas as well. While industry is responsible for a significant portion of the necessary investments to ensure the reliable and adequate supply of energy for consumers, they invest on the basis of economic returns. Investments in the energy sector may yield large returns, but determining the appropriate timing and choices can be a tricky. Market risks, including price levels and volatility, and regulatory risks, regarding environmental regulation and market design, are particularly thorny.

Price Risk

Investors in any market must deal with price risk, which affects their ability to ensure a sufficient return on investment within a reasonable period. Because investments in the energy sector are typically long-lived and capital intensive, price risk is a rather significant factor in investment. Low prices can deter investment in energy supply. However, price volatility is also a significant factor for energy investors. While the expected growth in demand is encouraging new investments in supply, if demand rises faster than supply, the market might experience severe price shocks. Though an increase in supply generally encourages more investment, price volatility can pose a threat to investment.

A 2001 regression analysis done by IEA, noted that an increase in oil price volatility is associated with a decline in investments by the oil industry. They explain that an increase in price volatility can reduce the willingness of people to invest, due to a perceived increase in the uncertainty of future returns. With higher risk premiums, energy companies may be dissuaded from investment, thus exacerbating the problem of shortage supplies. As the authors state:

> *Bearing in mind the very capital-intensive nature of the energy industry, the mutually reinforcing volatility effects may have a significantly adverse impact on oil supply due to the increase in the rate of return demanded by the source of capital* (IEA 2001, 15).

Resulting high prices from supply-demand imbalances will likely help to curb demand. However, rigidities in the market, such as the transportation sector's large dependence on oil, make the prospects of delays in change and subsequent economic and social costs during imbalance likely.

Regulatory Risk

Given the long-term, large-scale nature of required investments, investors would like to assure that they receive sufficient returns. Fostering good working relationships with host countries is a key component of this. Private investments are also of interest to policymakers because of the energy security and environmental implications of their choices. Political stability and transparency in emerging markets helps cultivate investor confidence. Internalizing externalities is another way policymakers can assist. However, political instability, or inability to reach consensus on a long-term policy framework can impede private investment by increasing the chance that investments become stranded, and lower expected returns. This in turn can add to financing costs. Industry's expansion of production to new areas may also incur political challenges. Restrictions on foreign direct investment, for example, pose a challenge to developing resources.

The issues of climate change and energy security are difficult on their own. Economic and scientific uncertainties about climate change and energy security make valuation of when and how to respond to or preempt climate change difficult. However, political confusion in addressing these issues may also add to the challenge for investors, if such debate affects regulatory stability. Because private investment accounts for a significant portion of the energy system, the need to balance fostering private investment while correcting for market externalities is an important one for policymakers. Further discussion on the challenge of developing appropriate strategies, for industry and policymakers, follows below. First, a brief discussion of uncertainties in climate change and energy security leads into why such decisions may be difficult.

Scientific and Economic Uncertainties of Climate Change and Energy Security

The following details some of the current uncertainties regarding climate change and energy security. Both the impacts and possibility of failures in energy security and existence of climate change remain uncertain.

Climate Change Uncertainties

The existence of climate change and its potential for damage is generally agreed upon. However, the details of its causation and impact remain elusive. While further research and development may resolve uncertainties in the near-term, the complexity of the Earth's climate system means that uncertainties will likely remain. As a 2005 joint statement by eleven national academies states: "There will always be uncertainty in understanding a system as complex as the world's climate" (National Academies' Joint Statement 2005).

Despite a general recognitions that the average global temperature is warming and anthropogenic emissions is in part responsible, the causation and potential for future climate change is as of yet unclear in many regards. For example, scientists cannot specify the sensitivity of climate change to emission concentrations. As the IPCC noted in their 2001 Assessment, "There is a wide band of uncertainty in the amount of warming that would result from any stabilized greenhouse gas concentration" (IPCC 2001, 19). Also, while the uncertainties regarding radiative forcing from anthropogenic GHG are small, the indirect effects of aerosols on clouds are not well quantified. Furthermore, the existence and strength of climate feedback mechanisms is vague. Experts believe that large-scale, abrupt, non-linear changes in the climate are quite possible. However, the particular mechanisms, and thus the time-scales, and likelihood are unclear. The irreversibility of such effects is currently indeterminate too. The IPCC notes that:

> *Some of the projected abruption/non-linear changes in physical systems and in the natural sources and sinks of greenhouse gases could be irreversible, but there is an incomplete understanding of some of the underlying processes* (IPCC 2001, 14).

The uncertainty regarding the magnitude and nature of natural climate variability also obscures understanding about the ultimate effect the anthropogenic contribution to emissions concentration will have. Finally, the regional trends in climate change are also difficult to estimate.

In addition, the impact and mitigation costs of climate change are highly uncertain. Currently, scientists have a limited ability to produce reliable details of local and regional climate change projections. For example, the probability distributions of temperatures and sea-level projections are unsure. This makes assessing the economic impact of climate change difficult. Assessments are also imprecise as they rely on a number of assumptions. Integrated assessment models, for example, require predicting society's response to climate change, and developing estimates or scenarios for technological development, economic growth, and population growth, amongst a multitude of other variable factors. In addition, a short period of history offers only a limited set of data to study the correlation between economic activity and climate change. William D. Nordhaus, a prominent economist from Yale University who has extensive experience researching climate change, has noted the difficulty of modeling the impacts of climate change. In a 2000 book, with co-author Joseph Boyer, he observed:

> *In reviewing current research, it is clear that the results are highly conjectural and that it continues to be difficult to make solid estimates of the impacts of climate change* (Nordhaus & Boyer 2000, 69).

Overall, there is agreement in the scientific community that anthropogenic emissions are on the rise and that they contribute to the presently noted phenomenon of global climate change. However, the complexity of the issues, and the assumptions they require for analysis, makes assessing the extent of climate change a grueling task. Despite continued research, a number of uncertainties regarding the extent, and the environmental and economic impacts of climate change, remain. Many believe that the complicated nature of the issue will prevent us from being able to resolve such uncertainties before the consequences are realized.

Energy Security Uncertainties

As noted earlier climate change is linked to other energy objectives such as energy security. Uncertainties in energy security affect actions for climate change. For example, the challenges of one issue may affect the desirability to invest in the market in general. Also it may be difficult to develop integrated strategies if it is not clear how strong or weak the tensions and overlaps between goals are. The following highlights some of the uncertainties regarding energy security in terms of its consequences and the potential for problems, focusing on reserve estimates and estimates of the cost to the economy.

Reserve Estimates

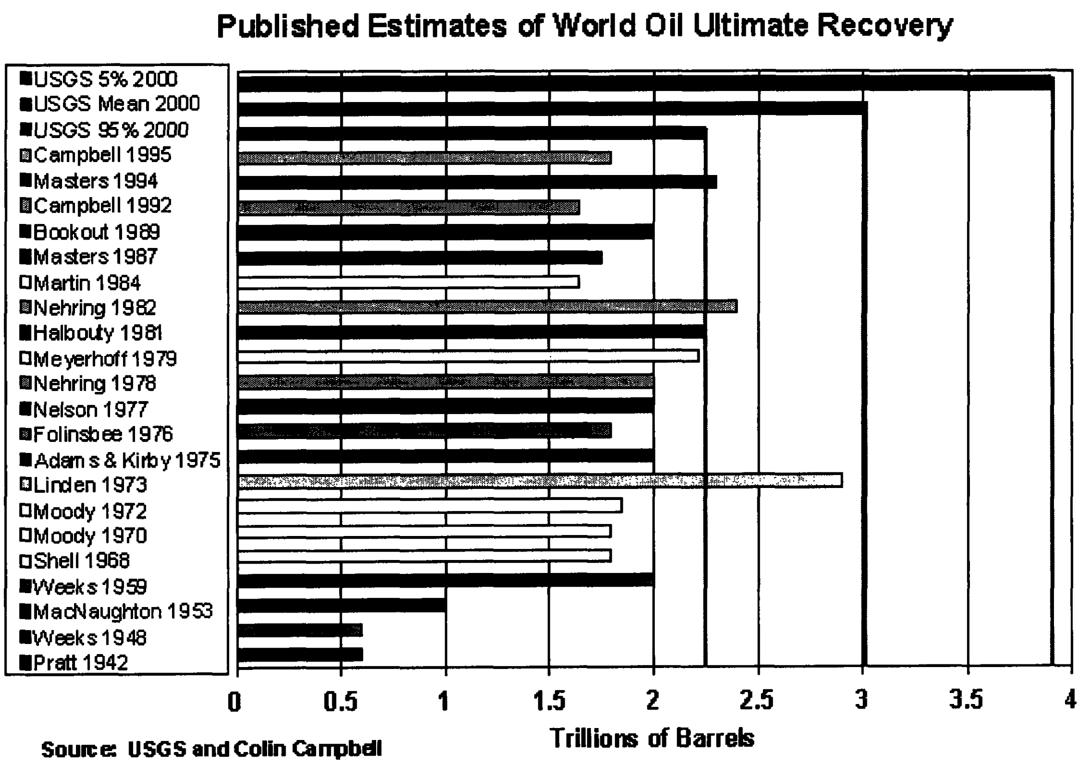
The question of global energy supply is a controversial one. The issue of energy supply is contentious because there are many uncertainties regarding reserve estimation for fossil fuels, today's predominant global energy source. The topic of oil supply is particularly intense. For years, and to this day, pundits have disputed the day when oil will run out. A 2001 USGS report on reserve growth noted: "Assessments of the remaining oil and gas potential of the United States and the world are strongly affected by the assessor's models and forecasts of future reserve growth" (Schmoker & Verma 2001, 1). Historically, industry and governments have underestimated the reserve sizes for fossil fuels. Figure 7 shows the variation in estimates of the world's ultimate oil recovery since 1942.[19] According to the same authors, the trend of increasing ultimate recovery estimates over time "is primarily due to increases in the quantity and quality of geological, geophysical,

[19] Ultimate recovery refers to proven reserves plus past production.

and reservoir engineering information, and to the development of more rigorous estimation methodologies" (Wood et al 2000, Slide 9).

New technologies are also able to boost the efficiency of production, increase access to new areas, and lower costs, opening up previously non-conventional or uneconomic sources. This unforeseen 'expansion' of sources due to technological progress also aggravates the dispute, as innovation is unpredictable. Some worry whether innovation and deployment of new technologies will occur in the appropriate lead-time to prevent demand-supply imbalances. Adequate access to economic reserves and production capacity is critical to maintaining balance between supply and demand, and preventing price spikes. Technological progress in alternative energy sources is also uncertain, and helps determines the overall cost-effectiveness and availability of supply.

Figure 7. Estimates of World Oil Ultimate Recovery



Source: Wood et al 2000, Slide 9.

Price Impact

Generally, it is difficult to estimate the affect of energy security failures on the economy, because it is hard to distinguish their affect from of all the other factors that influence economic performance. The same ORNL study referenced in Chapter 2, that estimated the cost of oil price spikes to the US economy, states that deriving such numbers is a difficult task. In particular, they note that uncertainty about the key parameters impedes accuracy.

Tradeoffs, and Valuation and Justification Difficulties

Developing supply in time to meet growing demand, while mitigating the environmental consequences of production and consumption, is a serious challenge for businesses and policymakers alike. In the midst of uncertainties about energy security and climate change, stakeholders must balance the need to continue with investments in the face of uncertainty, with the desire to wait for new information or technological developments to mitigate the change of missteps. Ideally, one would consider the costs and advantages of delaying investments in clean energy technologies. However, scientific and economic uncertainties, and differences in the valuation of options, make this question difficult to answer. The fact that inaction is itself an action, makes investigating the cost of delay an important task. The following is a qualitative overview of the tradeoffs in delaying investments in clean energy, a brief summary on problems of valuation, and a discussion on disputes over the correct course of action.

Necessary Tradeoffs

Costs and Benefits over Time

While current energy efficiency initiatives, and some natural gas and renewable energy initiatives, can provide no regrets strategies, they cannot tackle the immensity of climate change on their own. Given that research and development is still needed to limit the conflict between policy goals, any approach to address climate change, or lack thereof, will face tradeoffs. In addition, because the costs of climate change are long-term, and the need to provide energy security is a constant concern, tradeoffs between goals may include a tension between satisfying today's wants with tomorrows. As researchers and authors William D. Nordhaus and Joseph Boyer noted in their 2000 book on climate change modeling:

> *... issues of greenhouse warming invokes the highest from of global citizenship – where nations are being called upon to sacrifice hundreds of billions of dollars of present consumption in an effort that will largely benefit people in other countries, where the benefit will not come until well into the next century and beyond, and where the threat is highly uncertain and based on modeling rather than direct observation (Nordhaus and Boyer 2000, 4).*

Without cost-effective alternatives to fossil fuels, the challenge of climate change comes down to two options. One could shift to new technologies if and only when they meet the same performance criteria and become cost-competitive with current applications, and risk the consequence of continued emissions. Alternatively, one could motivate earlier change to address climate change by internalizing the cost of carbon before the new and old technologies converge, and bear the potential costs to economic growth and energy security. The rate of technological development will determine if and when this tradeoff would be made. As the IEA notes:

> *The pace of technology development and deployment in these and other areas is the key to making the global energy system more economically, socially and environmentally sustainable in the long term. But consumers will have to be willing to pay the full cost of energy – including environmental costs – before*

these technologies can become competitive. Governments must decide today to accelerate this process (IEA 2005d, 31).

Appropriate Timing of Action

Both the harms and benefits of delaying or taking action to address an environmental risk are generally unknown. The assessment of future risks is limited given present information. The disagreement over how to take action to address an environmental risk essentially comes down to one over the decision to take precautionary action or wait for proof before action (Kinzig et al 2003).

The degree of acceptability for measures to address climate change is strongly related to their economic and security costs and the risk aversion of decision-makers. Some argue that faced with uncertainties and long-term damages, society should take precautionary action now. Others argue that as information is so limited, steps should be taken as they become cost-competitive with traditional energy applications. In other words, finding that climate change is real does not justify taking prompt action because the costs and benefits of action are unclear.

Delaying action allows investors to gather more information and decrease uncertainties, which in turn helps them make 'better' investment decisions. These advantages are especially important for the energy industry which is capital intensive and whose capital tends to be long-lived. Thus, by delaying, investors may decrease the possibility of making a bad, irreversible investment. However, the choice to delay investments that address an environment risk must be balanced by the irreversible harms of that environment risk. Thus, one considers the irreversible and constraining expenditures of an investment, versus the irreversible harm of an environmental risk that has not been addressed (Dixit & Pindyck 2002).

The uncertainties associated with any adoption of a technology, such as the timing and extent of diffusion and adoption, are compounded by uncertainties regarding the effectiveness of a technology to address an environmental risk. Furthermore, should a solution rely on the creation of a new technology, research and development (R&D) uncertainties regarding the timing, and performance and cost improvements of an innovation, contribute to the problem of appropriately addressing an environmental risk.

Valuation Difficulties

Willingness to Pay

Uncertainties make it difficult to value the cost and benefits of climate change mitigation strategies because it is not always clear what they are. However, even if they were known, quantifying them would still be difficult. Valuing the costs of damages from climate change is imprecise because many of the items under threat have no market value. They are not traded goods. In addition, many are public goods which are difficult to value a market framework (CBO 2005). Furthermore, how does one go about quantifying and agreeing on the cost of lost lives or species?

