Final Report

The MIT Low-Carbon Energy Economy Workshop

May 26-27, 2015, Cambridge, Massachusetts

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Forward

We would like to thank the U.S. Department of Energy for their support through Idaho National Laboratory (INL) and the National Renewable Energy Laboratory (NREL) and the MIT Energy Initiative as well as the speakers, discussion leaders, and participants in the workshop.

Abstract: The MIT Low-Carbon Energy Economy Workshop

A national objective is the development of a low-carbon energy system. The U.S. has adopted an incremental strategy in terms of research, development, and implementation with the embedded assumption that an incremental strategy will work. However, it may be that some of the technological choices and pathways can't reach the goal, or in fact may create institutional or cost barriers to a low-carbon world. The other part of the challenge is the lack of time. A serious transition must occur relatively quickly but the timeframe to develop new technologies is one or two decades with similar deployment times because of the scale of the energy enterprise—about 10% of the global income.

To address these issues the Massachusetts Institute of Technology (MIT) Energy Initiative conducted a Low-Carbon Energy Economy Workshop on May 26-27, 2015. Each session addressed a single question where two speakers provided their perspectives followed by discussions. This report summarizes workshop results.

Low-carbon Energy Economic Overview: R. Prinn (MIT) and J. Long (California Low-Carbon study). Recent trends suggest that (1) carbon capture and sequestration is more expensive than originally thought, (2) the potential for economic cellulosic biofuels has improved, (3) solar and wind costs have decreased but intermittency is a major challenge and (4) nuclear power in China and the far east have lowered costs increasing the viability of the nuclear option. A low-carbon strategy requires improved efficiency, electrify where possible, decarbonize the electric sector, and decarbonize fuels. That implies a doubling of electricity demand.

Near-Term Strategies That Will Lead to Long-Term Cost-Effective Renewables. R. Koningstein (Google Inc.) and F. O'Sullivan (MIT): MIT Future of Solar Study. Incremental advances in technology will not enable large-scale renewables. Disruptive breakthroughs are required with R&D to support breakthroughs. For solar the challenge is that large-scale solar results in electricity price collapse at times of high solar input. Lower cost solar and energy storage are required for global solar impact.

Nuclear Systems Performance Requirements. C. Forsberg (MIT) and H. Safa (CEA, France): Nuclear Cogeneration. Nuclear reactors generate heat, unlike PV and wind that generate electricity. That heat can be used to generate electricity and meet industrial, commercial, and residential heat demand. Heat is much cheaper to store than electricity thus base-load nuclear plants using heat storage can provide the variable electricity required by the gird.

Strategy for Low-Carbon Liquid Fuels. B. Dale (Michigan State Univ.) and Lee Lynd (Dartmouth College). There is no good substitute for liquid fuels for about half the transport market—especially aircraft and heavy vehicles. Low-cost biofuels could potentially meet this need but it requires improved technologies and appropriate policies that create the right incentives for farmers. Central to achieving this transformation is to recognize that over 80% of agricultural land is used to produce animal feeds, not human foods directly that enable a wider set of options.

Nuclear Fuel Cycles and Non-proliferation Requirements. F. Carre (CEA, France) and M. Bunn (Harvard Univ.). Countries build nuclear weapons for reasons of national security, prestige, internal politics, and internal institutional imperatives. A nuclear power program can reduce technical barriers to nuclear weapons development by creating more skilled people or discourage the development of a nuclear weapons program because of concerns that the international challenges of a weapons program will set back

nuclear power implementation. Thus, the policy goal is to create the institutional and technical structure that nuclear power developments discourage nuclear weapons programs.

Renewable Energy Systems Long-Term Requirements and Options. What are the Geographical Implications. A. Bloom (NREL) and J. Reilly (MIT). Wind and solar vary with location. It is technically feasible to provide up to 80% of all electricity by renewables in the United States with increased system flexibility but there are cost and institutional challenges—particularly the need for long-distance transmission lines. Global biomass studies indicate the potential for biofuels to be a major contributor to liquid fuels production but only a minor global contributor to production of heat and electricity.

General conclusions. R. Armstrong (MIT) and R. Budnitz (LBNL). Common themes emerged throughout the workshop. There is the need to reduce costs of low-carbon options because energy represents about 10% of the global economy. Significant increases in energy costs have large impacts on standards of living. Energy systems are so large that subsidies and governmental development can help jump-start new technologies but not result in large-scale deployment. Efficiency is important because it reduces the requirements on other low-carbon technologies and because so many of the gains in efficiency are cost effective, they save money. Last, many of the challenges are at the systems level.

From a policy perspective nothing would accomplish more than a price on carbon because it would get the major incumbents, such as the oil companies, engaged with their extraordinary technical and organizational skills. On the technology side, the U.S. needs to revitalize the innovation chain that must include public private partnerships where public funding helps start technologies, but where the discipline of the market minimizes costs.

Last is the need for government leadership. Markets will not lead but will respond.

Executive Summary
The MIT Low-Carbon Energy Economy Workshop

May 26-27, 2015, Cambridge, Massachusetts

Charles Forsberg and Michael Golay

INTRODUCTION

A national objective is the development of a low-carbon energy system. The U.S. has adopted an incremental strategy in terms of research, development, and implementation. That strategy has the embedded assumption that an incremental strategy will work. However, it may be that some of the technological choices and pathways can't reach the goal, or in fact may create institutional or cost barriers to a low-carbon world.

The other part of the challenge is the lack of time. A serious transition must occur relatively quickly but the timeframe to develop new technologies is one or two decades with similar deployment times because of the scale of the energy enterprise—about 10% of the global income. Each option comes with its own constraints. Nuclear has flexible siting but large institutional challenges including public perceptions associated with safety, wastes, and non-proliferation. Renewables have inflexible geographical siting and intermittency. Biofuels have potential conflicts with other land uses from food to environmental impacts. Central to such a change are development of policies that enable public-private development of appropriate technologies with the discipline and efficiency of the private sector to find cost effective solutions.

To address these issues the Massachusetts Institute of Technology (MIT) Energy Initiative (Robert Armstrong, Director and Workshop Chairman) conducted a Low-Carbon Energy Economy Workshop on May 26-27, 2015 at MIT under Chatham House Rules (no attribution). This report summarizes that workshop.

Each workshop session addressed a single question with two speakers who provided their perspectives followed by discussion where half or more of the time was reserved for discussion. The website [1] provides further information.

WORKSHOP OBJECTIVES, QUESTIONS AND STRATEGIES

The workshop objectives were:

- Examine fundamental questions on how to achieve a low-carbon world
- Begin to define viable pathways forward
- Evaluate whether an incremental strategy will work

This leads to a series of questions:

- What are the technology energy options? Which should receive emphasis and should any be off the table?
- Does every "CO_2-guilty" energy consumption sector need to be attacked? Are all equal or are there any exemptions?
- Do costs need to be "close" to current costs, or is the world ready for substantially higher costs? Under

[1] http://mitei.mit.edu/may-26-2015

what circumstances could substantially greater costs be tolerated or worse, be required?

- How much difference in costs can be tolerated nationally and worldwide based on geographical considerations? The issues of cost-sharing across the U.S. or within any other country and cost-sharing among numerous countries internationally are, in fact, very different.
- What subsidies would be needed and would be politically tolerated?
- Are there credible energy-transportation strategies to help levelize costs and access?
- What short-term actions or policies might seriously compromise our long-term goals? How can such outcomes be avoided?
- Is the "good" (which is available now or soon) the enemy of the "excellent" (which might be available only a few decades hence)? If we wait, the problem to be solved will likely get much harder to address.
- Who needs to act first? Can the U.S. make a sufficient difference if we "act first" whether or not others follow?
- Will an "incremental" strategy work on the technological front? Will it work on the sociological/political front? How much "risk" of "not working" can the planet tolerate?

GENERAL OBSERVATIONS

Three strategic challenges appeared as common themes across sessions:

- The need to incorporate high-levels of low-carbon electricity into the grid
- The need for low-carbon liquid transportation fuels
- The need for improved efficiency—particularly in the transportation sector and in other parts of the economy where it is expensive or difficult to reduce greenhouse gas releases.

Market penetration of low carbon technologies to reduce greenhouse gas emissions by half is much easier than additional large reductions in greenhouse gas emissions for both low carbon electricity and low-carbon transportation. New or major modifications of existing technologies are required.

SESSION 1: LOW CARBON ENERGY ECONOMIC OVERVIEW

Ronald Prinn (MIT): *The Climate Challenge: Toward a Low-Carbon Energy Economy;* Jane Long (California Low-Carbon study): *The California Low-Carbon Study: What Was learned*[2] [3].

The scale of the climate challenge is not appreciated (Prinn). The proposed goal of no more than a 2°C increase in global temperature by 2100 implies a multiple of that at the poles and a long-term rise in ocean sea levels. While increased carbon dioxide emissions receive the most attention, there is a significant contribution from other manmade gases—equivalent to 85 ppm CO_2.

Recent trends suggest that (1) carbon capture and sequestration is more expensive than originally thought, (2) the potential for economic cellulosic biofuels has improved, (3) solar and wind costs have decreased but intermittency is a major challenge and (4) nuclear power in China and the far east have

[2] California Council on Science and Technology, *Policies for California's Energy Future – How to Choose a Climate Friendly Electricity System for the Future*, June 2014

[3] Peter J. Loftus et al., "A Critical Review of Global Decarbonization Scenarios: What Do They Tell Us About Feasibility", *Advanced Review*, *WIREs Clim Change* 2014. doi: 10.1002/wcc.324

lowered costs and thereby increased the viability of the nuclear option. Limiting CO_2 levels is ultimately an economic challenge. One way to address this challenge is by a revenue neutral price on carbon (money collected from CO_2 tax rebated to the citizens).

The first detailed engineering study (Long) of how to achieve a low-carbon world (although limited to achieving only a zero-carbon California) was conducted by California with three ground rules: get carbon accounting right, use feasible technology, and do not leak carbon--such as using more than California's share of national or international low-carbon technologies such as biomass. The study had a four-part strategy: improve efficiency, electrify, decarbonize the electric sector, and decarbonize fuels.

Multiple routes to a zero-carbon California were assessed that led to several general conclusions. Major improvements in efficiency are required in order to reduce the size of the supply problem, but there is a large difference in the cost versus consequences of different energy efficiency strategies. Efficiency can make a more important impact if focused on measures where low-carbon technologies are not available, such as in transportation. All scenarios required a doubling in electricity generation. The major technical challenges (particularly for high renewable scenarios) were meeting variable electricity demand without excessive dependence on natural gas. The best solutions were those that used renewable energy, natural gas with carbon capture and storage and nuclear power. Biofuels will not likely solve the remaining fuel problem. Fully meeting the requirement for 80% reductions in CO_2 emissions will require complex industrial solutions. The political and social challenges together are equally as significant as the technological challenges.

The discussions led to other observations. The advanced world can afford some expensive options but the developing world cannot. When addressing CO_2 releases, accurate accounting for leakage is a major challenge—much of the apparent reduction in CO_2 releases to the atmosphere in many wealthy countries disappears if one accounts for the embedded CO_2 atmospheric releases in imported products. Accounting for CO_2 is particularly difficult with biofuels because different agricultural practices can increase or reduce carbon inventories in the soil at least in the short term.

SESSION 2: NEAR-TERM STRATEGIES THAT WILL LEAD TO LONG-TERM COST-EFFECTIVE RENEWABLES

Ross Koningstein (Google Inc.): *The Google Adventure with Renewables: Why Incremental Advances are Inadequate to Solving Climate Change* [4] and Francis O'Sullivan (MIT): *MIT Future of Solar Study*[5]

The Google experience (Koningstein) with renewables is that major reductions in renewables costs are required—incremental advances in technology will not enable large-scale renewables. Disruptive breakthroughs are required with R&D to support breakthroughs.

A large-scale global transition off of carbon fuels will not happen unless there are large financial incentives (profits) for replacing energy sources. The rate of transition depends upon the profits. If traditional utility rates of return exist for a new technology, the deployment of a new

[4] Ross Koningstein and David Fork, "What It Would Really Take to Reverse Climate Change," *IEEE Spectrum*, November 18, 2014

[5] Richard Schmalensee et al, *The Future of Solar Energy: An Interdisciplinary MIT Study*, Massachusetts Institute of Technology, 2015

technology will take a half century or more. If venture capital rates of return occur that allow firms to raise cash from current profits, new technologies can have widespread adoption over shorter time frames.

The MIT *Future of Solar* study reached similar conclusions about solar but from a somewhat different perspective. The central feature of solar (and wind) is that the output is limited to times of high solar insolation (and wind) at a given site. This results in electricity price collapse (Fig. 1) with large-scale deployment at times of high output—an economically non-viable system. Small levels of deployment can be competitive with near-term technology.

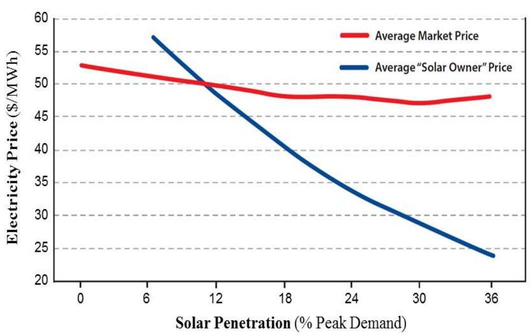

Fig. 1. Price of Solar Electricity versus Percentage of Electricity by Solar at Times of Peak Solar Output

To enable large-scale solar requires (1) major reductions in the cost of solar installations and (2) large-scale low-cost electricity storage in order to avoid electricity price collapse. These are strongly coupled conclusions (Fig. 2)—more expensive storage requires lower solar costs in order to address storage costs and to enable competitive large-scale solar.

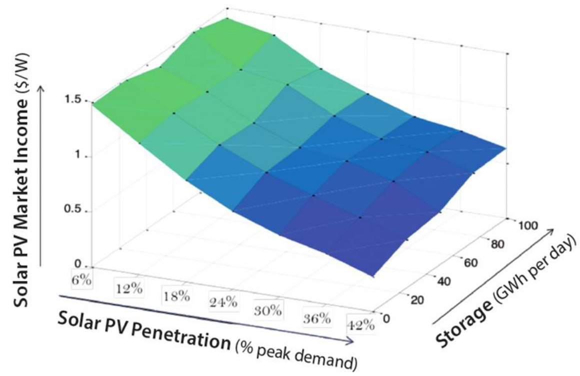

Fig. 2. Storage Reduces Revenue Collapse with Large-Scale Solar Deployment

The MIT report defines multiple technology pathways and institutional strategies to meet required goals for more economic solar.

The discussions amplified several points from the presentation. Levelized cost of electricity has little connection to the economics of real electrical systems. It's an accounting concept to compare two different base-load power plants and does not apply to systems with non-dispatchable electricity generation and real world revenue collapse. Expanding long-distance electricity transmission is difficult, expensive and problematic.

There has been a serious underestimation of the technical challenges associated with long-term performance of renewable technologies. For example, the thermal stresses and thus thermal fatigue that a heat exchanger will see in 30 years in a coal plant occur within three months in a solar power tower. Similarly there are assumptions on photovoltaic (PV) lifetimes that have not been demonstrated under real world conditions on a large scale. The expectations for large-scale expansion are based on a small experience base.

There are major problems in the institutional structure for developing renewables technologies. New technologies require government support but also the discipline of the private sector and the marketplace to sort out the economic from the uneconomic. In the 1970s the Electric Power Research Institute (EPRI) provided a key mechanism to help the transition from the laboratory to industrial scale. With electricity deregulation, that function of EPRI diminished significantly and has not been replaced. Developing effective public-private partnerships is essential for rapidly advancing the technology, but that is a difficult task.

SESSION 3: NUCLEAR SYSTEMS PERFORMANCE REQUIREMENTS

Charles Forsberg (MIT) [6, 7, 8]: *Base-load Nuclear Power to Meet the Need for Variable Energy Output: The Value of Heat* and Henri Safa (CEA, France)[9]: *Nuclear Cogeneration*

Nuclear energy is the large-scale base-load low-carbon heat source that can be used to provide electricity production and heat for industry and commerce. This is in contrast to PV and wind that produce electricity. Unlike renewables, nuclear power systems can be built almost anywhere with output independent of the external environment.

As a large-scale base-load heat source nuclear energy can provide variable heat to meet variable energy demand using a combination of existing and new technologies via three sets of technologies (Forsberg). As such, nuclear energy may be the enabling technology for a low-carbon world and for large-scale renewables.