Discounting
Even if one had precise numbers on the costs and benefits of action, valuation is still not clear cut because of the necessary tradeoffs between now and the future. Conventional economic analysis would discount the long-term benefits and costs, to account for the opportunity cost of money. However, by discounting future values, the cost incurred now to address climate change would be weighed more heavily than the benefits of mitigation received later. The exact choice of a discount rate affects how significant this weighting is.

Choosing a Discount Rate

As noted earlier in the discussion of investment risks, investors prefer projects with less variability in return on investment due to risk aversion, so they often require a premium before they are willing to accept projects with more uncertainty. As such, they tend to adjust the discount rate for uncertainty, to increase rate of return. Because projects differ in risk, it is reasonable for one entity to use several discount rates. Economists have developed ways to determine an appropriate discount rate, such as the Weighted Average Cost of Capital (WACC), or the Capital Asset Pricing Model (CAPM), which accounts for risk.[20] However, the theory is sometimes difficult to implement due to practical impediments, such as difficulty in calculation, and 'non-rational' reasons such as risk aversions (de Neufville 2003). Overall, despite an economically rational theory for choosing a discount rater, individual risk perceptions can affect the choice. Also, difficulties in calculation can provide the opportunity for debate on numbers.

Difficulty in Justifying Action
Regulatory Disputes
Theory

Many areas of policy rely on scientific facts to rationalize action. At times the science goes undisputed, and controversy focuses on other considerations. However, in many cases, opposition to the policy actions is made with claims that the science behind it is contestable. In particular, a lack of scientific consensus or causal explanation especially leaves science, and the policy that relies on it, vulnerable to challenge. In a 1987 article, "Contested Boundaries in Policy-Relevant Science," Shiela Jasanoff, a Professor of Science and Technology Studies at Harvard, considers the interaction of science and policy (Jasanoff 1987). She presents the idea that science is 'deconstructed' and then 'reconstructed' in the regulatory process. She also notes that the distinction between science and policy is difficult to resolve not only because science is indeterminate, but also because these delineations have political implications that make them politically charged. Furthermore, the contest amongst actors to define who can influence the

[20] The CAPM method of choosing discount rate adjusts the discount rate to incorporate risk. It does this by distinguishing market risk from project risk. It observes that one can theoretically minimize individual project risk by creating a diverse portfolio of projects that balance each other's individual risks out. It then develops an index of undiversifiable market risk, called beta, against which one can measure the riskiness of a project, and accordingly adjust discount rate. However, the method is not foolproof. Developing beta can be tricky, and in practice, the choice of discount rate may still be affected by past experiences with projects and comparable opportunities for investment. Furthermore, risk aversions differ among people (de Neufville 2003).

outcomes, takes place via boundary-defining language. Examples of these boundary disputes are evident in dialogue.

According to Jasanoff, the rulemaking process takes an adversarial approach to establishing claims, and in so doing exposes the uncertainty in and challenges the authority of science. After 'deconstructing' knowledge, the regulator must then 'reconstruct' the knowledge to maintain her own authority and construct a plausible rationale for action. In addition, Jasanoff asserts that this process of deconstruction and reconstruction induces competition amongst policy-makers, scientists, and political interest groups. The definition of an issue as a policy or a science issue affects who has the authority to interpret the facts, and potentially affects the issues outcome. Either to protect their authority or to influence the outcome, Jasanoff notes that actors use boundary-defining language to distinguish science from policy, and ultimately further their interests.

Health, environment, and safety regulation often becomes embroiled in debate over what factors should be considered in decision-making, how credible the science used in decision-making is, and who ultimately has control over deciding. Frequently complicating the process is that experts can identify fundamental correlations but the causation or extent of correlation is as yet indeterminate or not agreed upon by the scientific community. Spurred by new identification of potential harms, policy-makers often seek to take action. However, the basis of specific policy action is frequently left contestable due to the limited understanding or pending scientific community's consensus. As the former chairman of the Clean Air Scientific Advisory Committee (CASAC), Joe Mauderly, noted:

> *It is a rare circumstance where a scientist can look at the existing data at any one time and prove beyond uncertainty that a specific level [of pollution] is the right one to set [for the standard]* (Breslin 2000, A176).

The focus case of this section is the contest over the credibility of climate change science. It notes some recent disputes over climate change to highlight the difficulty of rationalizing action when the science of causation and impact is still under development. It then looks specifically at some of the policy options for taking action to note the effect that uncertainties associated with climate change can have on policy-making.

Examples of Dispute and Indecision

For decades, politicians have debated the existence of climate change and the adequacy of science to confirm it. A recent example in the U.S. demonstrates the contest between politicians and scientists that can emerge in the face of scientific uncertainty. Another example involving national scientific academies illustrates the fine line between objective scientific input and political action, and the discontent that may ensue should policymakers perceive that the line has been crossed.

Congressman Joe Barton from Texas has been chairman of the House Committee on Energy and Commerce since 2004. In June of 2005, he sent five letters to the National Science Foundation, the IPCC, and Dr. Michael Mann, Dr. Malcolm K. Hughes, and Raymond S. Bradley, requesting information regarding global warming studies. The letter to Dr. Mann, for example, offered eighteen days to provide a large quantity of information including: a full list of his studies, financial support by study and source, data sources and analysis methods, and defense of criticisms of his work. While a congressional request to scientists for clarification on issues is not uncommon, many saw Barton's actions as aggressive, and an attempt to discredit scientific research. A letter in response to Barton's request, from the American Association for the Advancement of Science illustrates such concerns:

> *Your letters, however, in their request for highly detailed information regarding not only the scientists' recent studies but also their life's work, give the impression of a search for some basis on which to discredit these particular scientists and findings, rather than a search for understanding. With all respect, we question whether this approach is good for the processes by which scientific findings on topics relevant to public policy are generated and used.*
> – AAAS, June 13th 2005. [21]

While Congressman Barton cited that the political implications of the scientific studies justified their questioning, Barton's critics worried about keeping scientific review in the scientific community. The AAAS letter continued:

> *While we fully understand that the policy-making functions of the Congress require integrating the best available understanding of relevant science with other considerations, we think it would be unfortunate if Congress tried to become a participant in the scientific peer-review process itself.*
> – AAAS, June 13th 2005.

Thus, apart from the wording or manner of investigation, the dispute was also territorial, concerning who had the right to contest indeterminate science that has a significant affect on policymaking.

A slight controversy over a joint statement on climate change made by national science academies highlights the difference in approaches that countries are taking on climate change, but also illustrates the fine line between objective scientific input and making political statements. On June 7th, 2005, shortly before world leaders were to meet at Gleneagles for the annual G8 Summit in July, eleven heads of national science academies around the world urged international leaders to take action on climate change, and noted six action items.[22] In their words: "The scientific understanding of climate change is now sufficiently clear to justify nations taking prompt action." While the timing and specificity of the statement may have implied political advocacy to some, a dispute between two administrators who signed the agreement illustrates just how fine the line boundary science and politics is. Lord May of the Royal Society in the United Kingdom issued a controversial press release the day the joint statement was issued. In it, he said:

> *The current US policy on climate change is misguided. The Bush administration has consistently refused to accept the advice of the US National Academy of Sciences (NAS). ... President Bush has an opportunity at Gleneagles to signal*

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[21] Available online at: http://www.aaas.org/news/releases/2005/0714letter.pdf.
Also, a full copy of a letter sent from Chairman Barton to Dr. Mann, and the letter from the AAAS to Chairman Barton is available in Appendix III.

[22] Please see Appendix IV for the full statement.

that his administration will no longer ignore the scientific evidence and act to cut emissions" – Lord May, June 7th 2005.[23]

A day after, the head of the National Academy of Sciences in the U.S., Dr. Bruce Alberts, wrote to Lord May to express chagrin at Lord May's statement. He also accused him of misinterpreting the work for the US NAS and stated, "You have in fact vitiated much of the careful effort that went into preparing the actual G8 statement" (Dr. Alberts, June 8th 2005).[24] In addition, US members of Congress became involved in the dispute when Senator Larry Craig of Idaho wrote to Dr. Alberts expressing concern over the statement.[25]

Several elements of Jasanoff's thesis ring true in the case of climate change. While the above examples are not an exhaustive study of the climate change issue, they do provide some evidence that stakeholders of the rulemaking process have engaged in boundary disputes that centered on the issue of science's credibility. The political implications of scientific results make credibility a contentious issue. As Jasanoff notes, the distinction between science and policy is difficult to resolve because the science is indeterminate, but also because these delineations have political implications that make them politically charged. Dispute over who has the authority to clarify and interpret uncertainty exemplifies the problem of justifying policy action when the science is indeterminate. It also highlights the potential for ensuing regulatory uncertainty.

Uncertainty and Indecision about Policy Mechanisms

Even given agreement on the credibility of science behind climate change studies, the appropriate policy response, including if one is even needed, is still contestable. The timing, stringency, and appropriate mechanisms are the focus of much debate. The following highlights the potential problem of regulatory uncertainty given that agreement over the appropriate mitigation policies is still lacking.

Policymakers around the globe have derived several options to mitigate GHG emissions. Some of them have already been implemented. However, policy mechanisms continue to develop. Policymakers and analysts debate the best approach to mitigate GHG emissions, in part because of differences in valuation and risk aversion. However, uncertainty about the costs and benefits per GHG reduction make crafting the optimal policy even more trying as it exacerbates differences in opinion about what is the optimal approach. Some of the most commonly debated policies include economic incentive policies such as price-based and quantity-based mechanisms. Uncertainty plays in.

A price-based mechanism for reducing GHG emissions is a GHG emissions tax. By placing a tax on GHG emissions, the policy increases the cost of using carbon-intensive

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[23] Available online at http://craig.senate.gov/royalsociety060705.pdf

[24] Available online at http://craig.senate.gov/nas060805.pdf

[25] Note: Senator Larry Craig wrote: "Indeed, it appears to me that the Joint Statement is being hijacked by the Royal Society for reasons that have nothing to do with the advancement of scientific understanding of this most complex and controversial subject. I would appreciate a clarification of the meaning of the Joint Science Academies Statement. I am also interested in the origins of this Statement and am very curious about the timing of the release of this Statement" (Senator Craig, June 8th 2005). Available online at http://craig.senate.gov/larrycraig060805.pdf

energy sources and encourages mitigation. Taxation of upstream sources (input fuels) would make the policy relatively easy to implement and quite comprehensive. Because regulated entities would take mitigation measures below or equal to the cost of the tax level, the upper limit of mitigation costs is apparent. The amount of emissions that would be reduced from the policy, however, is uncertain.

An alternative to a price-based mechanism is a quantity-based mechanism such as a cap-and-trade system. Such a system caps overall emissions and allocates or auctions allowances, the right to emit, to regulated entities. The total of allowances equals the cap. This mechanism assures a set level of emissions reductions, and permits mitigation to be done cost-effectively as regulated entities can trade allowances as needed. However, the overall cost of mitigation is uncertain. Also, administrative and enforcement difficulties could limit the program to a smaller and more manageable number of entities.

Both mechanisms have advantages and drawbacks, and equity issues are a concern for each. Furthermore, setting the stringency for either mitigation policy is difficult given the uncertainties. Ideally, one would want to set the marginal cost of abatement to the marginal benefit, and both are unknown. However, the presence of uncertainties also leads to disagreement in determining the appropriate policy mechanism, regardless of stringency. If the benefits were the only unknown, either policy would be suitable. Stringency would be the only issue as both would 'miss their mark' by the same amount. However, because costs are also unknown, a policy tradeoff arises: is society more concerned about uncertainty in the cost of mitigation or more about uncertainty in the amount of reduction? A US Congressional Budge Office (CBO) report on the matter asserts that analysts prefer price-based mechanisms in this scenario because one has a better chance of minimizing the cost of choosing the wrong stringency. However, they also note that if nonlinear effects exist, such as a threshold above which abrupt climate change occurs, quantity-based mechanisms may be more preferable.[26]

Overall, uncertainty in the particulars of climate change makes it difficult to justify action. Even if corporations and the policymakers agreed to take precautionary action, however, the mechanism by which to do that is still unclear.

Examples of Divergent Strategies

<u>Policymakers</u>

While there are many similarities in strategic approaches addressing climate change, such as increased energy efficiency and renewable energy use, many regions' initiatives vary. The difference in programs highlights the tension between policy goals, and the tradeoffs that must be made in the face of lack of technological solutions. For example, though the United Kingdom is accountable for less than 2% of global emissions (UK 2004), it has set stringent emissions reduction target levels and is one of the leading countries in Europe to take action. Also, a 2004 review of by the Climate Change Secretariat notes that Europe has tended to use financial measures to incorporate the cost of carbon and incentivize innovation (Climate Change Secretariat 2004). The United States, on the

[26] For more specifics on the debate, please see (CBO 2005).

other hand has relied on a voluntary approach that focuses on technological innovation. A 2005 White House fact sheet on climate change notes the Administration's preference for waiting for technological solutions:

> *Like us, developing countries are unlikely to join in approaches that foreclose their own economic growth and development." … "The President promotes technological innovation to achieve the combined goals of addressing climate change, reducing harmful air pollution and improving energy security* (White House 2005).

In addition, support for policy actions can vary, even amongst the same category of decision-makers. A comparison of two statements made by the Senate, one passed in 1997 and the other passed in 2005, reveals such a situation. In July of 1997, circa international talks about the Kyoto Protocol, the US Senate passed a resolution that expressed their disfavor of mandatory GHG emissions limits (U.S. Congress 1997).[27] However, as a component of an energy bill passed by the Senate in 2005, the Senate expressed their support for mandatory steps to mitigate climate change (U.S. Congress 2005).[28]

<u>Industry</u>

Companies have also taken a variety of approaches for dealing with climate change, different in terms of both timing and stringency. A 2002 study of multinational oil companies' response to climate change provides insight. Please see Table 3 for a summary of findings on climate position. Authors Kolk and Levy note that the divergence in action may in part to be due to different valuations of tradeoffs and varying risk aversions among the institutions in the countries in which they operate.

> *Markets are embedded in social and political structures, so their rationality is contingent upon these broader frames of references. Managers attempt to make rational calculations on cost and benefits of various strategies, but these calculations are premised upon assumptions and forecasts that are themselves shaped by interactions with competitors, governments, the media, and other institutions* (Levy & Kolk 2002, 297).

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[27] Note: "The United States should not be a signatory to any protocol to, or other agreement regarding, the United Nations Framework Convention on Climate Change of 1992, at negotiations in Kyoto in December 1997, or thereafter, which would: (A) mandate new commitments to limit or reduce greenhouse gas emissions for the Annex I Parties, unless the protocol or other agreement also mandates new specific scheduled commitments to limit or reduce greenhouse gas emissions for Developing Country Parties within the same compliance period, or (B) would result in serious harm to the economy of the United States…"

[28] Note: "It is the sense of the Senate that Congress should enact a comprehensive and effective national program of mandatory, market-based limits and incentives on emissions of greenhouse gases that slow, stop, and reverse the growth of such emissions at a rate and in a manner that--

> (1) will not significantly harm the United States economy; and
>
> (2) will encourage comparable action by other nations that are major trading partners and key contributors to global emissions."

Corporate actions are also related to other business decisions such as organizational structure and market position, highlighting the interaction that climate change strategy can have with other corporate goals.[29] A 2001 study by the same authors noted for example: "Exxon's tradition, structure and strategy-making process seems to have made it more prone to insular thinking than a decentralized company such as Shell" (Levy & Kolk 2001, 506).

A separate analysis of strategic planning in major oil companies notes the challenges that the industry face today. Author Robert M. Grant observes the difficulty of developing strategy when prediction provides limited accuracy. He also describes their attempts to reconcile difficulties. He writes:

> *The challenge of making strategy when the future is unknowable encouraged reconsideration of both the processes of strategy formulation and the nature of organizational strategy* (Grant 2003, *493*).

His study also reveals the limited use of new strategy tools and concepts, and questions the effectiveness of recent adaptations.

> *Decentralization and informality of strategic planning processes permitted access to a broader range of expertise, but there was limited use of new tools and concepts of strategic analysis and little evidence that the systems of strategic planning were conducive to strategic innovation* (Grant 2003, 515).

Overall, the variation of corporate strategies and evidence of limited innovation in the area of strategic analysis, exemplifies the difficulty of developing ways to address climate change. Uncertainties about the development, benefits and costs of options to cope with climate change make valuation of strategies difficult. Other issues such as organizational structure and regulatory uncertainty affect the development and implementation of climate change strategies.

[29] For more detail on these other aspects, see (Levy and Kolk 2001).

Table 3. Summary of Major Oil Companies' Responses to Climate Change

Topic	BP	ExxonMobil	Shell	Texaco
Climate science	Precautionary principle	Science too uncertain for action	Precautionary principle	"Need to move beyond science"
View on Kyoto Protocol	Broadly supportive	Opposed	Broadly supportive	Supports mandatory controls, but not Kyoto specifically
Global Climate Coalition membership	Left in 1996	Stayed until end of individual memberships in 2000	Left in April 1998	Left in February 2000
'Pro-active' partnerships	Pew Center, EPA Climate Wise Program, California Fuel Cell Partnership, trading system with EDF, EPA voluntary GHG reporting, WBCSD, International Emissions Trading Association	California Fuel Cell Partnership (since early 2001)[2]	Pew Center, California Fuel Cell Partnership, WBCSD, International Emissions Trading Association	California Fuel Cell Partnership, WBSCD
Trading and monitoring of GHGs	Started measurement and internal trading in 1997; appointed external accountants in 6/1999 to verify internal system.[3]	Internal measurement of emission data	Began reporting CO_2 emissions and global warming potential over 1998 in externally verified HSE report. Launched internal trading in 1/2000.[4]	Internal measurement of emission data
Quantitative GHG targets		NA	Target set 10/1998 to reduce GHG more than 10% by 2002.[6]	NA
Main investments in renewables	Owns Solarex, world's largest PV producer. Invested $100 m. in 5/2000 in online green retail electricity company.[7]	NA	Solar factories in Germany, Japan, and Netherlands. Announced renewables investments of $500 m. in next 5 years in 10/1997.[8] Solar joint venture with Siemens and EON since 2001.	Invested $67.3 m. for 20% interest in ECD (advanced batteries, fuel cells and solar technology).[9]
Main fuel-cell activities	Partnership with Ford in 2000	Exxon-GM and Toyota in 2000	Daimler and Ballard since 1998	Texaco Energy Systems in 1999

Source: Levy and Kolk 2002, 287.

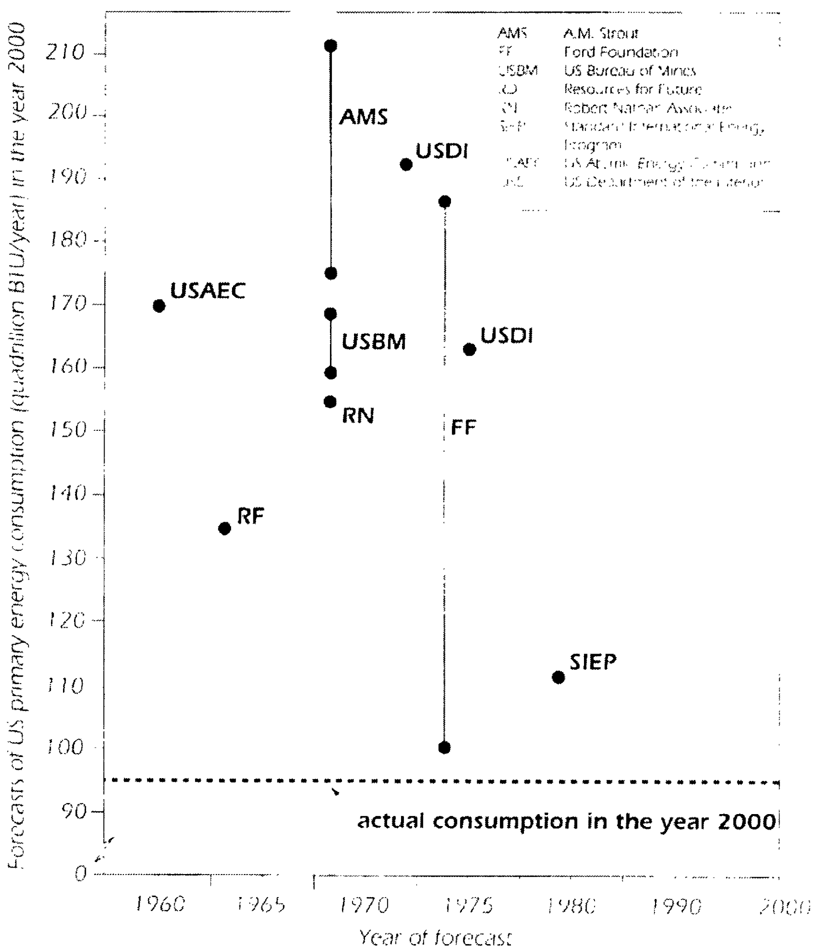
Notes: 1) According to the authors, where no sources are given, data are derived from company interviews and the official website. For details on other sources, please see original document.

2) While noting the divergent approaches to climate change, the authors also note that the global nature of the problem and the market in which the companies operate, along with more scientific information, means that companies' approaches are converging. The above chart does not note changes since 2002.

The Limitations of Prediction

Energy forecasts have gone amiss for as long as they have been made, regardless of the expertise used to develop one. Figure 8 highlights some notable misses in forecasting energy consumption. Other forecasts of the future of nuclear and solar power, and the exhaustion of energy resources, have gone awry regardless of predictor's credentials.[30]

Figure 8. US Primary Energy Consumption Forecasts



Source: Smil 2000, 255.

The task of prediction is an inherently troubled one. Increasing the reality of a model, for example, produces its own problems. As Vaclav Smil, a researcher at the University of Manitoba noted in paper about the troublesome issues he had with forecasts:

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[30] See Vaclav Smil 2000 for more detail on examples.

Greater complexity that was required to make the forecasts more realistic also necessitated the introduction of longer chains of concatenated assumptions—and this necessity was defeating the very quest for greater realism (Smil, 2, 2000).

Several other challenges to modeling make accurate forecasting difficult. Professor John Sterman, Director of Massachusetts Institute of Technology's System Dynamics Group, notes other modeling issues. For example, delays in data reporting and calculation lessen one's ability to respond to current changes and trends. To address this issue, one may consider shortening the delays. However, this often compromises the reliability of the data.

In addition, discerning temporal fluctuations from trends in the data can be a difficult task. Increasing the time horizon of analysis may help elucidate noise from trend. Nevertheless, it reduces the ability of stakeholders to respond promptly to changes in the system. In general, Sterman notes, it often takes time to recognize and accept a trend as genuine, as well as generate and implement the appropriate steps to react to once it is acknowledged.

Because it is difficult to discern noise from fact, and as forecasts often rely on knowledge of the past to speculate the future, forecasts tend to be most precise when the behavior of system drivers is steady. Changes in drivers may have an unexpected impact on the system and thus the item one is forecasting. Technological breakthrough, for example, is a difficult event to predict, which may have a significant effect on the system. Sterman notes:

"...forecasting methods are particularly poor when there are changes in trends, noise, and other sources of turbulence. These are precisely the times when people are most interested in forecasts" (Sterman 2000, 655).

Overall, there are multiple factors that affect the system one is forecasting from, and even if many are well understood, their interaction may not be. Even when systems are believed to be well understood, unforeseen events can dramatically change ones results. Forecasts, which are often used to make decisions to adjust to or affect the future, are thus often wrong just when you need them most. While forecasts can give a good sense trends that *may* continue to the future, their predications may well be erroneous. The future is not guaranteed, and as seductive as forecasts may be to help guide policy, it is not necessarily wise to build to their prediction.

Conclusion

How, if, and when energy systems are going to evolve to provide a cleaner, more secure energy future is unclear. It depends on the choices that consumers, government, and industry make. Expected trends include increasing regulation of carbon, increased regulation and incentive for energy efficiency, and a diverse energy portfolio including more clean energy technologies. Markets can change quickly and are unpredictable, due to policy changes, variance in consumer preference and technological breakthroughs. Furthermore, payoffs that would ordinarily justify investments can be unclear.

Unfortunately, forecasting provides limited help. To minimize the disruption and costs that impending changes may induce, or to even operate successfully in a climate of change, industry and government will need a deeper understanding of and better management tools for multiple uncertainties.

Also, given the multiple goals and constraints the energy system is faced with how should one take action to maximize future gains while maximizing current gains? Actors need to be able to judge what an appropriate cost of an action is even if they do not know exactly what the payoff is. They need to know what to look for, be able to gauge some of the uncertainties discussed above, and develop criteria to determine when and how to take action.

Understanding climate change is difficult because of all of the uncertainties of its impacts and causation. Coping with it is even more problematic because of the interaction it has with other goals of energy security and poverty reduction. To promote a cleaner, sustainable future, actors need to understand the costs and benefits of investments, and develop a way to examine and determine the appropriate time and extent to invest.

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Chapter 4: Approaches to Looking at the Cost of Delaying Investments

Research Question – Two Interpretations

The motivating question for this research is what is the cost of delaying investments in clean energy? One could approach this question with two consequences in mind — the impacts on the environment or those on businesses. The two overlap, but can lead down different research paths. For example, one could focus on the environmental impacts and attempt to fiscally quantify the environmental cost of what is irreversible, quantify the economic cost of clean-up for what is reversible, and quantify the indirect public health costs from both types of damage. This effort focuses on assessing the impact of an environmental harm, and is somewhat similar to the current efforts of localities to quantify their risk from climate change.

Alternatively, one could frame the question in terms of a business, and consider the business impacts of changes in environmental policy. This analysis would look at the usual risks of investment and design for engineering projects, but in an environmental context. A modern trend of addressing environmental harms by internalizing the cost of externalities or setting standards is changing the setting in which businesses operate. For example, environmental standards may confer advantages to businesses able to respond more quickly. Alternatively, regulation may spur markets for new products. Under a market approach to dealing with environmental harms, investors may face several new uncertainties with a shift in environmental policy. Multiple technology choices exist, and uncertainties about their adoption and ability to effectively address an environmental harm (while being cost effective) make evaluating the choices difficult. In addition, uncertainties about the timing of implementation and adoption make timing an investment tricky. Businesses' response to emerging or impending standards and new energy pricing will likely affect their success in the short- and long-run.

Analysis of both of the above contexts is a difficult task given the large uncertainties associated with the causation and impact of some environmental harms and the intricacy that unpredictable human response contributes to the calculation. Both also require interdisciplinary knowledge in economics, engineering, or science and how to cope with uncertainty. However, while both areas are fertile grounds for research, understanding about the latter seems slower to emerge. This research focuses on the business impacts of environmental policy changes and the ways in which decision-makers can cope with uncertainties brought about by those changes. The following note proposed ways to address the question of what is the cost of delaying investments in clean energy, from a private investment perspective. The subsequent chapter looks more closely at the tools of system dynamics and real options as feasible ways to carry out the first method.

Method – Two Approaches

To focus on the business aspects of the original research question—what are the costs of delaying investments in clean energy?—one might consider the current tools for investment decision-making or look to historical data for insight. The following describes the two research paths and elucidates my preference for analyzing and developing decision-making tools.

Scenario Analysis to Develop Uncertainty Distributions

Proposed Method: Develop a dynamic model of the endogenous supply and demand factors in a market for a clean energy technology. Conduct a sensitivity analysis to understand the potential pathways for market development under varying values of exogenous factors. This may be accomplished by generating scenarios based on expert judgment or by simulating random values for the exogenous factors. This step helps to understand the sensitivity of the market to various inputs and inform decision-makers what factors to monitor for potential changes in the market. Next, generate an uncertainty distribution for demand growth given simulated scenarios and determine an expected return using a set decision rule for investment.[31] Then, alter the decision rule for investment and compare how changes in the timing and extent of investment affects expected returns (over a range of demand scenarios).

A model of the endogenous factors of supply and demand, along with scenario analysis of the exogenous factors, could provide a useful tool for understanding the characteristics of uncertainties associated with clean energy investments and resulting market growth. In addition, it could help understand the advantages or disadvantages of investment strategies.

EXAMPLE DATA NEEDS

<u>Supply</u>

- Costs
  - Learning curves for construction and operation
  - Base costs for natural gas reserves, production costs, transportation of product
- GTL production facility characteristics

<u>Demand</u>

- Costs
  - Refinery processing costs to meet fuel standards
  - Costs for facility upgrades
- Refinery facility characteristics
- Average oil reserve quality
- Sulfur emissions produced per combustion of a certain standard fuel

[31] Decision rules may include a traditional method of forecasted demand based on forecasting, and a positive NPV calculation. More on the NPV calculation follows in Chapter 5.

ADVANTAGES

- This approach will develop a tool that is useful for making decisions under uncertainty in multiple situations, rather than just cases where a market for a pollutant has already developed (see discussion below).
- This approach does not rely on historical data. This is important as the future may not be like the past. In addition, carbon emission markets, a potential source of data on climate change, are still settling.

POTENTIAL ISSUES

- 'Accuracy' of scenarios and probability assignments
- Model accuracy (simplifications, unforeseen contributors to potential market development)

OTHER COMMENTS

- Even if the model does not accurately 'predict', one would expect to still gain insights from the process of modeling (e.g. sensitive factors for market growth).
- Further issues to consider:
  - -Is this an appropriate use of system dynamics and what are the pitfalls?
  - -How to accurately create a probability distribution from an analysis of the model?

Please see Chapter 5 for more discussion on system dynamics.

Analyze Historical Data

Method: Mine historical data on emissions markets and mitigation costs to see if there were any gains or losses from delaying investments to meet a standard. A comparison of businesses' investment decisions, and their cost of compliance with credit purchases versus technology investments, may provide insight.

Alternatively, one could consider historical data to forecast future market volatility and conduct a real options analysis of potential clean energy investments for the future. The price of emissions would be the underlying asset, and the price volatility could be extracted from data to estimate uncertainty. The investment in an emissions mitigation technology would be an option. The option expiration time would be linked to the timing of compliance assessments.

EXAMPLE DATA NEEDS & SOURCES

- Price of emissions over time (e.g. carbon or sulfur)
- Investment timing, costs, and effects
- European Climate Exchange
- Chicago Climate Exchange

ADVANTAGES

- Data is concrete, and little guesswork about uncertainty profiles is needed.