Storage. The U.S. Department of Energy has defined long-term goals for the capital cost of electricity storage ($150/kWh) and heat storage ($15/kWh) to provide the basic service of fossil fuels—variable energy on demand. Heat storage (nitrate salts, steam accumulators, geothermal rock, etc.) is an order of magnitude less expensive than electricity storage (batteries, compressed air storage, etc.). While heat is not as useful as electricity, it can be converted to electricity. Heat storage coupled to nuclear reactors is more economic than other forms of heat storage because of (1) economics of scale and (2) the ability to use those storage devices more times per year because nuclear reactors operate year-round at high capacity factors. It follows that one economic low-carbon strategy to meet variable electricity and heat demand is coupling nuclear energy to heat storage with that heat storage used for satisfying variable electricity demands and to provide heat to industry.

There is a second class of heat storage technologies, Firebrick Resistance-Heated Energy Storage (FIRES), where electricity is used to heat firebrick to high temperatures when electricity prices are low. Fans push air through the firebrick to provide hot air as a substitute for burning natural gas to industrial furnaces and kilns. It is a strategy to move energy from the electricity sector to the industrial sector at times of excess electricity to avoid revenue collapse (Fig. 2).

Nuclear Air-Brayton Combined Cycles (NACC). In the last 50 years there have been dramatic improvements in gas turbines with the development of natural-gas combined cycle plants with gas-to-electricity efficiencies of 61%. Those improvements enable coupling gas turbines to advanced high-temperature reactors (Fig. 3) such as the proposed Fluoride-salt-cooled High-temperature Reactor (FHR). This specific

[6] Charles W. Forsberg et al., "Baseload Nuclear with Variable Electricity to the Grid," *Nuclear News*, March 2015

[7] Daniel Stack and Charles Forsberg, "Improving Nuclear System Economics using Firebrick Resistance-Heated Energy Storage (FIRES), Trans. American Nuclear Society Annual Meeting, San Antonio, Texas, June 7-11, 2015.

[8] Charles Forsberg, "Hybrid Systems to Address Seasonal Mismatches Between Electricity Production and Demand in Nuclear Renewable Electrical Grids," *Energy Policy* **62**, 333-341, 2013.

[9] H. Safa, "Heat Recovery From Nuclear Power Plants," *Electrical Power and Energy Systems*, **42**, 553-559, 2012

concept has a base-load heat-to-electricity efficiency of 42%.

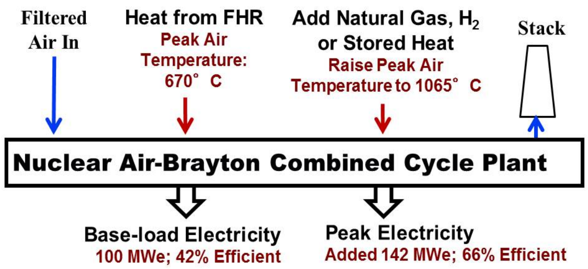

Fig. 3. Simplified Schematic of FHR with NACC

In a gas turbine added heat (natural gas, hydrogen, FIRES stored heat) can be used to further raise air temperatures after nuclear heating. In this specific example the peak temperature increases from 670 to 1065°C with an incremental heat-to-electricity efficiency of 66%. With advanced designs optimized for peak power, the incremental heat-to-electricity efficiency can rise above 70%. These peak power efficiencies are greater than for any other heat-to-electricity technology in existence because peak power is a topping cycle above a "low-temperature" 700°C bottoming cycle. The peak turbine temperatures are significantly below those for existing natural gas turbines. If such a plant were to exist today, the nuclear plant revenue in states such as California and Texas would increase by 50 to 100% relative to a base-load nuclear plant after paying for natural gas for peak power production.

For fundamental thermodynamic reasons, these topping cycles are the most efficient method to convert heat (natural gas, hydrogen, biofuels, ammonia, other combustible fuels or stored heat sources) into variable electricity on demand. The efficiency is significantly higher than that of stand-alone gas turbines. That efficiency translates into potentially the most economic method for non-fossil variable energy output on demand.

Hybrid Energy Systems. Hybrid energy systems use two or more energy inputs to produce two or more products—usually electricity and a second product. Such systems have the potential for lower costs because they fully utilize the output of two or more energy generating technologies and minimize the use of energy storage with its associated capital costs and energy inefficiencies.

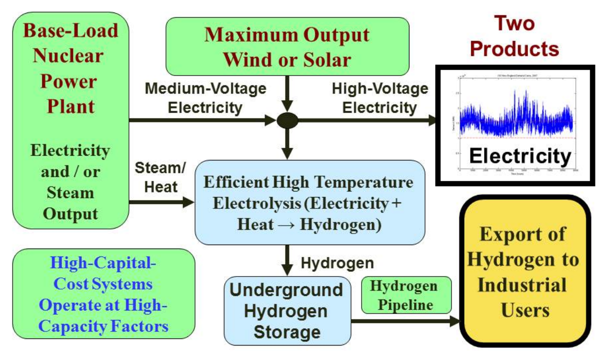

Fig. 4 Nuclear Renewable Hydrogen Hybrid System

Hybrid systems come in many forms. Proposed nuclear renewable hydrogen systems (Fig. 4) have the goal to produce hydrogen and variable electricity. In a low carbon economy a third of all primary energy input could be in the form of hydrogen. About ten million tons of hydrogen are used today—primarily for fertilizer production and refining of crude oil into liquid fuels but also on a limited scale for direct reduction of iron ores to iron. Future uses could include replacing carbon in conversion of metal ores into metals, increasing liquid fuel production yield per ton of biomass feedstock and possibly using hydrogen directly as a transport fuel.

In a nuclear renewable hydrogen system the nuclear reactor, wind, and solar systems operate at full capacity to minimize costs. At times of low wind or solar output, nuclear provides the required electricity to the grid. Hydrogen is generated using high-temperature electrolysis (HTE)—the most efficient method to produce hydrogen from water. HTE is steam electrolysis that requires input of heat and electricity. When electricity production exceeds demand, the reactor provides heat with wind and solar providing electricity to HTE. Hydrogen can be stored underground using the same low-cost technologies used for natural gas. Long-distance pipelines provide the low-cost method to transport hydrogen from areas of low-cost renewables to markets. Such pipelines exist in Texas and neighboring states where they connect refineries, storage facilities, and hydrogen production facilities. The energy throughput of a single pipeline exceeds that of a dozen large electricity transmission lines. The system design potentially enables capital intensive technologies to operate at high capacity factors to minimize costs while providing variable power to the grid from remote low-cost renewable sources.

Electricity is a large fraction of total energy demand but the next largest fraction is heat (Safa)—particularly low temperature heat for industrial, commercial and residential use. In France 40% of energy demand is heat and 20% of global energy demand is low temperature heat. Much of this heat demand occurs in winter at times of low solar and wind output. The heat requirements must be met for any credible low-carbon future. In this context, there have been rapid advances in long-distance transport with very low heat losses of hot water over distances of 100 to 200 kilometers—something not viable 20 years ago. This high performance is a consequence of better methods of insulation around the joints between prefabricated insulated pipe and of instrumentation that can find where the heat losses are occurring to enable repair of low-heat loss pipes. That development in countries such as France may enable nuclear power to provide large-scale industrial and district heating at potentially competitive rates relative to fossil fuels.

The discussions noted that heat storage is often ignored—it does not appear high-tech and is often not considered when comparing options or as an area for R&D funding. Many government incentive programs are written defining technology storage solutions rather than what is important—lowest cost storage.

SESSION 4: STRATEGY FOR SYNTHETIC LIQUID FUELS / WHAT ARE THE OPTIONS FOR LIQUID HYDROCARBON FUELS WITH ZERO NET CARBON?

Bruce Dale (Michigan State Univ.): *Biomass Fuels Imply Rethinking Agriculture*[10] and Lee Lynd (Dartmouth College)]: *Biofuels and Climate Change Mitigation: Need, Land, and Development*[11]

Biofuels are essential if we wish to meet demands for sustainable transportation fuels (Dale). Five different, independent studies[12] have found that approximately 25% of global energy demand (138 EJ/year) must be met by bioenergy to achieve a low-carbon energy sector, mostly for liquid transportation fuels for which we have no sustainable substitutes. Biofuels can potentially provide a low-carbon liquid fuel option because CO_2 is extracted by plants from the atmosphere, converted to liquid fuels, burnt, and returned to the atmosphere with no net change in atmospheric CO_2 levels.

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[10] Bruce Dale et al. "Biofuels Done Right: Land Efficient Animal Feeds Enable Large Environmental and Energy Benefits," *Environmental Science and Technology*, **44**, 8385-8389, 2010

[11] Lewis Fulton et al., The Need for Biofuels as Part of a Low-Carbon Energy Future," *Biofuels, Bioproducts, and Biorefining*, 2015

[12] Bruce Dale et al., "Take a Closer Look: Biofuels Can Support Environmental, Economic and Social Goals," *Environmental Science and Technology*, **48**, 7200-7203, 2014

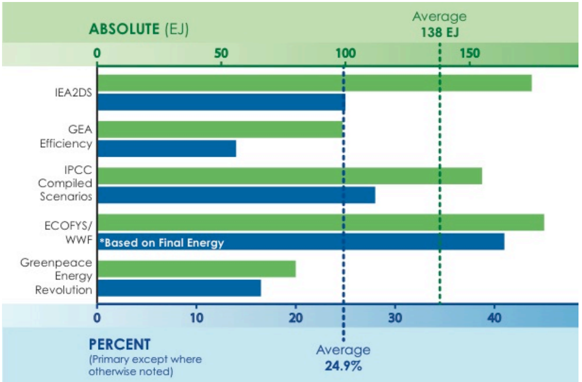

Fig. 5. Potential Contribution of Biomass to Meet Low-Carbon Energy Needs—Primarily Biofuels

There are significant technical, economic, and policy challenges to achieving large scale, sustainable biofuel production. Essentially, we must now redesign U.S. and world agricultural systems to produce biofuels, food and animal feeds, and also provide large-scale environmental services. Agriculture is currently not designed to meet any objectives other than food/feed provision. Important environmental services include reducing fertilizer consumption, limiting erosion and loss of nitrogen and phosphorus to surface and groundwater, improving biodiversity, and significantly increasing carbon stored in the soil—a potentially enormous carbon sink. Increasing the carbon inventory of the soil may in fact be the lowest cost option for sequestering carbon dioxide. Done poorly, biofuels can conflict with food production, wildlife values, and other land uses, and reduce soil carbon. Thus, the future of biofuels depends as much on good policies as advancing technologies.

Agriculture has changed many times in the past and can change again to maximize production of food, fiber, biofuels, and environmental services at lower costs. Central to achieving this transformation is to recognize that well over 80% of agricultural land is used to produce animal feeds, not human foods directly. Thus, there is a much wider choice of options to simultaneously increase biofuels and animal food production than would be the case if we also had to change human food consumption habits. More sustainable agricultural practices would include more double cropping, greater use of no till and conservation tillage practices, more use of perennial grasses and trees in sensitive areas, etc. These and other changes are well within the capabilities of farmers to implement—but would also require new incentive structures for farmers to change their practices, as they have done in the past.

For cellulosic or "second generation" biofuels, advances in many technologies are required. Perhaps most important are methods to convert locally-available biomass into dense intermediate commodity products that can be economically stored and shipped long distances. Creating commodity biomass feedstocks enables large-scale, lower-cost biorefineries and also creates national markets for production by the most efficient, most sustainable methods feasible. Commodity cellulosic biomass feedstocks would create the environment for farmers to respond to market demand for cellulosic biofuels. This environment does not now exist.

The cost of lignocellulosic feedstock ($20-100/ton) is sufficiently low that biofuels are potentially competitive with fossil liquid fuels (Fig. 6); however, there are major questions and challenges (Lynd).

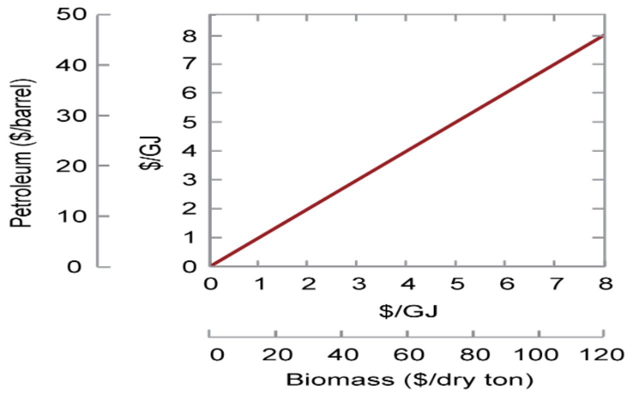

Fig. 6. Cost of Biomass Feedstock vs. Price of Petroleum

While there are large quantities of biomass, it is unclear if it could fully meet global demand for low-cost liquid transport fuels. The capability of biofuels to provide low-cost transport options depends upon the total demand; that, in turn, depends upon fuel efficiency, alternative fuels, and developments such as hybrid vehicles. Current estimates is that about half the liquid fuel demand is for applications (airplanes, heavy trucks) where there are few or no alternatives to liquid fuels.

The discussions focused on challenges and the need for a coherent biofuels strategy. Biofuels is not a single technology—it is a complex set of options where it has been difficult to get a coherent discussion of options. Biofuels couples three complex systems: (1) the biomass production system where how it is done can have a large impact on stored carbon in the soil (good or bad) and thus atmospheric CO_2 levels, (2) the larger agricultural system and (3) the biomass-to-fuels conversion system with multiple liquid fuel options that couple different ways to the transport sector.

In the area of biomass-to-liquid fuels conversion there are three complementary strategies for liquid transport biofuels that can strongly affect quantity of liquid fuels per ton of feedstock and net CO_2 releases to the air.

Biomass as feedstock and energy source. Biomass can be used as the feedstock for a biofuels refinery and the energy source to operate the biorefinery.

Biomass as a feedstock. The conversion of biomass into liquid fuels is energy intensive. If external sources of heat and hydrogen from nuclear, wind and solar can be provided, the liquid fuels yield per ton of biomass feedstock can be doubled with dramatically lower feedstock requirements.

Biomass for low-carbon bio and fossil liquid fuels. Many of the biomass-to-liquid-fuel processes produce nearly pure CO_2 as a byproduct that could be sequestered underground. The sequestration of this CO_2 would allow burning an equivalent amount of fossil liquid fuel to be used with no net change in atmospheric CO_2 levels. This option may provide the lowest cost option for a zero-carbon liquid fuels future.

Carbon dioxide capture and sequestration from fossil plants today is expensive and energy intensive—primarily because of the cost and energy requirements to recover and concentrate CO_2 from dilute stack gases. The sequestration step is relatively cheap. Certain biofuels processes produce nearly pure CO_2 and thus would have dramatically better economics for sequestration of CO_2. At the same time, the cost of biomass will increase as the demand increases—meeting total liquid fuels demand using biofuels may become very expensive. A more economic option for a zero-carbon liquid fuels future could be conversion of some biomass into liquid fuels, sequestration of carbon dioxide from those plants, and limited use of fossil liquid fuels.

The research and development (R&D) needs are in three areas. How does one change agriculture to obtain the added biomass without significantly impacting food or fiber production while maintaining or increasing carbon storage in the soil? How does one transport biomass to biorefineries to create a viable commercial business model? Last, what are the conversion options from biomass to liquid fuels? To date there have been frequent changes in policies and goals in a field where R&D associated with the production steps on the land have long lead-time lines. Stability of R&D funding and policies are required for major advances.

SESSION 5: NUCLEAR FUEL CYCLE AND NON-PROLIFERATION REQUIREMENTS / WHAT TECHNOLOGIES AND INSTITUTIONS ARE NEEDED FOR SUSTAINABILITY?

Frank Carre (CEA, France); *Challenges and Issues Associated with the Nuclear Fuel Cycle for Sustainable Growth of Nuclear Power* and Matt Bunn (Harvard Univ.)[13]: *Avoiding Nuclear Proliferation in a More Nuclear Future*

There were common perspectives by the speakers on many aspects of nonproliferation and nuclear energy. Countries that build nuclear weapons do so for reasons of national security, prestige, internal politics, and internal institutional imperatives. The existence or non-existence of a nuclear power program is secondary. A nuclear power program can reduce technical barriers to nuclear weapons development by creating more skilled people. A nuclear power program can discourage the development of a nuclear weapons program because of concerns that the international challenges of a weapons program will set back nuclear power implementation.

There are many strategies to increase the potential for nuclear power expansion that increase the incentives for countries not to develop nuclear weapons. The most important barrier may be coupling national nuclear power program between countries to develop local incentives for domestic nuclear programs to be opposed to weapons programs because of the risk of disruption to electricity programs by a breakout weapons program.