POTENTIAL ISSUES

- It may be difficult to access data on investment costs.

• The markets are still stabilizing for carbon emissions trading, and the scope of this study is somewhat limited to clean energy investments where markets exist.

Chapter 5: Real Options and System Dynamics

Uncertain timing, causation, and impact of environmental risks encourage deferral of investment. But the opportunity cost of investment, lag to develop options, and delay between action and effect limit the ability to defer action without consequence. Options cultivate the flexibility to respond to environmental risks whose magnitudes are currently uncertain. However, strategic investments are necessary because options come at a cost, and path dependencies may link past investments to future opportunities. Theoretically, system dynamics and real options could help to understand pathway limitations, address uncertainty, and allow action while avoiding building to a prediction.

The following reviews the theory of real options by highlighting its advantages over traditional practices, as well as some of its limitations. The next section discusses system dynamics, and again addresses its potential advantages as well as limitations.

Real Options

Introduction

The phrase 'real options' was first coined by Stewart Myers in 1977. An extension of financial option theory, real options theory considers physical projects rather than financial assets.[32] By using analysis methods borrowed from financial options theory, real options analysis is able to quantify the value of increased flexibility in a project, which allows managers to respond better to an uncertain future. Such options include flexibility in investment timing or even in the physical design of an engineered project. Though still a relatively new field, researchers have explored real options theory for an array of subjects, spanning from oil field investments to biotechnology research and development, to flexible design in architectural spaces.

The following section reviews real options theory to note its potential benefits and limitations with regard to the problem of clean energy investments. Without going into mathematical detail, it considers the evolution of the theory's application from 1994 to 2005. It then specifies how the theory, in its many forms, can help address some of the issues of clean energy investment, noted in Chapter 3. It also notes the potential limitations of real option theory. Finally, it discusses some examples of real options theory in practice to examine how it has so far been applied to problems of energy, the environment, or both. Thus, while this chapter does not review financial option theory or discuss real options calculations in detail, it does provide a brief overview to demonstrate how the theory fits in with the issues of clean energy investment.[33]

[32] Financial assets such as: property or commodities, rather than stock, currency, and debt.

[33] More detail can be found in the references of this chapter. For examples, Wang 2005 provides a quick and basic introduction to financial options and real options theory. More detail on analytical application of real options theory can be found in Wang 2005, Dixit & Pindyck 1994 and Smit & Tirgeorgis 2004.

The Theoretical Contribution of Real Options

The underlying concepts of real options theory provide a unique view of investment and design, and offer the possibility of valuing flexibility. Researchers over the years have presented various approaches to and uses of real options analysis. The approaches overlap to some extent, but also vary in their perspective. Overall, they are a good source for potential innovation in strategic decision-making, design, and analysis. The following considers three developments relevant to clean energy investment decision-making and the question of what is the cost or advantage of delaying investments. Despite the care of authors mentioned here, a word of caution from Adam Borison, a management and decision analysis expert, is worth noting for users. He warns against the inappropriate application of real options analysis. He observes that to use real options theory, and the financial analysis tools it borrows from, one must abide by specific assumptions. Veering from these assumptions can make application of theory easier and available for more issues, but also may skew or invalidate its results (Borison 2003).[34]

Real Options and Investment

In their 1994 book, *Investment Under Uncertainty*, Avinash Dixit and Robert Pindyck discuss the use of real options theory to derive rules for optimal investment decision-making. They focus on partially or completely irreversible investments where there is uncertainty about the future rewards of the investment and where it is possible to defer investments. The crux of their argument questions the traditional net present value (NPV) investment rule,[35] including its assumption that investments are inflexible and are now or never. Dixit and Pindyck posit that should one have the ability to defer an investment, one may gain more information in the time of delay before making the investment. In the midst of uncertainty, this could improve the design of and resulting rewards from the investment. In contrast to the traditional NPV approach, a real options view of investment values the option of waiting for new information by acknowledging the opportunity cost of making an investment immediately.

Real options theory derives this result by drawing an analogy between an investment opportunity and a call option. As such, an investment opportunity may be seen as the right, but not the obligation, to buy an asset at some future time. Thus, when one makes an investment expenditure, he or she exercises the option to invest, and gives up the possibility to wait for new information. In terminating their opportunity to wait by investing immediately, the investor looses the option value of their investment. The opportunity cost of investing now, is thus the lost option value.

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[34] Financial options theory is able to quantify the value of an option by comparing it to a group of assets whose value correlates with the option as the market changes over time. This group of assets is otherwise known as a replicating portfolio. The existence of a replicating portfolio and the idea that the market are free of arbitrage, are two critical assumptions for valuation. These assumptions may be quite difficult to abide by for physical assets that are not traded on the market. To work within these criteria, analysts often make assumptions about the projects and the assets they are correlated to. Some of these assumptions are non-controversial while others are.
For an outline of real options analysis approaches, see Borison 2003.
[35] At its most basic, this rule is to invest (or abandon investment) when NPV > 0.

A real options view of investment thus modifies the NPV rule to incorporate the opportunity cost of investment. It becomes: invest if the Value of Investment > Cost + Value of Option to defer. Along with deriving this formula, Dixit and Pindyck provide examples of how real options analysis can result in new critical values for investment. To do so, they make use of dynamic programming and contingent claims analysis.

Similar to financial option analysis, the option cost and value of investment are sensitive to the uncertainty of future values of the project. The option value increases with an increase in uncertainty. Another similarity to financial options analysis is the ability to limit the downside of an investment. If the rewards of an investment increase in value, then the payoff from investment increases. However, should the asset decrease in value, investors may choose not to invest and they would lose only the cost of creating the option to postpone the decision.

Dixit and Pindyck's important modification to the traditional NPV rule applies only under the conditions of irreversibility and uncertainty mentioned above. Without an amount of irreversibility or an ability to make the same investment in the future, the opportunity cost of investing today would be irrelevant. Also, value from the option to defer comes from the fact that the future value of the asset obtained by investing is uncertain and payoffs might not be as expected. If they were known, deferral would add no value. Furthermore, the influence of irreversibility on an investment decision decreases as the time to delay decrease, or the larger the cost of delaying. Overall, however, Dixit and Pindyck note that given the availability, deferring an investment to tomorrow should be a choice one should consider today, because it can add value to a project.

<u>Limitations</u>

Despite the value of the framework Dixit and Pindyck present, difficulties in application of the theory remain. First, the option to defer is not always clear cut: the same exact investment opportunity might not be available in the future. For example, it may not still be available or if there may be irreversible costs to delaying. Such costs could range from foregone cash flows, to loss of strategic position, or irreversible environmental consequences, depending on the situation one is considering. Dixit and Pindyck indeed note that while the benefits of waiting for new information could be large, one should weight the cost to delay against its benefits. Pindyck gives the issue of irreversible environmental costs more attention in a 2002 paper of his, discussed more below. In addition, the option analysis framework does not discuss or resolve potential issues of timing lags and path dependencies in investment projects, which may affect the attractiveness of options. With regard to valuation, real options theory is able to incorporate a risk-neutral discount rate. However, Dixit and Pindyck posit that the correct discount rate need not be constant over time and not equal to the weighted average cost of capital. Rather, they say that options analysis yields the appropriate discount rate. Nevertheless issues of valuation due to the choice of discount rate could still persist as many view economic valuation with skepticism. Finally, as Dixit and Pindyck note in the book's conclusion, methods used to calculate option values, can get very complicated very fast. In order to use the financial tools of financial options theory, real options must abide by the same rules. Doing so is difficult when underlying assets being analyzed are not traded on the market.[36] Furthermore, many of the calculations involve non-linear equations.

Real Options and Strategic Theory

Han Smit and Lenos Trigeorgis discuss the combination of game theory and real options theory in their 2004 book, *Strategic Investment*. By combining the two theories, they are able to value and quantify flexibility in decision-making while acknowledging the strategic value of limiting flexibility for reasons of competition. Commitment to a plan of action, for example, can influence how competing firms choose to invest.

By resolving the potential conflicts between the theories, they devise a framework to help managers develop and quantitatively assess strategic moves in the face of uncertainty. While real options theory encourages investors to create options that give them the flexibility to respond to situations as they unfold, competitive strategy encourages investors to limit their flexibility in order to send a credible signal of commitment to rivals. In order to acknowledge this potential tradeoff, and do a complete analysis of strategic factors, Smit and Trigeorgis present a new investment criterion. The revised NPV criterion becomes: Expanded (strategic) NPV = (passive) NPV + flexibility (option) value + strategic (game-theoretic) value (Smit & Trigeorgis 2004, 13).

Smit and Trigeorgis find unity in the seemingly conflicting theories in that both contribute to overall strategy formulation. In the words of the authors:

> *The combined framework provides a dynamic view of business strategy to assist practitioners in the building of long-run competitive advantages and strategic adaptability* (Smit & Trigeorgis 2004, 439).

Rather than simply promoting or discouraging flexibility, as the theories may imply individually, together they acknowledge the potential value of switching strategic paths over time, and recognize that strategy is often formed in the midst of a competitive environment. The concept of real options is thus valuable beyond individual project considerations, to strategic market considerations. Real options theory is useful for strategic considerations, according to the authors, because it recognizes that investments are made sequentially over time.

In using real options theory to consider strategic investment, Smit and Trigeorgis view firms' growth potential as, "a package of corporate real options that is actively managed by the firm and that my influence and be affected by competitive action" (Smit and Trigeorgis, xxv). During the discussion of growth potential, Smit and Trigeorgis note the path dependency of firms' investment possibilities. They refer to Dynamic Capabilities theory that views competence as a factor of growth potential, and note that competence-building strategies are path-dependent.

By expanding real options theory beyond project evaluation to strategy adaptation, Smit and Trigeorgis help create a quantitative framework for evaluating strategy in a dynamic,

[36] Please see Borison 2003 for more detail.

uncertain environment. This framework balances the tradeoffs of investing right away versus deferring. As game theory reveals, it is not always valuable to keep options open. Real options theory, in turn, can be used to help managers capitalize on the unforeseen opportunities and avoid downside losses. As noted before, real options theory reveals the fact that increased uncertainty can actually increase the value of options, which asymmetrically positions a project to avoid the downside while taking advantage of the upside.

Limitations

Smit and Trigeorgis directly address analyzing the potential cost of delay by incorporating game theory with real options. They do, however, restrict their analysis to corporate competitive strategy. The authors also briefly discuss the potential path dependency among strategic options for a company. While they highlight the issue and bring attention to the dynamic dimension of strategy, however, they do not present detail on how to consider path dependencies and incorporate analysis within the real options framework. Discussion regarding the existence of time lags to develop and receive returns on options is also not notable. On a separate note, while the use of decision trees and computer programming can help keep analyses manageable, the potential for calculations to become complicated is quite high, and care is needed. Furthermore, while combining real options and game theory analysis provides a valuable approach, it requires broader knowledge. This could pose a problem for the adoption of such methods. Throughout, however, the authors do pay attention to the need for simple methods to calculate option values. Overall, the authors present an impressive framework for evaluating strategy, which combines qualitative and quantitative theories. The above discussion of limitations is not meant to criticize their work. Rather, it is a notice of areas where further work in the field could help address issue of clean energy investment decision-making.

Real Options "In" Versus "On" Projects

Professor Richard de Neufville and Tao Wang, among others, expand real options theory beyond the traditional focus of investment to that of design. Apart from flexibility of an investment, one may be able to embed flexibility in the function of a project. De Neufville notes the distinction between flexibility on an investment and that related to its design. He and Wang term the two option types as 'on' versus 'in', respectively. 'On' options are concerned with project while 'in' options are concerned with design (Wang 2005).

Developing 'in' options is another way to adopt the benefits of real options theory. It allows one to adjust operations as conditions change over time. In the face of uncertainty, such flexibility can increase the value of a project by limiting its liability or increasing its rewards. By allowing managers to deal with uncertainty proactively, 'in' options take advantage of uncertainty when possible and adapts to situations as they unfold. Timing flexibility is thus not the only way to incorporate flexibility into an investment

However, the creation and use of 'in' options is slightly different than traditional applications of real options theory. To develop 'in' options for a project, one must have sophisticated and technical understanding of it. According to Wang, even identifying 'in' options can be a difficult task because of the slue of design variables and parameters. Like strategic 'on' options, 'in' options can be path-dependent. Wang notes, however, that interdependence is likely a larger issue of 'in' options. Wang provides a general comparison of the differences between 'in' and 'on' options in his 2005 PhD dissertation (please see Table 4).

Table 4. Comparison of 'in' and 'on' Real Options

Real Options 'on' Projects	Real Options 'in' Projects
Value opportunities	Design flexibility
Valuation important	Decision important (go or not go)
Relatively easy to define	Difficult to define
Interdependency / Path-dependency less of an issue	Interdependency / Path-dependency an important issue

Source: Wang 2005, 294.

Limitations

The concept of 'in' options is a unique and valuable way to make use of flexibility to increase the value of projects. The novelty of designing flexibility in engineered projects, while exciting, may present additional challenges through. For example, current real options analysis requires assumptions that may stray far from the reality of 'in' projects. As Wang notes, "real options 'in' projects are different and need an appropriate analysis framework – existing options analysis has to adapt to the special features of real options 'in' projects" (Wang 2005, 295). In response to this problem, Wang develops and tests a framework for 'in' options. It involves two phases: options identification using an optimization model, and then an option value analysis phase using stochastic mixed-integer programming with real options constraints. Wang also notes the general difficulties in using a real options methodology, including access to historical data and teaching others to understand and have confidence in the method. Historical data about financial markets is necessary for an objective analysis. Though simulations are feasible, they can inject assumptions into the model. Overall, similar if not more difficulties arise with the use of 'in' options. However, its concept is exciting and applications have so far shown its value.

Real Options and Energy and the Environment

Analysts have used real options theory to evaluate investments in energy and the environment since the 1980s. The majority of research and application has pertained to 'on' projects, which focuses on valuation of projects to determine if and when an investment should be made. Some analysis has been broader than that, such as the use of real options to analyze ways to spur private investment of thermo-power in Brazil (Wang 2005).[37] Analysts have used real options to study traditional and new technologies, on a range of issues from capacity sizing to resource valuation. Pindyck even uses real

[37] Wang 2005 references this piece, authored by Rocha, Moreira and David in 2002.

options to consider when to implement environmental regulation. The following considers some of the many relevant and notable examples of real options analysis of energy and environmental issues.

Dixit and Pindyck discuss the tradeoffs involved in investing in a production facility's capacity. Large production capacity can make use of economies of scale and help new facilities move up the learning curve. However, if demand is uncertain, commitment to large production size can turn out to be a liability. Adding capacity in increments can increase flexibility and allow investors to respond to market conditions, limiting their liability if the market turns sour. However, this flexibility comes at the expense of foregone cost reductions. Real options analysis can help decision-makers optimize their capacity investments in the face of uncertainty. Such evaluation is useful for new energy technologies which likely face the need to reduce costs to penetrate an uncertain market. According to Dixit and Pindyck, the issue of incremental capacity has been used to study investments in traditional energy supply, like electric utility capacity.[38]

Real options analysis also has a notable history of helping to value reserves and determine the appropriate time for their development. The following table from Dixit and Pindyck shows the option analogy. They draw a connection between the value of an undeveloped reserve and a call option on a stock. Such analysis may be useful for modern reserve analysis of traditional and non-traditional sources.