The other incentive would be development of fuel cycles with leased fuel where major countries manufacture the fuel, lease the fuel, and take back the fuel and dispose of the wastes. The Russian government currently does this, but no western country has made such an offer. For small nuclear programs, this approach avoids the need to develop geological repositories and fuel cycle facilities. In a competitive market, fuel leasing should lower costs for countries with small programs because of the large economics of scale of many parts of the fuel cycle going from uranium enrichment to the waste repository. Such services have not been offered by any western country because of the difficulty in siting repositories for disposal of spent nuclear fuel or high-level wastes. That may ultimately change given the potential for large profits and revenue for countries that sell full fuel cycle services, and the ability to offer such services if reactors are bought from the same country.

The disagreements noted by the speakers are over the choice of open (Bunn) or closed fuel cycles (Carre). Open fuel cycles minimize concerns about proliferation but are inefficient in the use of uranium. Currently uranium prices are low and thus there is no incentive to deploy closed fuel cycles. However, the future is uncertain and the time required to develop such closed fuel cycles can be long.

There is also an economic constraint. Economic forces are very strong (Bunn) and thus enforcing the need for non-proliferation strategies that align economics with goals. What approaches are economically attractive?

[13] National Academy of Sciences, *Internationalization of the Nuclear Fuel Cycle: Goals, Strategies, and Challenges*

The discussions focused on several challenges. The first is the path forward on fuel cycles where the west's incapacity to develop a fuel leasing (spent nuclear fuel [SNF] take-back) versus Russian SNF take-back implies that global nuclear power policies will increasingly be determined by Russia and China. The other reality is the need for energy; that need implies nuclear power will be used in many countries where the western view that only some countries should have access to nuclear power comes up against the realities of energy needs.

SESSION 6: RENEWABLE ENERGY SYSTEMS LONG-TERM REQUIREMENTS, AND OPTIONS. WHAT ARE THE LONG-TERM GEOGRAPHICAL IMPLICATIONS OF RENEWABLES IN TERMS OF ECONOMICS AND INSTITUTIONS?

Aaron Bloom (NREL): *Renewable Energy Futures* [14,15] and John Reilly (MIT): *The Feasibility, Costs, and Environmental Implications of Large-scale Biomass Energy*

Recent studies (Bloom) indicate it is technically feasible to provide up to 80% of all electricity by renewables in the United States with increased system flexibility. A variety of flexibility options were presented for reliably managing the power system under very high penetrations of variable generation. Also, several analyses of reliability at a variety of timescales were presented. NREL analysis indicated that several currently available technologies could be used to facilitate the efficient and reliable integration of variable generation. However, to better compare the value of different options (e.g. transmission, storage) computational challenges must be overcome.

Global biomass studies (Reilly) indicate the potential for biofuels to be a major contributor to liquid fuels production but only a minor global contributor to production of heat and electricity. The incentive structures have to be carefully defined to avoid large-scale deforestation or soil degradation with loss of large existing carbon sinks.

The second result of these global economic models is that with standard assumptions even with high prices for carbon ($99/ton CO_2) do not limit warming below 2°C.

Workshop participants observed that adding long-distance transmission lines is often the most cost-effective option to integrate added renewables to the grid. However, building new long distance transmission lines has become very difficult in the U.S. and Europe when they cross political boundaries. In the U.S., most major new long distance lines have been built in a single state (Texas, Minnesota, etc.) reflecting the institutional structure in the U.S. constitution of independent state and federal governments—versus countries such as France where there is a single national government. Large-scale renewables without major transmission upgrades, large-scale deployment of storage technologies, hybrid systems or other technologies implies major challenges to grid reliability. There were a series of discussions about the scale of these challenge based partly on experiences in Germany.

SESSION 7: CLOSEOUT: AGENDA FOR CREATING THE LOW CARBON ENERGY FUTURE

Robert Armstrong (MIT) and Robert Budnitz (LBNL)

[14] E. Ela et al. *Evolution of Wholesale Electricity Market Design with Increasing Levels of Renewable Generation*, NREL/TP-5D00-61765, National Renewable Energy Laboratory, September 2014

[15] Trieu Mai, *Renewable Energy Futures Study*, National Renewable Energy Laboratory

Common themes emerged throughout the workshop. First is the need to reduce costs of low-carbon options. Because energy represents about 10% of the global economy, any significant increases in energy costs have large impacts on standards of living. The political challenges are greater if there are high costs. Energy systems are so large that subsidies and governmental development can help jump-start new technologies but not result in large-scale deployment. Second is the role of efficiency—partly because efficiency reduces the requirements on other low-carbon technologies and partly because so many of the gains in efficiency are cost effective, they save money. Third, many of the challenges are at the systems level. As noted in the MIT Future of Solar study, dramatic drops in component costs such as PV cells do not assure economic systems where the requirement is delivery of variable electricity to the grid on demand.

From a policy perspective (Armstrong), nothing would accomplish more than a price on carbon because it would get the major incumbents, such as the oil companies, engaged with their extraordinary technical and organizational skills. As many others have proposed, a carbon price can be revenue neutral with revenue returned to the public. On the technology side, the U.S. needs to revitalize the innovation chain that must include public private partnerships where public funding helps start technologies, but where the discipline of the market minimizes costs.

There are several specific challenges (Budnitz). Mankind has burned carbon (firewood and then fossil fuels) for a quarter of a million years and varied energy output by throwing a little more carbon on the fire. The technology has changed from the cooking fire to the gas turbine but not the energy policy that is based on storable carbon. A low-carbon world must find the replacement for storable carbon. Timing is a central issue. The longer one waits, the greater the challenges. There must be a major emphasis on R&D.

The discussions focused on the characteristics of the challenge. Climate change does not lend itself to a Manhattan (atomic bomb) or Apollo (space) type program because economics is central—one cannot afford massive increases in the cost of energy given the size of the energy sector. There is a massive mismatch between a political system that thinks in 2, 4 or 6 year time frames versus a long-term challenge. In all cases, what happens in China and India will have major impacts on future atmospheric CO_2 levels.

Any options involving renewables (solar, wind, and biomass) imply the need for regional thinking because of the very unequal regional distribution of such energy sources. This is unlike fossil and nuclear options where the fuel (fossil fuels, uranium) can be transported long distances at low costs creating similar energy (opportunity) costs almost everywhere in the world.

The question arises with respect to contingency planning. Contingency planning asks the question "What should the U.S. do when something must be done?" It is expected that the military will do contingency planning but the concept of contingency planning has not been given serious consideration with respect to climate change. There have been proposals for geo engineering if climate change accelerates rapidly—such as putting particulates in the atmosphere to lower global temperatures. Many participants viewed it as worth investigating but as a very high-risk strategy because of the uncertainties in how the climate would respond. What is clearly worthwhile is to develop a better understanding of the impacts of different strategies and technologies if there was a decision to quickly address rising carbon dioxide levels in the atmosphere. Equally important, what options can be developed and commercialized in a short period of time. This has only been partially explored.

Last is the need for government leadership. Markets will not lead but will respond. Internationally large actors (i.e., U.S., China, India and Europe) must cooperate but leadership and incentives are required to make this happen.

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Table of Contents

SESSION 1: Low Carbon Energy Economy Schedule and Overview

1.1 Session question

Framing the challenge: What are the time scales of needed response in creating the low carbon energy future? What options are especially worth investigation?
What are the challenges?

1.2 Introductions

Michael Golay: For the first session we have got Ronald Prinn who is here from the Joint Program on Climate Change at MIT, we asked him to help set the stage concerning the climate change situation. And Jane Long will follow who led the California Energy Study, which is one of the most important studies on this topic.

1.3 Lead Presentations on Low Carbon Energy Economy

1.3.1. The Climate Challenge: Toward a Low-Carbon Energy Economy: Ronald Prinn (MIT)

Session 1-1 covered the significant capabilities in predictive modeling that allow one to estimate effect of future economies and technologies, and obtaining climate and air pollution consequences. The MIT Integrated Global System Model (IGSM), consisting of both the Emission Projection and Policy Analysis (EPPA) and Earth System Model (MESM) components, was used to model three scenarios in order to determine the magnitude and pace at which low-and zero-carbon energy policies need to be implemented. The model looked at world economies and the carbon footprints of all human activities, and through a joint venture with the MIT Energy Initiative, incorporated feasible predictions for when new technologies might emerge and when they could be affordable. Due to the uncertainties in the sensitivities in the global climate response, three scenarios were explored in order to determine what it would take to achieve the target of no more than a 2°C temperature increase over pre-industrial levels by 2100. All three scenarios show that the goal of a maximum of 2°C increase could be achieved, but that the needed efforts and costs vary greatly depending upon the global climate's sensitivity to greenhouse gases.