Table 5. Reserves as an Option

Call Option	**Undeveloped Reserve**
Stock price	Value of developed reserve
Exercise price	Cost of development
Time to expiration	Relinquishment requirement
Volatility of stock price	Volatility of value of developed reserve
Dividend on stock	Net production revenue from developed reserve less depletion

Source: Dixit & Pindyck 1994, 398.

In addition, Dixit and Pindyck discuss the use of real options to evaluate the appropriate response to or implementation of environmental policy. They discuss an analysis of electric utility compliance options for the US Clean Air Act (Dixit & Pindyck 1994, 405). Such options include relying on allowances, which are of an unknown price but are flexible, versus investing in mitigation measures, which limits flexibility in the long-run. A separate discussion and analysis of timing environmental policy also is a good case to examine the real options thinking as applied to environmental problems. It reveals the factors involved in evaluating a potentially sunk cost versus a potentially irreversible damage. They do not derive a quantitative answer but do analytically demonstrate the tradeoffs.

The application of real options theory to 'in' options is still fairly limited. Work by Lara Greden in 2004 and 2005 demonstrate the use of real options to formally value flexibility in architectural design (Greden & Glicksman 2004). Tao Wang analyzes the

[38] Dixit & Pindyck 1994 cite previous work they did with Sawhill in 1989.

development of a hypothetical river basin for hydropower. Various design alternatives include station siting, reservoir capacity, and installed capacity.

Summary

Overall, real options theory provides an array of opportunities for quantitatively assessing the value and timing of project design and corporate strategy. This is useful for justifying actions that violate traditional rules of investment. In addition, real options theory provides an opportunity to actively manage uncertainty rather than defend against it (Wang 2005). Because it permits one the flexibility to respond to situations as they arise, real options theory can increase the value of a project. Managers can prepare now to react in the future, and take advantage of upside potentials while avoiding downside risks. Table 7 summarizes aspects of real options theory that address investment decision-making challenges.

Table 6. The Contribution of Real Options

Investment Challenges	Contribution of Real Options Theory
Desire to optimize the total returns over time; Evaluate tradeoffs between now and the future.	Real options increase flexibility. While they come at a cost, the 'insurance' they provide may prove valuable, and increase overall project value over time.
Politics of valuation; Choice of an appropriate discount rate	Some, though not all, of the analytical tools use a risk-adjusted interest rate. However, there may still be room for disagreement.
Justify actions in the face of uncertainty	Real options theory provides a quantitative way to analyze options and directly incorporate uncertainty into decision-making process.

However, current limitations in application methods restrain its usage for a limited set of projects. Options analyses for example, cannot be directly applied to many engineering projects, as there is not sufficient associated market data. Borison provides more detail on assumptions of various real options applications and the limiting factors of applying the theory, though it does not specify difficulties of analyzing 'in' options. Time lags and path dependencies are also a real issue that could benefit from a more rigorous method for analysis. Wang begins to develop methods for analyzing path dependence amongst 'in' options. Finally, while real options theory greatly improves upon the traditional rule of invest if NPV>0, it may not fully satisfy skeptics, weary of the choice of discount rates. Table 6 summarizes potential difficulties of applying real options analysis to investment problems.

Table 7. Difficulties and Progress in Application of Real Options Theory

Potential Difficulties	Study & Progress
Analysts must abide by the assumptions of financial option theory, which may be difficult for projects with no correlated assets.	Adam Borison brings attention to the issue of assumptions in a 2003 paper (Borison 2003). Researchers continue to study the issue.
The calculations of real options theory can get complicated quickly, especially in continuous time models.	All mentioned authors acknowledge this fact and take care as best as possible to address it. While computer programming can help, researchers continue to work on increasing the accessibility of real options analysis
The issue of path dependence between options can complicate the analysis of their benefits, and the understanding of how to create them. Time lags to develop, implement, and benefit from options can be significant and uncertain.	Wang analytically assesses path dependence among physically designed options; Smit & Trigeorgis qualitatively discuss dependence amongst strategic options. Methods to explore this issue and link it to real options analysis appear to be limited.
It can be difficult to identify and quantitatively examine the costs of deferring options.	Researchers have made significant progress in this area. Smit & Trigeorgis use game theory to evaluate strategic costs. Pindyck studies the issue of irreversible environmental costs (Pindyck 2002).

System Dynamics

Introduction

Since 1956, Jay W. Forrester has developed the field of system dynamics. Work in the field continues today under the expertise of many others as well, including MIT's System Dynamics Group which Forrester founded in the early 1960's. Like real options theory, system dynamics has been used by researchers to study a number of subjects that range from urban studies to national energy policy to dispute resolution.

The following introduces the basics of system dynamics and notes it potential benefits and limitations in the area of clean energy investment. It also discusses examples of the use of system dynamics to study issues in the realm of energy and environment.

The Theoretical Contribution of System Dynamics

System dynamics is both a tool and an approach to understanding the world. It focuses on patterns of behavior and the structures that cause these patterns. It examines causal relationships, through modeling, in a way that accounts for delays, amplifications and distortions throughout time. By incorporating the means to examine non-linear relationships, system dynamics models can consider feedbacks among elements of a system. This allows one to analyze system behavior not immediately apparent by the behavior of its components.

While the approaches to using system dynamics may vary by some extent, they all focus on portraying the structure of a system related to the question at hand via stocks and flows. Stocks are elements of the system that accrue over time. Flows represent the information or material flows that contribute to or drain from the stocks (such as water flowing into a bathtub or draining out). Elements of a system may be physical or non-measurable items. The use of stocks and flows allows system dynamics models to represent delays in the system. The use of 'hard' and 'soft' variables helps incorporate information into the model, which may be difficult to quantify in traditional terms, but have significant relevance to the issue at hand.

Jay Forrester described the process of modeling and learning with system dynamics via five steps (Forrester 1999). I summarize these here as follows:

1) Define Goals
2) Describe the Situation (to clarify the nature of factors relevant to the question)
3) Construct the Model (and complete the description of the system)
4) Test the Model (Using simulation on can generate a history of patterns based on varying inputs)
5) Interpret Results (and go back to adjust as necessary)

The description and representation of a system allows one to test how it responds to various policies and to explain its behavior. The ultimate goal of system dynamics is to explain behavior, and develop policies and organizational structure that improve the system. The following discusses the potential advantages and limitations of system dynamics in more detail.

<u>Advantages</u>

System dynamics helps users understand the potential behavior of a system despite its complexity. For example, running various scenarios on a system dynamics models helps users understand how the system changes over time and what the range of possible outcomes are. Also, understanding the system in terms of the variable sensitivity and leverage points can in turn help stakeholders develop strategies to operate productively within the system or successfully interact with the system.

System dynamics is also a very accessible in that it does not require understanding of non-linear mathematics to learn about non-linear behavior in systems. System dynamics employs stocks and flows to develop feedback loop structures, and relies on computer programs designed specifically for system dynamics to model non-linear structures. The visual nature of these programs means that several assumptions of the model are visible to its viewers. Because the modeler develops the non-linear relationship between components, for example, system dynamics avoids automatically attaching trends to specific components. Modelers must identify feedback loops, and the interaction of loops may result in different sorts of behavior (such as exponential growth, oscillation, or decay).

Overall, system dynamics helps its users think through the consequences of actions, and leaves it to modelers to build dynamic structures based on observations about the system's structure, rather than on projections of historical behavior. It provides a simple yet profound means of analyzing system behavior.

Limitations

Discussion on the limitations of system dynamics theory appears to be sparse. David Lane discusses and defends allegations against system dynamics, but mainly at a level of theoretical assumptions rather than application (Lane 2000). In addition, many of these allegations seem to derive from misperceptions of the field rather than its actual practice. George Richardson also offers a critique of the field (Richardson 1996). However, his remarks focus more on the community than the theory and practice. The following looks at potential limitations of system dynamics, as collected from a relatively small set of sources.

According to George Richardson, the adequate validation and confidence of system dynamic models is a concern for the community. He notes that while Jay Forrester and researcher Peter Senge published tests to help establish user confidence in models in 1980, work on the subject since has been limited. Furthermore, a separate study found that many of the tests Forrester and Senge prescribed were not always used in practice (Richardson 1996). System dynamic projects address a variety of audiences, and the prescription for what validates a model can vary. Logic, intuition and a shared change in perspective is sufficient for some projects. The private sector has made a lot of use of system dynamics modeling. However, as noted earlier, public policy is prone to dispute, and such validation may not wear well in debates. The use of system dynamics has tended to focus on business applications or academic research, and validation may be one barrier for its use in other areas. Nevertheless, because system dynamics does not focus on outputs as much as behavior, it could potentially avoid contentious discussion over numbers and focus the debate on structure and accuracy of representation. Forrester notes the distinction between accuracy and precision, and observes that system dynamics models seek accuracy rather than precision (Forrester 1999).

Somewhat related to confidence and validation, is a relatively recent debate in the community about the effectiveness and appropriateness of qualitative versus the traditional quantitative system dynamic models. George Richardson and Geoff Coyle provide an introduction to the issue (Richardson 1996 and Coyle 2000). The primary concern is under what conditions can qualitative models yield reliable insights? Some practitioners note that forcing quantification of a system that has several uncertain variables can lead to misleading results, and that the qualitative process can yield valuable insights. However, others note that model simulation, which requires quantification, is a necessary step to test one's hypothesis. Richardson sums up the question to the community as: "What are the wise uses of qualitative mapping approaches, and what are the conditions that require formal, quantitative modeling" (Richardson 1996, 7)?

Finally, users of system dynamics should be aware that there is some disagreement within the system dynamics community about the role of system dynamics for forecasting. James Lyneis discusses the debate in a 2000 article, and concludes that if forecasts are to be done, system dynamics does it best. However, he also notes Forrester's weariness of forecasts because of their inaccuracy and potential to mislead managers into taking counter-effective actions. Much work in system dynamics highlights the problem of forecasting, including John Sterman's work referenced in this thesis (Sterman 2000).

System Dynamics and Energy and the Environment

The emergence of a market around a new technology is inherently unpredictable. Breakthroughs in technology or competing technologies, or factors that affect demand are beyond the control of any single stakeholder. However, modeling is a useful tool to understand the potential pathways for development of a market under varying scenarios of uncontrollable factors. In the words of Jay Forrester, the father of system dynamics:

> *We should look less for prediction of specific actions in the future and more for enhancing our understanding of the inherent characteristics of the system. There seem to be good reasons why models cannot be expected to predict specific system condition far enough into the future to be particularly significant* (Forrester 1999, 54).

System dynamics is effective for considering the uncertainties of investment in new clean energy technologies as it allows one to consider feedbacks between supply and demand and the stabilities or instabilities in a new market. Furthermore, system dynamics helps investors understand what factors 'to look for' to see if certain scenarios are playing out. Thus, investors may be able to take preemptive action rather than react after the system has already started to change, when they have less ability to change its course.

Also, its focus on dynamic relationships makes system systems an ideal tool for analyzing time lags in option development, implementation and payoff, and path dependencies amongst investments. In his 2004 Ph.D. dissertation, Kaare Gether used system dynamics to explore the issues of path dependency and non-linearity in the transition to large-scale use of hydrogen (Kaare 2004). He developed a model to evaluate the dynamic interaction among energy technologies, such as competition between end-products, which contribute to the overall energy system behavior. In particular, he looks at path dependence amongst technology options and infrastructure investments, and the potential for lock-in to particular development pathways. To evaluate the long-term benefits of new technologies, and to help investors avoid costly mistakes, he uses system dynamics to develop a way to understand the nature of change within a dynamic, unpredictable energy system. In addition, he discusses the advantages and limitations of various forms of modeling, including the method of his approach. His work is highly relevant to the issues of clean energy investment, beyond the study of hydrogen.

In addition, because the insights from system dynamics are not necessarily numerical outputs but rather understanding about the working mechanisms of a system, system dynamics could facilitate strategy discussions while avoiding problems of numerical valuation. Also, its compatibility with scenario analysis allows it to avoid overdue reliance on historical data, and avoid imbedded assumptions about the future continuing as the past. Furthermore, by challenging stakeholder assumptions through modeling emergent and often unexpected behavior, system dynamics helps change discussion on what to do from an adversarial debate to a conversation. Modeling can expedite the learning process, and because system dynamics allows one to model dynamic, socio-technical systems, it may be very useful for analysis on clean energy investment approaches. Table 6 highlights the contribution that system dynamics can have for addressing investment challenges.

Table 8. The Contribution of System Dynamics

Investment Challenges	Contribution of System Dynamics
Desire to optimize the total returns over time; Evaluate tradeoffs between now and the future.	Because options now may affect those that are available later, a long-run view is useful for optimizing total returns over time. System dynamics' focus on dynamic relationships makes it a practical tool to consider both the past and present. It is an ideal for investigating time lags and path dependencies over time.
Politics of valuation; Choice of an appropriate discount rate	The insights from system dynamics are not necessarily the numerical outputs, but rather the understanding of how factors contribute to unpredictable system behavior. This allows one to avoid arguments over specific numbers. In addition, the modeling technique helps forces transparency as many of the assumptions of how elements are interrelated are visible in the model.
Justify actions in the face of uncertainty	System dynamics provides a quantitative or qualitative way to analyze the effects of actions throughout the system. Also, its compatibility with scenario analysis makes it suitable for evaluating actions in the face of uncertainty.

A Potential Decision Framework

The combination of system dynamic and real options has the potential to provide a practical framework for making clean energy investments in an uncertain future (Please see Table 9). Real options theory provides a way to value options, which can cultivate the flexibility to respond to the future as it unfolds. System dynamics is a useful tool for considering strategic path dependence and time lags.

Pindyck and Dixit refer to the fact that uncertainty of timing, causation, and impact of environmental risks can encourage deferral of action. However, the opportunity cost of investment, lag to develop options, and delay between action and effect limit ability to defer action without consequence. Strategic investments are necessary because options come at a cost, and path dependencies link past investments to future opportunities. The combinations of system dynamics and real options may help to understand pathway limitations, address uncertainty, and allow action and avoid building to a prediction. Table 9 summarizes a potential joint framework.

Table 9. Combining Real Options and System Dynamics

Design for flexibility rather than rely on prediction • Examine potential development pathways given existing constraints (System Dynamics) • Develop options: determine potential, evaluate worth, and maintain options (Real Options) • Act on options: determine decision thresholds (System Dynamics and Real Options), enable quick action, and allow information updates. Develop ways to move along the possibility frontier

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Chapter 6: Case Study of Gas-to-Liquids Technology

Introduction

The purpose of the case study was to consider the use of system dynamics for understanding market dynamics. In the case of markets for emergent technologies, demand and supply costs, affected as they are by many factors, are prone to sudden changes. The case study examined the potential timing and extent of market growth of the emerging technology GTL, a proven technology that converts natural gas to low-sulfur diesel fuel. The complexities of the market make the potential outcomes of investment-decisions difficult to reason through, let alone predict. The study looked to system dynamics as a learning tool, and considered system dynamics as an aid in planning scenarios, which could ultimately help decide which technology to invest in and when to invest in it.

Several energy companies have invested in GTL projects. However, only a handful of GTL projects exist, partly because of the large capital expenditures they require, but also because the product is cost-effective in only a few markets. Over time, due to cost reductions or changes in demand, the market could potentially grow. The high quality diesel fuel it produces could potentially help refineries meet increasingly stringent fuel standards. Also, because GTL produces a liquid product from natural gas, and liquid fuel transportation is less costly than gas fuel transportation, GTL can make use of gas reserves previously considered stranded. It is an interesting technology also in that its fundamental conversion processes are available to other sources and uses. For example, conversion of biomass to diesel uses relatively the same process as GTL. In addition, the production of syngas in the GTL process may prove adaptable to hydrogen production.

The characteristics of GTL technology lend it to the study of both 'in' and 'on' real options. The current system dynamics model would focus more on the 'on' option of investment. This study did not tie real options analysis with the system dynamics model, however the potential exists.

The following provides detail on the system dynamics GTL model and offers resulting observations on the use of system dynamics. The model currently only details the supply side of the market. Further research on the demand side would help to garner more understanding about the application of system dynamics to this issue.

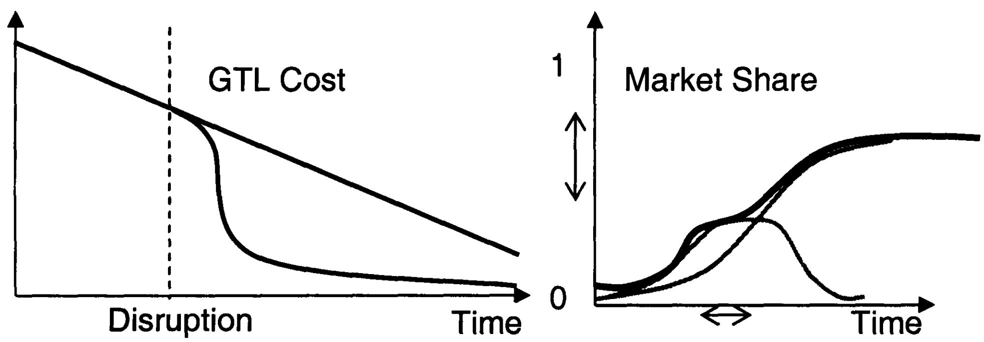
Gas-to-Liquids Model

Introduction

GTL is a technology for which many uncertainties are fairly limited. The technology primarily faces diffusion and adoption uncertainties, rather than uncertainties about research and development (R&D) or its ability to address environmental concerns. The narrow range of uncertainties associated with it makes it an ideal initial case study to examine the use of system dynamics as a decision-support tool. Further breakthroughs in the technology would at this point potentially improve adoption. Thus, diffusion and adoption, and market growth around this technology are largely uncertain.

The model attempts to consider the timing and magnitude of market growth. To do this, it looks at the dynamic factors in supply costs and demand. So far, the dynamic supply curve has been completed. Future work would embed a dynamic demand curve in the model to examine the feedback between supply and demand, and the effect of external factors such as technology breakthroughs and reserve availability on market growth. Figure 9 illustrates the patterns of behavior for GTL demand and supply that the model seeks to investigate.

Figure 9. Expected Patterns of Behavior



Source: Jessica Harrison, Tammy Greenlaw, Kate Parrot, 2005.

<u>Supply</u>

The supply portion of the model consists of fixed relationships between costs, and two dynamic components – construction learning and operation learning. Technology breakthroughs are dynamic in the sense that they can be programmed to occur at various times as the model runs. Furthermore, costs associated with natural gas reserves are endogenous and may be programmed to vary over time. Thus, they are fixed unless externally adjusted. The decision to invest is based on a continuous net present value calculation over previously outputted profits, to model stakeholder decision-making.

The following takes a more detailed look at the supply portion of the model, broken out into four sections: operation learning, construction learning, the decision to invest, and aggregated costs. Figure 10 highlights key elements of the overall model.

OPERATION LEARNING: The operation learning unit represents the phenomenon that as plant production increases, plant managers are able to operate the plant more efficiently due to increased knowledge. The increase in management efficiency in turn lowers unit operating costs, and decreases total costs. A 'knowledge diffusion' factor accounts for the fact that not all knowledge will circulate to other facilities. As the cost of supply decrease, suppliers are able to decrease price, which can increase the quantity demanded and spur increased production.

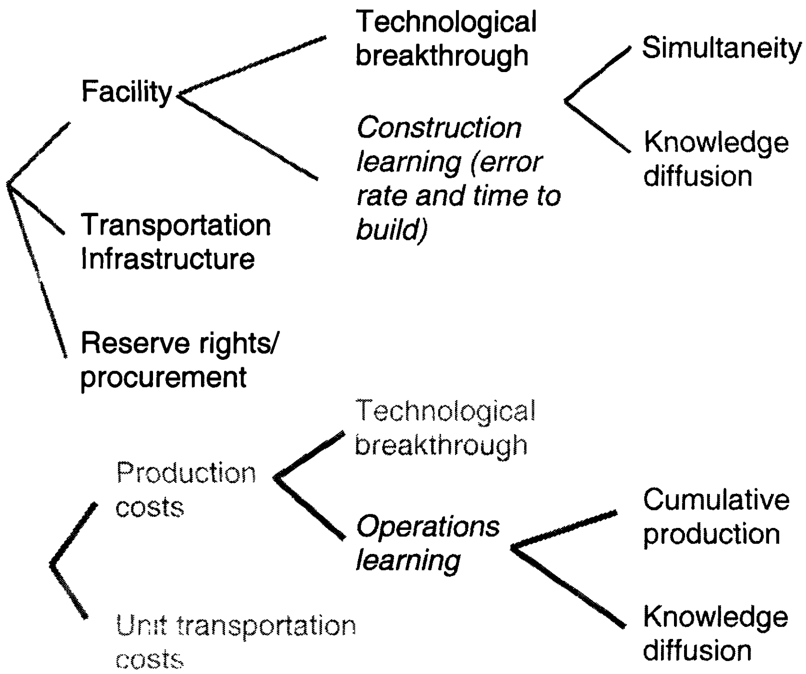
CONSTRUCTION LEARNING: Similar to the operation learning unit, construction learning accounts for the fact that as more plants are built, experience with designing and constructing plants increases. As experience with construction increases, the error rate and the time to build decreases, lowering per unit construction costs. Again, a 'knowledge diffusion' factor accounts for the fact that not all knowledge will circulate to other facilities. In addition, the model takes into consideration the fact that less learning occurs if facilities are simultaneously constructed versus constructed in parallel. This is incorporated into a 'simultaneity factor.' Also, decreases in construction costs lower the cost of supply. As the cost of supply decrease, suppliers are able to decrease price, which can increase the quantity demanded and spur increased construction.

DECISION TO INVEST: The decision to invest is modeled as a calculation of unmet demand, and net present value. Unmet demand is determined by the quantity demanded at a given price, minus existing capacity and the capacity already in construction. The net present value of investments is calculated as a weighted average of historical profits discounted as an annuity over a fixed time period. If the net present value and unmet demand are positive, and unmet demand is larger than facility capacity, then a decision to start construction of additional facilities is made.

COSTS: The model calculates an aggregate unit cost from a unit capital cost and a unit operating cost. The capital costs consist of a cost to permit, commission, and build a facility, transportation infrastructure costs per facility, and reserve right costs per facility. These are then amortized over an assumed facility life and production to derive a unit capital cost. Unit operating costs are calculated from a unit transportation cost and a unit production cost.

The model assumes an average operating and capital cost per facility. However, it allows these base costs to be adjusted over time according to the average characteristics of aggregate natural gas reserves. Such characteristics include onshore versus offshore, associated or non-associated with oil, which affect construction, transportation and production costs, and the geography of the reserves, which affects construction costs and transportation costs.

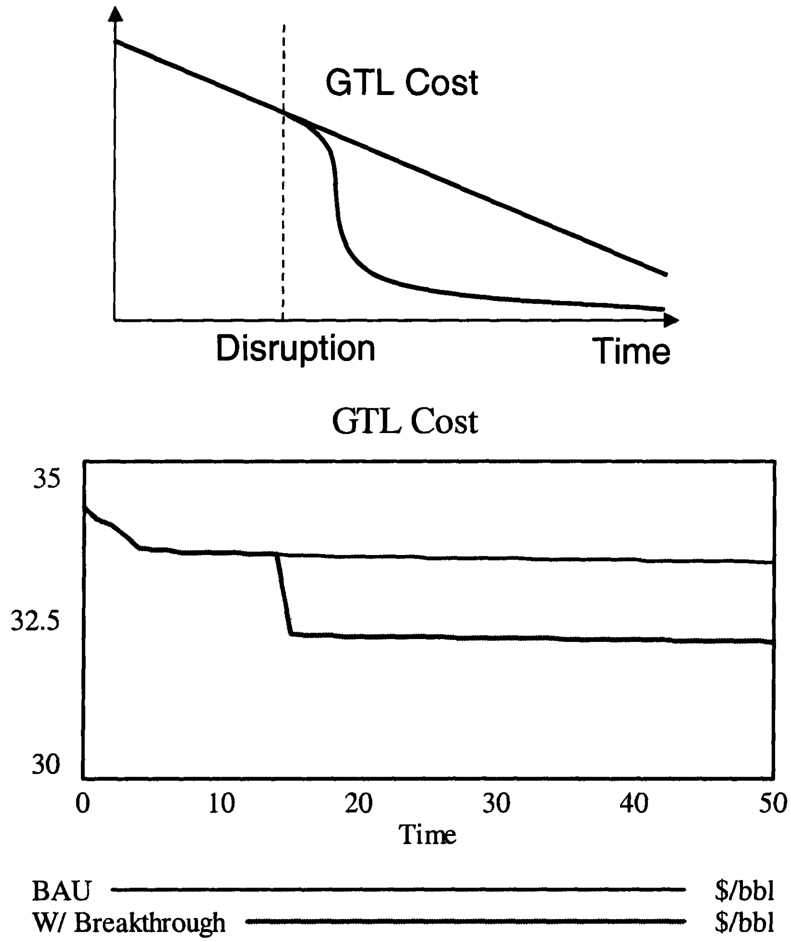
Figure 10. Model Overview - Supply



Note: Italicized items illustrate endogenous, dynamic variables
Source: Jessica Harrison, Tammy Greenlaw, Kate Parrot, 2005.

Comparison of the model outputs to the reference mode demonstrates that the supply portion of the model behaves as expected. Costs decrease incrementally over time due to learning, unless interrupted by a technology breakthrough. The output of the model, however, is highly sensitive to the inputs of learning curves and demand curves. For example, the shapes of the operation and construction learning curves directly determine the size and shape of cost reductions. Given the sensitivity of GTL costs to the learning effects, and the shape of the demand curve, the insights from the model outputs are limited in terms of predictability. However, dynamics are still valuable to consider. As noted above, the model may be very useful for generating scenarios to examine the characteristics of uncertainties.

Figure 11. Comparison of Expected Behavior to Model Output



Source: Jessica Harrison, Tammy Greenlaw, Kate Parrot, 2005.

The initial bend in both the top and the bottom curves illustrate decreases in cost from 'operation learning' as cumulative production increases. The cost reductions diminish over time, representing a limit to the benefits of operation learning. The bottom curve displays the cost reductions from a breakthrough. A breakthrough in the model is represented as a decrease in the size-to-capacity ratio of a plant. This may occur if a plant is able to reduce its footprint and produce the same output, or if a facility improves its efficiency to produce more output for the same facility size. Reducing the size-to-capacity ratio reduces per unit capital costs, lowering overall aggregate cost.

The only dynamic interactions that occur in the supply portion of the model are construction and operation learning. This is in part because demand is currently exogenous to the model. If the demand curve were endogenous to the model, one would be able to consider if and when demand would be large enough at a given price to allow these learning effects to operate. For example, if demand were too small at a given price to justify building more than one facility, no construction learning effects would occur, and operation learning would be very limited. If no breakthrough occurs, and learning is limited, costs may not drop significantly enough to increase demand and warrant the construction of another facility. Thus, the construction and operation learning is prevented from occurring.

Demand

GTL may be used as a diesel end-fuel, or as way to dilute diesel fuels to allow them to meet sulfur standards. Demand is currently static in the model. However, there are many interesting dynamics to demand that are worth considering. Initially, one would expect a niche market to develop from refineries or from luxury fuel consumers. Nevertheless, there are several factors at play into the development of demand. These include the availability of GTL substitutes, environmental regulations that decrease the sulfur content of fuels, and increasingly 'dirty' oil reserves. All affect either the quantity demanded at a given price, or the price of competing products. In addition, the remoteness of natural gas reserves and the ability to take advantage of associated gas affects the attractiveness of GTL.[39]

Resulting Observations on System Dynamics

The strength of system dynamics is that it allows one to examine the uncertain timing and sensitivities of the market growth of a new technology. In addition, though the GTL case study model was not explicit about the sources of technology breakthrough, the model could potentially detail areas of possible breakthrough, and examine the sensitivities of breakthroughs to cost. This would be a useful way to focus R&D allocations. Like other models, however, this system dynamic model's prediction accuracy is limited by its assumptions and inputs. Scenario development is an important task to fully learn from the model. The task of developing scenarios is not a simple one and analysis is limited by the ability to generate useful scenarios. However, the combination of system dynamics and scenario analysis could improve understanding in an area currently shrouded by uncertainty. Further research is necessary to gather input about the potential of system dynamics to aid in investment decision-making and design.

[39] Generally, as refinery capacity decreases, the price of diesel increases and the attractiveness of GTL as an end use fuel increases. Also, as clean oil availability decreases or fuel standards increase, refinery demand is likely to increase, unless refineries develop and implement new processing techniques.

Chapter 7: Conclusion

Rising concerns about energy security and climate change are prompting change in energy systems worldwide. But how should stakeholders react? What timing and types of investment are appropriate? Should stakeholders even attempt to change course given the uncertainties about the timing and impact of climate change and the uncertainty about the ability of various energy sources to meet our needs?

The original motivation for this thesis was to evaluate the advantages of taking early action to address energy and environment concerns such as climate change. However, a literature review of current challenges and approaches revealed that the question is difficult to objectively assess in a quantitative manner. Disputes in the policy arena and varied approaches by industry about the stringency and timing of action to address climate change intimate such troubles. With the thought that new tools might improve upon current strategy, this thesis went on to examine the benefits and limitations of a real options approach and system dynamics. It concludes that these tools may be a good start to addressing some of these issues and calls for more research on ways to apply real options and system dynamics. Having found limited information on the current strategic-planning tools in use, this thesis also suggests further research with industry and policymakers to learn more about the specific tools and processes they use to strategize their policies and investments. The following summarizes research conclusions.

Decision-Making Difficulties

Uncertainties of environmental risks, such as timing, causation, and impact, encourage deferral of action. However, the ability to defer without consequence is limited due to constraints in investments, development lags, and delays between action and effect. Options cultivate the flexibility to respond to uncertain environmental risks. However, strategic investments are necessary because of option costs, path dependencies linking past investment to future opportunities, and time lags to develop, implement, and realize the benefits of an option. Making strategic investment requires:

- Examining potential pathways given constraints;
- Developing options: determining their potential, evaluating their worth and maintaining them; and
- Acting on options: determining decision thresholds, enabling quick action, and updating information.

In order to cope with uncertainties, one may design for flexibility rather than predict a future and build to that future. However, the value of flexibility must be weighed against other considerations, such as competitive strategy. System dynamics and real options may help to understand transition pathways, address uncertainty, and allow action while avoiding picking a prediction. The following notes potential strengths and weaknesses of system dynamics in addressing the initial question of investments in clean energy technology.