The low sensitivity case showed that total radiative forcing would continue to increase until reaching its peak at around the year 2100, at a level just below 4.5 W/m^2, and that CO_2 could increase to 520 ppm. Including the CO_2 equivalents of all the greenhouse gases, which really drives the total radiative forcing, up to almost 640ppm CO_2-eq. The price of carbon (in 2010 dollars) for this case rises from $50 to $1400 per ton in 2100. Peak energy usage rises to 500EJ at around 2040 before energy efficiency increases start to lower the demand. Also, at around 2040, oil and natural gas usage starts to decline and those of nuclear and renewables increase, leading to about a 40% share of fossil energy in the total.
In the medium sensitivity case, the total radiative forcing would need to slow down much quicker, and reach a maximum of around 3.5 W/m^2 by around 2080, with CO_2 levels settling at around 460 ppm and 530 ppm CO_2-eq. The price of carbon for this case is double that of the low sensitivity case and rises from $100 to $2800 per ton in 2100. Global peak energy use reaches a maximum of 400 EJ per year, again at around 2040, but without having built additional oil and coal-fined

capacity in the interim. So, the final contribution of fossil energy in 2100 is reduced to about 25%, with a larger fraction coming from both renewables and nuclear. This case also estimates that energy use will dip from the years 2040 to 2060 before rising in 2090.

Finally, the high sensitivity case shows that we've almost reached the maximum total radiative forcing allowed, and that we already need to be implementing efforts to greatly reduce this so that it does not increase above 2.9 W/m^2 with CO_2 levels peaking around 420 ppm (475 ppm CO_2-eq) in 2080 before slowing decreasing. Again, the cost of carbon rises and is about triple the cost of the low sensitivity case, rising from $150 to $4200 per ton. The maximum annual energy use is also much lower, reaching a peak of 350 EJ around 2035. This case requires a much quicker implementation of renewable and nuclear technologies, reducing the fraction of gas, oil, and coal to about 20% of the energy total in 2100.

The analysis used the EPPA model to resolve all major national economies and trade between them, as well as having very detailed energy and non-energy sectoral treatments, making it more realistic than other models that typically yield lower costs. Some recent trends in the viability of low and zero emission technologies that have influenced the results are: (1) carbon capture and sequestration are more expensive than originally thought, (2) the potential for economic cellulosic biofuels has improved, (3) solar and wind costs have decreased but intermittency remains a problem, and (4) nuclear power in China and the Far East have lowered costs and thereby increased the viability of the nuclear option. Carbon capture and sequestration use were therefor limited in each of the scenarios due to its high cost. The results show for all three cases, that in response to carbon price increases, the efficiencies in energy use and the fractions of non-fossil energy production both increase.

All three scenarios determined the cost of carbon by assuming efficiently implemented policies, and showed that each could be affordable. However, they would require a very unlikely global agreement, starting in 2015, involving all nations and an efficient market mechanism that minimizes costs, and is revenue neutral in order to gain acceptance. Restricting cumulative emissions to levels that allow a 50% chance of keeping the future global average surface temperatures from rising 2 to 3 °C above preindustrial values is feasible, but the technological, economic, and political challenges for meeting the 2°C goal are very large. The political challenges appear to be the most troublesome, and cost reductions seem to be the best way to alleviate them. Developing affordable technologies for CCS would help meet these challenges, and would also provide a "safety valve," allowing large scale biomass-based electric power generation with CCS to create a gigatons-level carbon sink. Many of these efforts also have the co-benefit of significantly reducing air pollution, which many consider to be worth the cost even without creating the climate challenge problem.

Unfortunately, many of the problems associated with climate change have already begun to appear. The future 2°C global temperature rise implies an increase of 4°C at the poles, and a sea level rise of 4-8 meters, but the climate response can already be seen in the increased rate of coastal disasters. Superstorms Sandy and Irene happened recently, as well as an increase in the number of category 4 and 5 typhoons in the west Pacific, and provide impressive evidence to the growing of the size and frequency of these massive storms and their total destructive power. The total global climate response is still unknown, and the best modeling efforts are being used to determine how to reduce humankind's impact. The best chance at mitigating the consequences will come from global cooperation towards improving efficiency, and reducing costs so that reduced carbon technologies can replace what is in use in developed countries, and can be implemented from the start in other countries as they become more developed.

1.3.2 The California Low-Carbon Study: What was learned: Jane Long

California's Energy Future study looked into how California could reduce its emissions to meet its three legislative targets: AB 32, requiring greenhouse gas (GHG) emissions to be reduced to 1990 levels by 2020, S-3-05 requiring emissions reductions to 80% below 1990 levels by 2050; and most recently, Governor Jerry Brown's 50-50-50 plan for 2030 of having 50% less energy use in buildings, 50% satisfying renewable portfolio standards, and 50% achieving less fossil fuel use. Complete carbon accounting was done such that everything that left a carbon footprint was counted, and only counted once, and no inter-territorial leaks were allowed—such as using more than California's share of national resources or importing and attributing the carbon production from manufacturing elsewhere. The study looked at what could be achieved individually by increasing efficiency, electrification, decarbonizing electricity, and decarbonizing fuels, as well as what could be achieved through a combination of each. It was found that California usage could be reduced to 60% of 1990 GHG levels by 2050 through vigorous policy and technology implementation but that it would still need to import 13 billion gallons of gasoline equivalence in biomass, and the remaining 20% of usage would still constitute a liquid fuel problem having no current solution.

Efficiency imporovement was found to offer the largest effect because results are immediate and improvements can be made across all sectors.

1.4 Discussions on Low Carbon Energy Economy Schedule and Overview

1.4.1 Introductory remarks

Michael Golay: One of the important factors implicit in the first presentation is that, if you wish to satisfy the two degree temperature increase goal, given current practices, then you are looking at a time scale of about sixty years for changing the global energy economy. Regardless of the technology mix that you use to get there, how as an engineering problem, do you reach that kind of goal? Part of what we're trying to achieve in this workshop is to transform treatment of this transition from being an ideologically driven discussion, which is rather disorganized and tends to be focused on magical technological solutions, into a systems and engineering problem, coupled to policy. Looking at the technical options, as already has been implied in the presentations, we're really coming down to looking at some combination of the renewables and nuclear.
This leads us to a two-part problem. One was alluded to in Jane Long's presentation of a near term problem concerning how do you introduce the renewables on the scale that actually makes a difference, and that doesn't get in the way of their long-term acceptance? That is, what we have right now is essentially the renewables being forced into the electric economy through mandates in a way that is producing resistance from the incumbent technologies and industries, which if that continues, is likely to inhibit the acceptance of the renewables and probably lead to in the long term to undesirable results.

In particular, I draw attention to two things. We have mostly have had a focus on electricity as the sector where change can be obtained. This is partly because electricity is much more regulated, and can be affected more easily through coordinated policies. The part that hasn't gotten nearly the attention that it deserves is nonelectrical consumption, such as from heat and liquid fuels. Most energy today is not consumed as electricity. This is a global problem that is going to remain dominating the story. If we don't want fossil fuels being consumed for the nonelectrical demands you must have some substitutes. That's one of the reasons why we have a session in this workshop on that topic.

If you go to an energy economy in the long run that has heavy production of synthetic fuels, then such fuels become your important energy storage mechanism. I bring this up because most discussion of the near term storage problem has been focused on electricity, which has to do with storing charge. That is one of the areas where heavy investments in that approach to storage can actually detract both attention and resources from the broader long term energy storage problem. Synthetic fuels production could actually be a much bigger portion of the overall energy sector the other energy storage options.

The other point is that we have tended to talk about technologies. At least in the U.S. that has been the focus, rather than the role of carbon taxes, which is a surrogate for various policies. I want to suggest that you really have to design whatever you attempt as a creative combination of the two. It's not just about hardware, but is particularly about using policy mechanisms to stimulate the private sector. Governments play a role here, but the private sector is really the important engine that can be amplified and guided if done in the right way. I want to suggest that as a consideration.

We have had very clearly coherent presentations, bringing in many factors, where the purpose of this first session is to set the stage for the overall workshop. There will be opportunities to come back to topics that may come up now. We ask you to think about what would be a productive approach to decarburization of the energy economy on a global scale within about a 60 year timeframe and doing it in a way that is going to be able to attract the required international cooperation? It's not an American problem. It's not a European one. It's a global one that demands a lot of cooperation. As was brought out very early, this is a really tough problem, but it's the problem that we face.

1.4.2. Carbon Capture Systems performance was shown to be able to contribute greatly to emissions reduction, but the focus seems to be on a renewable and nuclear based energy economy. The question is why isn't CCS build as part of the solution?

Ronald Prinn: The problem with CCS at the current time is the cost. I also pointed out rather strongly at the end of my presentation the enormous importance of getting that technology into our energy system, especially for limiting the price of electric power, if you can get the CCS cost portion of it down. We used to think it would add maybe 25%, and now it's up to double the cost. I put very high priority on this, because also as a scientist I am looking at the possibility that if we are at the high end of the range of response of the climate system to given amounts of greenhouse gases, we're probably going to need have in our back pocket a large scale sink for taking carbon dioxide out of the atmosphere, because of the effects of developing countries.

This morning we had two presentations, mine was a global look and the second was looking at California. We need to take what is being done in California, which is the equivalent of a very rich country, and relate them to achieving the needed emissions reductions for the whole world. Those were the numbers that I presented. Having carbon capture and sequestration as a proven affordable technology says that we can continue to use fossil sources, but also that we can perform a fuel switch later on as we learn more about the climate. Unfortunately, its worse as one goes towards the bad end of the climate response. We must have available a carbon sink, that can treat a large fraction of the electric power production in the world. From biomass burning in thermal power plants, with carbon capture and sequestration, we can take many gigatons per year of carbon out of the atmosphere. So, why not have that as an option as well? I suggest that CCS should be kept as an option.

Participant 1: The last time when I looked carefully the United States still took CO_2 out from under the ground for chemical process reasons, and piped it around Texas and the Gulf of Mexico. That seems to be going in the wrong way. I know it's a small effect, and that not all wells produce CO_2, but it has a price. You make money by taking CO_2 out from underground, and you do not make money sending it the other way. Re Ron's point, the link actually comes from something that Jane Long said, which I agree with. It's just about carbon. It's not about anything else. In my view, we need to link two major problems facing humanity, economic inequality and the climate change threat. To be provocative, why don't we try to bundle these policies together and cure cancer as well and end war. Then we'd have a collective policy that does all those things?

1.4.3 Emissions often vary with GDP and have lead to global solutions that fail because they tried to address wealth inequality as well. How can regional policies and strategies address this?

Participant 1: My sense is that curing the climate change problem is hard enough, but linking it to ending wealth inequality as well just kills it dead. The person who says that Kyoto is dead is Dieter Helm, saying that this process was given a chance, and it just doesn't work. It's time for plan B. Just in case you don't know what the carbon reduction plan B would be, from my continent, the European Union, we would say that we're going to have a local carbon price, we're going to estimate how much carbon it took you to make that LED TV, we know that our guess may be wrong, but we're going to levy that as a border tax anyway, so that the tax on the TV might be 110 euros, but it comes with a little green sticker from China saying taxed in China, you can keep the 110 euro in the Chinese economy. That's the Dieter Helm continental solution. I provocatively want to suggest that global solutions were given a chance and they failed.

Jane Long: I think what you're focused on is an issue that has to do with how do you combine various regional plans to make them add up to something. I think that that really needs a lot of thought. The leakage issue is almost impossible to avoid. In fact we tried so hard in our study to avoid it, via things like saying, "Well we only get to use our share of the biomass," for example. "We're 10% of the country. We get to use 10% of what is produced nationally." But it's just no matter of what you do, if one region pulls ahead they inevitably cause a reaction somewhere else, even if it's unintended.

Ronald Prinn: My third point in looking at what the various countries of the world are going to do for meeting the two-degree target is that you have to see that it's not just the United States and the rich countries that are going to do important things. They have to do something, but it's what the rest of the world, which is most of the population outside of the OECD countries that matters. What they do counts just as much, if not more than what we do in the rich countries. It has all got to be put together. That says at that end somehow the climate response must be international. We can't just talk at the state level. We have to understand how everyone will work together in different ways, and how the OECD countries can help many developing countries leapfrog the old technologies and go directly into low carbon ones where they make sense. It is a mistake to see this as being a problem to be solved in the OECD countries, when so much potential for the future sits outside of the OECD countries.

Michael Golay: I wish to emphasize the need for international cooperation in both developing policies and new technologies, as well as in implementing them. In organizing this conference, we tended to focus on Europe and the U.S. This is partly a reflection of where we found interest in addressing the questions that we're bringing up. It's not that they aren't important for many other people or that they don't have a stake in it, but that the visible activity levels are fairly small.

Participant 2: When you think of the future challenge it's not some sort of homogeneous system, the developing world which has an opportunity to deploy a very different paradigm. If they're allowed to deploy only what we have today it's going to take 30 years before those assets are going to be replaced by something better. So, there is an inherent lag which has to be dealt with now. That's important, because it's a very different paradigm from that of California, which has this dramatic incumbency of technological assets.

The second comment draws upon the California example. I think that it's very interesting, the way that California in the study, has defined the control volume around California. Of course the carbon issue is a global issue, and we're going to speak about this when we talk about solar in a moment, but even here in the States we have to go on a state-by-state basis now for our renewable portfolio standards (RPSs). This is inherently more expensive because of some of the provisions that are being put in place. For example, Massachusetts requires a certain amount of solar energy generation, and requires it to be generated in Massachusetts. These are very, very difficult issues, and people need to understand them before progress can be made. They arise mainly from policies.

Jane Long: That is such a good story to support the idea that I have about renewable portfolio standards in general, and why they're politically possible. I sat at a table once with energy advisors from about six states at a meeting. I asked them all if they could pass a cooperative zero carbon energy portfolio standard, and they all said no. They just couldn't get the political support to do this.

Michael Golay: I think this is a really important point. When we look at the renewables generally, there is going to be a natural drive to site renewable facilities where local conditions are favorable. That implies that the role of trade for their products is going to be more important than it might be for other technologies that can be sited more easily in many different places. So, the idea of looking for particular control volumes as being self-sufficient is probably not a helpful way of coming at the problem. Rather, viewing this in terms of looking at it globally, in terms of what contribution can be made from the renewable technologies, wherever they are employed may be more valuable.

Another point is that in addition to technologies and policy, there is a degree of freedom for coordination within the economy by state agencies. What I'm talking about are things like transportation network effects. One of the most striking embarrassments in the United States is the transportation system in southern California, where if you make the comparison between the rail network that has been developed in France over the last 30 years, first the parallels in what could be achieved are quite striking, and the disappointment about what hasn't been achieved in California is even stronger.

Why do I bring this up? Because it requires coordination at the institutional level in order to achieve such results. The important thing that has been achieved in France is not that you get people from one place to another quickly, which is the way we in the U.S. tend to look at high speed rail, especially. Rather, it is in terms of the way that the network transforms the way that people can live their lives, the efficiency with which they can undertake their business. Now, the central part of France is able to act as an integrated entity, permitting decisions and opportunities to be pursued that would just not be available if that network had not been have created.

There aren't that many such networks available, but the example in France is really quite an impressive one, and can be imitated elsewhere. This goes beyond just technology and just policy. That's why I bring it up.

1.4.4 Addressing three periods of time with a set of complementary parallel solutions may offer a greater chance of success than a two period plan with different goals.

Participant 3: We heard a lot about needing to think about what is the short to medium term, and what the long term is and how those are different. I suggest that I think us in terms of three periods of time. I think that one of the biggest problems is that we can't think of this as a single problem with one solution, or the set of solutions. I think that such thinking is what has created the problem with Kyoto. The short term, the next 30 years is one problem. It involves a lot of short lived climate pollutants that have amenable solutions. You have the medium term that Jane Long talked about, concerning how do we use CCS, how do we get the needed infrastructure built. Then, how do we totally decarbonize concerns the long term.

We need to start thinking about these as a set of parallel distinct goals, they are complementary, but they are not identical. If you use everything, to deal with CO_2 in the long term then you get the wrong answer in the short to medium terms. I challenge this group to think about this as a set of, a series of common complimentary problems, but not a single problem. Otherwise you do get a residual unsolved problem. That comes up also with the issue of adaptation. You need to ensure that you're going to do the least damage across time, not just with respect to the two-degree goal. If we focus just on the two-degree temperature limit goal, we'll not be minimizing our damage functions. You need to minimize your damage functions overall in order to increase your probability of success.