Tools Summary

Real Options

A real options approach allows one to avoid prediction and consider one's future under a range of possible outcomes. However, it is a precarious tool given the assumptions it requires and its current lack of focus on time delays or investments for reasons of competitive advantage (e.g. game theory). A Real options approach could potentially incentivize adoption of technologies that improve environmental performance by reducing the down side of investment and providing fallback options. System dynamics and scenario analysis may be a useful input to real options analysis. It could provide insight into what items to monitor in order to know when to implement a real option, or what sort of timing might be appropriate for implementation of an option. In addition, it could potentially generate uncertainty distributions to feed into real options analysis. However, further research is needed in this area.

System Dynamics

The strength of system dynamics is that it allows one to examine the uncertain timing and sensitivities of the market growth of a new technology. Like other models, however, this system dynamics model's prediction accuracy is limited by its assumptions and inputs. Scenario development is an important task to fully learn from the model. The task of developing scenarios is not a simple one and analysis is limited by the ability to generate useful scenarios. However, the combination of system dynamics and scenario analysis could improve understanding in an area currently shrouded by uncertainty.

This thesis helps answer the question why the cost of delaying investments is difficult to analyze. Furthermore, it offers an introduction to how one might best go about developing the tools and methods necessary to address this question. The area of clean energy investment decision-making is a complicated one, the outcome of which as serious implications. It is a rich field of study, and further research in this area could help innovate on decision-making tools and clarify the ambiguity of decision-making regarding urgent yet elusive energy issues.

Appendices

Appendix I: IEA Shared Goals

Available online at http://www.iea.org/Textbase/about/sharedgoals.htm

"The 26 Member countries of the International Energy Agency (IEA) seek to create the conditions in which the energy sectors of their economies can make the fullest possible contribution to sustainable economic development and the well-being of their people and of the environment. In formulating energy policies, the establishment of free and open markets is a fundamental point of departure, though energy security and environmental protection need to be given particular emphasis by governments. IEA countries recognise the significance of increasing global interdependence in energy. They therefore seek to promote the effective operation of international energy markets and encourage dialogue with all participants.

In order to secure their objectives they therefore aim to create a policy framework consistent with the following goals:

Diversity, efficiency and flexibility within the energy sector are basic conditions for longer-term energy security: the fuels used within and across sectors and the sources of those fuels should be as diverse as practicable. Non-fossil fuels, particularly nuclear and hydro power, make a substantial contribution to the energy supply diversity of IEA countries as a group.

Energy systems should have the ability to respond promptly and flexibly to energy emergencies. In some cases this requires collective mechanisms and action: IEA countries co-operate through the Agency in responding jointly to oil supply emergencies.

The environmentally sustainable provision and use of energy is central to the achievement of these shared goals. Decision-makers should seek to minimise the adverse environmental impacts of energy activities, just as environmental decisions should take account of the energy consequences. Government interventions should where practicable have regard to the Polluter Pays Principle.

More environmentally acceptable energy sources need to be encouraged and developed. Clean and efficient use of fossil fuels is essential. The development of economic non-fossil sources is also a priority. A number of IEA members wish to retain and improve the nuclear option for the future, at the highest available safety standards, because nuclear energy does not emit carbon dioxide. Renewable sources will also have an increasingly important contribution to make.

Improved energy efficiency can promote both environmental protection and energy security in a cost-effective manner. There are significant opportunities for greater energy efficiency at all stages of the energy cycle from production to consumption. Strong efforts by Governments and all energy users are needed to realise these opportunities.

Continued research, development and market deployment of new and improved energy technologies make a critical contribution to achieving the objectives outlined above. Energy technology policies should complement broader energy policies. International co-operation in the development and dissemination of energy technologies, including industry participation and co-operation with non-Member countries, should be encouraged.

Undistorted energy prices enable markets to work efficiently. Energy prices should not be held artificially below the costs of supply to promote social or industrial goals. To the extent necessary and practicable, the environmental costs of energy production and use should be reflected in prices.

Free and open trade and a secure framework for investment contribute to efficient energy markets and energy security. Distortions to energy trade and investment should be avoided.

Co-operation among all energy market participants helps to improve information and understanding, and encourage the development of efficient, environmentally acceptable and flexible energy systems and markets worldwide. These are needed to help promote the investment, trade and confidence necessary to achieve global energy security and environmental objectives."

The "Shared Goals" were adopted by IEA Ministers at their 4 June 1993 meeting in Paris.

Appendix II: Climate Change Uncertainties

Source: IPCC, Climate Change 2001: Synthesis Report, Summary for Policymakers, 2001. Available online at http://www.ipcc.ch/pub/un/syreng/spm.pdf

Table SPM-3 Robust findings and key uncertainties.[a]

Robust Findings		*Key Uncertainties*
Observations show Earth's surface is warming. Globally, 1990s very likely warmest decade in instrumental record (Figure SPM-10b). [Q9.8] Atmospheric concentrations of main anthropogenic greenhouse gases (CO_2 (Figure SPM-10a), CH_4, N_2O, and tropospheric O_3) increased substantially since the year 1750. [Q9.10] Some greenhouse gases have long lifetimes (e.g., CO_2, N_2O, and PFCs). [Q9.10] Most of observed warming over last 50 years likely due to increases in greenhouse gas concentrations due to human activities. [Q9.8]	**Climate change and attribution**	Magnitude and character of natural climate variability. [Q9.8] Climate forcings due to natural factors and anthropogenic aerosols (particularly indirect effects). [Q9.8] Relating regional trends to anthropogenic climate change. [Q9.8 & Q9.22]
CO_2 concentrations increasing over 21st century virtually certain to be mainly due to fossil-fuel emissions (Figure SPM-10a). [Q9.11] Stabilization of atmospheric CO_2 concentrations at 450, 650, or 1,000 ppm would require global anthropogenic CO_2 emissions to drop below year 1990 levels, within a few decades, about a century, or about 2 centuries, respectively, and continue to decrease steadily thereafter to a small fraction of current emissions. Emissions would peak in about 1 to 2 decades (450 ppm) and roughly a century (1,000 ppm) from the present. [Q9.30] For most SRES scenarios, SO_2 emissions (precursor for sulfate aerosols) are lower in the year 2100 compared with year 2000. [Q9.10]	**Future emissions and concentrations of greenhouse gases and aerosols based on models and projections with the SRES and stabilization scenarios**	Assumptions underlying the wide range[b] of SRES emissions scenarios relating to economic growth, technological progress, population growth, and governance structures (lead to largest uncertainties in projections). Inadequate emission scenarios for ozone and aerosol precursors. [Q9.10] Factors in modeling of carbon cycle including effects of climate feedbacks.[b] [Q9.10]
Global average surface temperature during 21st century rising at rates very likely without precedent during last 10,000 years (Figure SPM-10b). [Q9.13] Nearly all land areas very likely to warm more than the global average, with more hot days and heat waves and fewer cold days and cold waves. [Q9.13] Rise in sea level during 21st century that will continue for further centuries. [Q9.15] Hydrological cycle more intense. Increase in globally averaged precipitation and more intense precipitation events very likely over many areas. [Q9.14] Increased summer drying and associated risk of drought likely over most mid-latitude continental interiors. [Q9.14]	**Future changes in global and regional climate based on model projections with SRES scenarios**	Assumptions associated with a wide range[c] of SRES scenarios, as above. [Q9.10] Factors associated with model projections[c], in particular climate sensitivity, climate forcing, and feedback processes especially those involving water vapor, clouds, and aerosols (including aerosol indirect effects). [Q9.16] Understanding the probability distribution associated with temperature and sea-level projections. [Q9.16] The mechanisms, quantification, time scales, and likelihoods associated with large-scale abrupt/non-linear changes (e.g., ocean thermohaline circulation). [Q9.16] Capabilities of models on regional scales (especially regarding precipitation) leading to inconsistencies in model projections and difficulties in quantification on local and regional scales. [Q9.16]

Table SPM-3	Robust findings and key uncertainties.[a]	
Robust Findings		***Key Uncertainties***
Projected climate change will have beneficial and adverse effects on both environmental and socio-economic systems, but the larger the changes and the rate of change in climate, the more the adverse effects predominate. [Q9.17] The adverse impacts of climate change are expected to fall disproportionately upon developing countries and the poor persons within countries. [Q9.20] Ecosystems and species are vulnerable to climate change and other stresses (as illustrated by observed impacts of recent regional temperature changes) and some will be irreversibly damaged or lost. [Q9.19] In some mid- to high latitudes, plant productivity (trees and some agricultural crops) would increase with small increases in temperature. Plant productivity would decrease in most regions of the world for warming beyond a few °C. [Q9.18] Many physical systems are vulnerable to climate change (e.g., the impact of coastal storm surges will be exacerbated by sea-level rise, and glaciers and permafrost will continue to retreat). [Q9.18]	**Regional and global impacts of changes in mean climate and extremes**	Reliability of local or regional detail in projections of climate change, especially climate extremes. [Q9.22] Assessing and predicting response of ecological, social (e.g., impact of vector- and water-borne diseases), and economic systems to the combined effect of climate change and other stresses such as land-use change, local pollution, etc. [Q9.22] Identification, quantification, and valuation of damages associated with climate change. [Q9.16, Q9.22, & Q9.26]
Greenhouse gas emission reduction (mitigation) actions would lessen the pressures on natural and human systems from climate change. [Q9.28] Mitigation has costs that vary between regions and sectors. Substantial technological and other opportunities exist for lowering these costs. Efficient emissions trading also reduces costs for those participating in the trading. [Q9.31 & Q9.35-36] Emissions constraints on Annex I countries have well-established, albeit varied, "spill-over" effects on non-Annex I countries. [Q9.32] National mitigation responses to climate change can be more effective if deployed as a portfolio of policies to limit or reduce net greenhouse gas emissions. [Q9.35] Adaptation has the potential to reduce adverse effects of climate change and can often produce immediate ancillary benefits, but will not prevent all damages. [Q9.24] Adaptation can complement mitigation in a cost-effective strategy to reduce climate change risks; together they can contribute to sustainable development objectives. [Q9.40] Inertia in the interacting climate, ecological, and socio-economic systems is a major reason why anticipatory adaptation and mitigation actions are beneficial. [Q9.39]	**Costs and benefits of mitigation and adaptation options**	Understanding the interactions between climate change and other environmental issues and the related socio-economic implications. [Q9.40] The future price of energy, and the cost and availability of low-emissions technology. [Q9.33-34] Identification of means to remove barriers that impede adoption of low-emission technologies, and estimation of the costs of overcoming such barriers. [Q9.35] Quantification of costs of unplanned and unexpected mitigation actions with sudden short-term effects. [Q9.38] Quantification of mitigation cost estimates generated by different approaches (e.g., bottom-up vs. top-down), including ancillary benefits, technological change, and effects on sectors and regions. [Q9.35] Quantification of adaptation costs. [Q9.25]

[a] In this report, a ***robust finding*** for climate change is defined as one that holds under a variety of approaches, methods, models, and assumptions and one that is expected to be relatively unaffected by uncertainties. ***Key uncertainties*** in this context are those that, if reduced, may lead to new and robust findings in relation to the questions of this report. This table provides examples and is not an exhaustive list.

[b] Accounting for these above uncertainties leads to a range of CO_2 concentrations in the year 2100 between about 490 and 1,250 ppm.

[c] Accounting for these above uncertainties leads to a range for globally averaged surface temperature increase, 1990-2100, of 1.4 to 5.8°C (Figure SPM-10b) and of globally averaged sea-level rise of 0.09 to 0.88 m.

Appendix III: Letters Regarding Global Warming Studies

House Energy and Commerce Committee Letter Requesting Information Regarding Global Warming Studies

The House Energy and Commerce Committee Chair, Congressman Joe Barton of Texas, sent letters to the National Science Foundation, the IPCC, and Dr. Michael Mann and co-authors Drs. Malcolm K. Hughes and Raymond S. Bradley, requesting information about their research or use of research on global warming. The following letter is that addressed to climate change scientist, Michael Mann. A copy of this letter, along with the others are available online at http://energycommerce.house.gov/108/Letters/06232005_1570.htm

June 23, 2005

Dr. Michael Mann
Assistant Professor
Department of Environmental Sciences
University of Virginia
Charlottesville, VA 22904

Dear Dr. Mann:

Questions have been raised, according to a February 14, 2005 article in *The Wall Street Journal*, about the significance of methodological flaws and data errors in your studies of the historical record of temperatures and climate change. We understand that these studies of temperature proxy records (tree rings, ice cores, corals, etc.) formed the basis for a new finding in the 2001 United Nation's Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (TAR). This finding – that the increase in 20th century northern hemisphere temperatures is "likely to have been the largest of any century during the past 1,000 years" and that the "1990s was the warmest decade and 1998 the warmest year" – has since been referenced widely and has become a prominent feature of the public debate surrounding climate change policy.

However, in recent peer-reviewed articles in *Science*, *Geophysical Research Letters*, and *Energy & Environment*, researchers question the results of this work. As these researchers find, based on the available information, the conclusions concerning temperature histories – and hence whether warming in the 20th century is actually unprecedented – cannot be supported by the Mann *et al.* studies cited in the TAR. In addition, we understand from the February 14 *Journal* and these other reports that researchers have failed to replicate the findings of these studies, in part because of problems with the underlying data and the calculations used to reach the conclusions. Questions have also been raised concerning the sharing and dissemination of the data and methods used to perform the studies. For example, according to the January 2005 *Energy & Environment*, such information necessary to replicate the analyses in the studies has not been made fully available to researchers upon request.

The concerns surrounding these studies reflect upon the quality and transparency of federally funded research and of the IPCC review process – two matters of particular interest to the Committee. For example, one concern relates to whether IPCC review has been sufficiently independent. We understand that you were a lead author of the IPCC chapter that assessed and reported your own studies, and that two study co-authors were also contributing authors to this very same chapter. Given the prominence these studies were accorded in the IPCC TAR and your position and role in that process, we seek to learn more about the facts and circumstances that led to acceptance and prominent use of this work in the IPCC TAR and to understand what this controversy indicates about the data quality of key IPCC studies.

As you know, sharing data and research results is a basic tenet of open scientific inquiry, providing a means to judge the reliability of scientific claims. The ability to replicate a study, as the National Research Council has noted, is typically the gold standard by which the reliability of claims is judged. Given the questions reported about data access surrounding these studies, we also seek to learn whether obligations concerning the sharing of information developed or disseminated with federal support have been appropriately met.

In light of the Committee's jurisdiction over energy policy and certain environmental issues, the Committee must have full and accurate information when considering matters relating to climate change policy. We open this review because this dispute surrounding your studies bears directly on important questions about the federally funded work upon which climate studies rely and the quality and transparency of analyses used to support the IPCC assessment process. With the IPCC currently working to produce a fourth assessment report, addressing questions of quality and transparency in the process and underlying analyses supporting that assessment, both scientific and economic, are of utmost importance if Congress is eventually going to make policy decisions drawing from this work.

To assist us as we begin this review, and pursuant to Rules X and XI of the U.S. House of Representatives, please provide the following information requested below on or before July 11, 2005:

1. Your *curriculum vitae*, including, but not limited to, a list of all studies relating to climate change research for which you were an author or co-author and the source of funding for those studies.

2. List all financial support you have received related to your research, including, but not limited to, all private, state, and federal assistance, grants, contracts (including subgrants or subcontracts), or other financial awards or honoraria.

3. Regarding all such work involving federal grants or funding support under which you were a recipient of funding or principal investigator, provide all agreements relating to those underlying grants or funding, including, but not limited to, any provisions, adjustments, or exceptions made in the agreements relating to the dissemination and sharing of research results.

4. Provide the location of all data archives relating to each published study for which you were an author or co-author and indicate: (a) whether this information contains all the specific data you used and calculations your performed, including such supporting documentation as computer source code, validation information, and other ancillary information, necessary for full evaluation and application of the data, particularly for another party to replicate your research results; (b) when this information was available to researchers; (c) where and when you first identified the location of this information; (d) what modifications, if any, you have made to this information since publication of the respective study; and (e) if necessary information is not fully available, provide a detailed narrative description of the steps somebody must take to acquire the necessary information to replicate your study results or assess the quality of the proxy data you used.

5. According to *The Wall Street Journal*, you have declined to release the exact computer code you used to generate your results. (a) Is this correct? (b) What policy on sharing research and methods do you follow? (c) What is the source of that policy? (d) Provide this exact computer code used to generate your results.

6. Regarding study data and related information that is not publicly archived, what requests have you or your co-authors received for data relating to the climate change studies, what was your response, and why?

7. The authors McIntyre and McKitrick (*Energy & Environment*, Vol. 16, No. 1, 2005) report a number of errors and omissions in Mann *et. al.*, 1998. Provide a detailed narrative explanation of these alleged errors and how these may affect the underlying conclusions of the work, including, but not limited to answers to the following questions:

a. Did you run calculations without the bristlecone pine series referenced in the article and, if so, what was the result?
b. Did you or your co-authors calculate temperature reconstructions using the referenced "archived Gaspe tree ring data," and what were the results?
c. Did you calculate the R2 statistic for the temperature reconstruction, particularly for the 15th Century proxy record calculations and what were the results?
d. What validation statistics did you calculate for the reconstruction prior to 1820, and what were the results?
e. How did you choose particular proxies and proxy series?

8. Explain in detail your work for and on behalf of the Intergovernmental Panel on Climate Change, including, but not limited to: (a) your role in the Third

Assessment Report; (b) the process for review of studies and other information, including the dates of key meetings, upon which you worked during the TAR writing and review process; (c) the steps taken by you, reviewers, and lead authors to ensure the data underlying the studies forming the basis for key findings of the report were sound and accurate; (d) requests you received for revisions to your written contribution; and (e) the identity of the people who wrote and reviewed the historical temperature-record portions of the report, particularly Section 2.3, "Is the Recent Warming Unusual?"

Thank you for your assistance. If you have any questions, please contact Peter Spencer of the Majority Committee staff at (202) 226-2424.

Sincerely,

Joe Barton
Chairman

Ed Whitfield
Chairman Subcommittee on Oversight and Investigations

cc: The Honorable John Dingell, Ranking Member
The Honorable Bart Stupak, Ranking Member, Subcommittee on Oversight and Investigations

AAAS Letter to House Energy and Commerce Committee Regarding Request for Information About Global Warming Studies

The American Association for the Advancement of Science (AAAS) sent a letter to the House Energy and Commerce Committee Chair, Congressman Joe Barton of Texas, in response to their request for the information about research on global warming. The letter is available online at http://www.aaas.org/news/releases/2005/0714letter.pdf.

July 13, 2005

The Honorable Joe Barton, Chair
Committee on Energy and Commerce
U.S. House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

On behalf of the American Association for the Advancement of Science (AAAS), the world's largest general science society and the publisher of the peer-reviewed journal, Science, I am writing to express deep concern about letters recently sent by the

Committee to several scientists, including Drs. Michael S. Mann, Malcom K. Hughes, and Raymond S. Bradley, regarding their research in climate science.

We very much appreciate the Committee's interest in this important field. Your letters, however, in their request for highly detailed information regarding not only the scientists' recent studies but also their life's work, give the impression of a search for some basis on which to discredit these particular scientists and findings, rather than a search for understanding. With all respect, we question whether this approach is good for the processes by which scientific findings on topics relevant to public policy are generated and used.

Studies cited in the reports of the Intergovernmental Panel on Climate Change (IPCC) have been subjected to multiple levels of scientific peer review, first in achieving publication in a peer-reviewed scientific journal (which is a prerequisite for consideration by the IPCC) and then in multiple layers of the IPCC process itself. Where contending interpretations arise, these continue to be properly pursued over time in the peer-reviewed scientific literature and in the frequent assessments of such literature by groups such as the National Academy of Sciences and the IPCC.

While we fully understand that the policy-making functions of the Congress require integrating the best available understanding of relevant science with other considerations, we think it would be unfortunate if Congress tried to become a participant in the scientific peer-review process itself. More than that, we are concerned that establishing a practice of aggressive Congressional inquiry into the complete professional histories of scientists whose findings may bear on policy in ways that some find unpalatable could have a chilling effect on the willingness of scientists to conduct work on policy-relevant scientific questions.

In the particular case of the work of Drs. Mann, Hughes, and Bradley on the temperature history of the Earth, these studies have been peer-reviewed in connection with their publication in Nature, Geophysical Research Letters, Science, and elsewhere. The papers in question have described the methodology as well as the findings, and additional information has been provided in on-line supplements to the papers (an increasingly common practice in the science community).

As you state in your letter, the studies by Mann *et al.* were part of the basis for findings presented in the IPCC report: *Climate Change 2001: The Scientific Basis*. This having happened is a reflection of the Mann *et al.* work's passing muster in further layers of peer review within the IPCC process itself. The IPCC does not conduct research on its own, instead engaging top scientists from around the world to assess the current state of knowledge as reflected in articles published in peer-reviewed journals. There were more than 100 authors of Chapter 2 in the IPCC's 2001 "Scientific Basis" report, where the *Mann et al.* work was cited, and two extensive rounds of review by scientific experts and government representatives were conducted after those authors agreed on their initial draft. It should be added that the Mann *et al.* work was far from the only basis for the conclusion that Northern Hemisphere temperatures in the last part of the 20th century were likely the warmest in 1000 years; a variety of independent lines of evidence, summarized in a number of peer-reviewed publications, were cited in support of this conclusion.

It is true that studies that challenge the findings of Mann *et al.* have subsequently been published, as have other studies that support the Mann *et al.* findings. This point-counterpoint process is how science normally progresses. There is nothing about the way it is proceeding in this particular case that ought to arouse Congressional concern about federally-funded climate science or climate science in general. The peer-reviewed literature on Earth's temperature history will again be reviewed in the 2007 IPCC report.

Congress indeed has an important role in oversight of federally funded research, especially that which contributes to public policy. That role properly includes attention to both priorities and productivity in such research, but as to quality, the best guide for the Congress is the fate of federally funded research in the peer-reviewed literature and in the assessments of that literature by scientific bodies. As to the mechanisms for distilling from the available scientific knowledge the insights needed for the Congress to discharge its policy-making responsibilities, we believe that the tried and true approaches of hearings, meetings with individual experts in the field, and studies commissioned from the Government Accountability Office, the Congressional Research Service, and relevant Executive Branch agencies remain superior to the approach taken in your recent round of letters to climate scientists.

My colleagues and I would be pleased to discuss these matters with you and your staff should you so desire. Please contact Joanne Carney, director of the AAAS Center for Science, Technology and Congress (202 326 6798 or jcarney@aaas.org) if you have questions or would like additional information.

Sincerely,

Alan I. Leshner

cc: The Honorable John Dingell, Ranking Minority Member, Committee on Energy and Commerce
The Honorable Ed Whitfield, Chair, Subcommittee on Oversight and Investigations
The Honorable Bart Stupak, Ranking Minority Member, Subcommittee on Oversight & Investigations

Appendix IV: Joint Science Academies' Statement

The following statement was made by eleven of the world's national science academies on June 7th, 2005. The eleven academies were from: Brazil, Canada, China, France, Germany, India, Italy, Japan, Russia, United Kingdom, and the United States.
The statement is also available online at http://nationalacademies.org/onpi/06072005.pdf

Joint Science Academies' Statement: Global Response to Climate Change

Climate change is real
There will always be uncertainty in understanding a system as complex as the world's climate. However there is now strong evidence that significant global warming is occurring[1]. The evidence comes from direct measurements of rising surface air temperatures and subsurface ocean temperatures and from phenomena such as increases in average global sea levels, retreating glaciers, and changes to many physical and biological systems. It is likely that most of the warming in recent decades can be attributed to human activities (IPCC 2001)[2]. This warming has already led to changes in the Earth's climate.

The existence of greenhouse gases in the atmosphere is vital to life on Earth – in their absence average temperatures would be about 30 centigrade degrees lower than they are today. But human activities are now causing atmospheric concentrations of greenhouse gases – including carbon dioxide, methane, tropospheric ozone, and nitrous oxide – to rise well above pre-industrial levels. Carbon dioxide levels have increased from 280 ppm in 1750 to over 375 ppm today – higher than any previous levels that can be reliably measured (i.e. in the last 420,000 years). Increasing greenhouse gases are causing temperatures to rise; the Earth's surface warmed by approximately 0.6 centigrade degrees over the twentieth century. The Intergovernmental Panel on Climate Change (IPCC) projected that the average global surface temperatures will continue to increase to between 1.4 centigrade degrees and 5.8 centigrade degrees above 1990 levels, by 2100.

Reduce the causes of climate change
The scientific understanding of climate change is now sufficiently clear to justify nations taking prompt action. It is vital that all nations identify cost-effective steps that they can take now, to contribute to substantial and long-term reduction in net global greenhouse gas emissions.

Action taken now to reduce significantly the build-up of greenhouse gases in the atmosphere will lessen the magnitude and rate of climate change. As the United Nations Framework Convention on Climate Change (UNFCCC) recognises, a lack of full scientific certainty about some aspects of climate change is not a reason for delaying an immediate response that will, at a reasonable cost, prevent dangerous anthropogenic interference with the climate system.

As nations and economies develop over the next 25 years, world primary energy demand is estimated to increase by almost 60%. Fossil fuels, which are responsible for the majority of carbon dioxide emissions produced by human activities, provide valuable resources for many nations and are projected to provide 85% of this demand (IEA 2004)[3]. Minimising the amount of this carbon dioxide reaching the atmosphere presents a huge challenge. There are many potentially cost-effective technological options that could contribute to stabilising greenhouse gas concentrations. These are at various stages of research and development. However barriers to their broad deployment still need to be overcome.

Carbon dioxide can remain in the atmosphere for many decades. Even with possible lowered emission rates we will be experiencing the impacts of climate change throughout the 21st century and beyond. Failure to implement significant reductions in net greenhouse gas emissions now, will make the job much harder in the future.

Prepare for the consequences of climate change

Major parts of the climate system respond slowly to changes in greenhouse gas concentrations. Even if greenhouse gas emissions were stabilised instantly at today's levels, the climate would still continue to change as it adapts to the increased emission of recent decades. Further changes in climate are therefore unavoidable. Nations must prepare for them.

The projected changes in climate will have both beneficial and adverse effects at the regional level, for example on water resources, agriculture, natural ecosystems and human health. The larger and faster the changes in climate, the more likely it is that adverse effects will dominate. Increasing temperatures are likely to increase the frequency and severity of weather events such as heat waves and heavy rainfall. Increasing temperatures could lead to large-scale effects such as melting of large ice sheets (with major impacts on low-lying regions throughout the world). The IPCC estimates that the combined effects of ice melting and sea water expansion from ocean warming are projected to cause the global mean sea-level to rise by between 0.1 and 0.9 metres between 1990 and 2100. In Bangladesh alone, a 0.5 metre sea-level rise would place about 6 million people at risk from flooding.

Developing nations that lack the infrastructure or resources to respond to the impacts of climate change will be particularly affected. It is clear that many of the world's poorest people are likely to suffer the most from climate change. Long-term global efforts to create a more healthy, prosperous and sustainable world may be severely hindered by changes in the climate.

The task of devising and implementing strategies to adapt to the consequences of climate change will require worldwide collaborative inputs from a wide range of experts, including physical and natural scientists, engineers, social scientists, medical scientists, those in the humanities, business leaders and economists.

Conclusion

We urge all nations, in the line with the UNFCCC principles[4], to take prompt action to reduce the causes of climate change, adapt to its impacts and ensure that the issue is included in all relevant national and international strategies. As national science academies, we commit to working with governments to help develop and implement the national and international response to the challenge of climate change.

G8 nations have been responsible for much of the past greenhouse gas emissions. As parties to the UNFCCC, G8 nations are committed to showing leadership in addressing climate change and assisting developing nations to meet the challenges of adaptation and mitigation.

We call on world leaders, including those meeting at the Gleneagles G8 Summit in July 2005, to:

- Acknowledge that the threat of climate change is clear and increasing.
- Launch an international study[5] to explore scientifically informed targets for atmospheric greenhouse gas concentrations, and their associated emissions scenarios, that will enable nations to avoid impacts deemed unacceptable.
- Identify cost-effective steps that can be taken now to contribute to substantial and long-term reduction in net global greenhouse gas emissions. Recognise that delayed action will increase the risk of adverse environmental effects and will likely incur a greater cost.
- Work with developing nations to build a scientific and technological capacity best suited to their circumstances, enabling them to develop innovative solutions to mitigate and adapt to the adverse effects of climate change, while explicitly recognising their legitimate development rights.
- Show leadership in developing and deploying clean energy technologies and approaches to energy efficiency, and share this knowledge with all other nations.
- Mobilise the science and technology community to enhance research and development efforts, which can better inform climate change decisions.

Notes and references

1. This statement concentrates on climate change associated with global warming. We use the UNFCCC definition of climate change, which is 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods'.

2. IPCC (2001). Third Assessment Report. We recognise the international scientific consensus of the Intergovernmental Panel on Climate Change (IPCC).

3. IEA (2004). World Energy Outlook 4. Although long-term projections of future world energy demand and supply are highly uncertain, the World Energy Outlook produced by the International Energy Agency (IEA) is a useful source of information about possible future energy scenarios.

4. With special emphasis on the first principle of the UNFCCC, which states: 'The Parties should protect the climate system for the benefit of present and future generations of humankind, on the

basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities. Accordingly, the developed country Parties should take the lead in combating climate change and the adverse effects thereof'.

5. Recognising and building on the IPCC's ongoing work on emission scenarios.

Acknowledgements

I would like to thank friends and family, peers, staff, and above all, my advisors Professor David Marks and Steve Connors, for their support and guidance throughout my career at MIT. Their assistance, both moral and financial, has helped me get through the difficult times and enjoy the good ones.

Professor Marks and Steve Connors laid the groundwork for my research, and helped me stay focused as it progressed. I appreciate their patience and encouragement throughout. TPP and LFEE faculty, staff, and students were also invaluable. They provided a unique setting to explore my ideas in a rigorous manner. In addition, people like Professor Marks, Sydney Miller and Jackie Donoghue helped me navigate my way through MIT while keeping a bright perspective. I also appreciate the assistance of Cynthia Stewart.

I greatly enjoyed my time at MIT, and thank the above for their support.