Jane Long: That's a great point. I add to that that these three solutions are strategic in nature. They're not just economic or social. You have to bring in an element of strategy, much like engineering design. We have to think about this as a design problem, and then of how we're going to make it work.

Ronald Prinn: I also don't like the notion of saying, "Here are short term targets, medium term targets, and long term targets." The whole approach has got to be one that begins now and looks at various things that come to fruition in various timeframes, but most of what we need to do has to start now. It's not just looking at the low hanging fruit right now, and ignoring the medium and the long range. It's all going to have to start together, taking advantage of things that are low hanging fruit in the beginning.

1.4.5 Enhanced oil recovery and CCS were shown to have an immediate effect. Is there a combination of additional technologies that might also have an immediate effect?

Participant 4: Enhanced oil recovery was brought up, or putting CO_2 into depleted reservoirs as a particular option, such as what was investigated in Wyoming. It was mentioned that although some CO_2 could be captured it was not as much as previously expected. Could there be other easy solutions in the near term that we may be missing? I'll give you three examples. Could there a radical change of social behavior where instead of commuting to work maybe we would work in our local neighborhoods and offices, or even from home? That's a potential solution involving social behavior. Two, could it be something that Adel Sarofim, here at MIT, once suggested, that it could be as simple as coalification of biomass, meaning you take corn stover and residuals left from the agricultural areas, you char it and bury it. That is lower cost carbon capture and sequestration that could have a significant, very immediate effect? A third might just simply be growing algae and doing the same, sequestering it or turning it into fuel. Are there combinations of several things that we tend toward, as technology experts in nuclear and solar, and in these other not usually thought about that might also have immediate effects?

Jane Long: Well, so all those things are helpful, they are good, but we looked at both algae and bio-char in our study, and they just don't rise to the mass that you need, the amount that you need to make a big difference. It's not that they shouldn't be used or that there aren't other reasons to do them. But it's like, white roofs are a wonderful thing, but they don't add up to changing the temperature of the globe.

Concerning the first idea that you brought up, I probably didn't make this point as clearly as I wanted to. Where you don't have the technology, and we don't have the technology for fuel, that's where efficiency really matters. If we don't make houses really efficient, but we run them on electricity and we decarbonize electricity we're okay, but we still need fuel in the long run, as long as we continue our lifestyle. So, to the extent that we can make cars efficient, and keep people from driving, through land use and transportation planning, that is what is really important, because we don't have the needed technology. So, I think we're focusing a lot on buildings, but I would focus a lot on transportation when it comes to efficiency and conservation, because we don't have another choice.

1.4.6 How do we address the business of scale? Many of the technologies to address the climate problem have been demonstrated but are not available on the scale that is required in order to be productive.

Michael Golay: I want to suggest that this business of scale is a really important one that is easily overlooked in discussions of climate change. If you consider the options that we've been discussing in terms of categories, they are familiar to everybody, but if you look at the technology that is needed in order to be productive on the scale that is required, almost none of it exists. Jane Long has made this point clearly. One of the outcomes from this workshop, we hope, can be to make that message more coherent and effective in motivating the way that we look at things.

Ronald Prinn: Certainly this issue of looking at the scale of what is needed is essential, and that is a lesson we have learned from doing this work for 20 years. You can propose many things, but you must ask the question of how to get up to a hundred exajoules levels for producing energy. If it's carbon sequestration we need to talk about giga tons per year.

Participant 5: Concerning geothermal an important factor is enhanced geothermal systems can provide the scale and the zero-carbon footprint that we need in the future. So, I think it's very important to recognize that the technologies to be used need to have a zero footprint, and also be deployable at scale.

1.4.7 Biofuels are not one single fuel, and there is a wide variety of pathways for using biofuels with very different scales and very different carbon footprints. The question is what did the California study mean when it said "biofuels" and to what extent could they be used?

Jane Long: We looked at a whole variety of 'drop-in' fuels, and we looked at many different processes for making them. The work was done by the Biosciences Institute at Berkeley. They looked at the portfolio of possible solutions. Now, I would say that they didn't leave out many different pathways. I've heard people say that they're coming up with a gallon per square foot or a gallon per square meter type fuel solutions that maybe would change technology. I think that the issue is not whether, but when this happens.

Participant 6: It's important to realize that all of these things are going to take decades to reach maturity, so let's get started. In terms of biofuels, the opportunity to actually take carbon out of the atmosphere, and put it into a very proven sort of low cost carbon capture, which are called roots. The roots that we're talking about, dirt and organic matter and roots, is a pretty well proven solution; right, as in the gigaton scale, the potential, but you're not going to get there if you don't include those as options.

Jane Long: Just to be clear, I would not say stop looking at biofuels. All I'm saying is that we probably need another strategy beside only biofuels. I think we have gotten all of our eggs into the biofuel basket. Our study looked at every source of biomass that we could possibly capture and the best possible ways to convert it, and it all didn't come close to being enough. Then, we considered some optimistic solutions about importing that much again, and it didn't come to being even half of what we needed.

Participant 7: I have a similar sort of point. You're saying that you must look at biomass that comes from California, when there are really a lot of places that produce lots of biomass. Does California import a lot of oil? So, why would you expect to produce all your transportation fuel in California?

Jane Long: Sure you are right about that, but I think we tried to have an honest accounting in terms of how much of the biomass could be produced and captured. I mean if we captured all the biomass that were available in the world we could solve our problem, but we tried to put some rules on how we could proceed. We did allow imports. We just said that it had to be proportion to population. We didn't think that it was fair for people to import more than their share. We assumed that everybody in the world was doing what we were doing when we did it, just to make sure that we weren't trying to solve our problem at the expense of other areas.

Ronald Prinn: I want to emphasize that biofuels were significant in the results that I was showing you, and that this is a global problem. It's a global commons problem, and why one would have to do all of the production of the energy within states or countries, global trade is there and it has to be used. If we're going to solve this problem various countries will be making various contributions, and a lot of the biofuels would be grown in currently developing countries, as having low cost land. So, that is part of the optimition that I was showing coming out of the Joint Program here at MIT for biofuels is realizing that it is a globally traded commodity, and some countries would import it because it's very low net carbon emission, and others will be producing it. That's how you get things at the lowest cost, you produce it where it can be done at the lowest cost, and it's then available in the global trading system. So, that's why I was looking optimistically. It's because we were looking at it as we do in the Joint Program in terms of the global economy, because it's a global problem.

Participant 5: Where I work we have started looking more at the services provided rather than at fuels and electricity. So, for example, when we look at fuels we think primarily about mobility options. The mobility sector is very heterogeneous. There are certainly aspects to mobility in urban metropolitan settings that have more solutions and more technological options than, say, long distance transport of heavy objects or air transport.

So, for example, Jane Long, in your analysis it would be interesting to know what the carbon footprint of just the jet industry alone is in California, and whether you could even hit the 85-million-ton target if you didn't solve the jet fuel problem. In my opinion the solution can't be electrical.

Jane Long: That ends up as part of what you can't electrify, the heavy duty transport. One issue that is really important is that if you do get these biofuels, then the strategy is important. So whatever amount of biofuels you actually get, maybe you shouldn't be directing it towards automobiles, you should be directing it towards airplanes and heavy duty transport that you cannot electrify. That's what I meant about being strategic. You really have to think strategically about available technology solutions, and where are you going to use them. If you only have one solution, such as biofuels for air and heavy duty transport, then you also must think about efficiency and conversation since you don't have any technology.

Participant 5: That is my point. I totally agree that taking advantage of the heterogeneity of that mobility problem is really important. You mentioned that, and then on the other side in the urban settings electrified vehicles with their intrinsic batteries can provide grid services that are very valuable to slowing the overall mobility problem. So I think that this is a good start to the workshop, focusing on how to use the heterogeneity of the mobility system as an asset rather than a liability.

SESSION 2: Renewable Energy Systems Near-Term Integration Strategies and Requirements / How to Develop Strategies that Will Lead to Long-Term Cost-Effective Renewables?

2.1 Session Question

What are attractive market design options? Should there be a requirement for visible costs of subsidies (Germany) and greenhouse release estimates in order to provide political feedbacks? What attractive options can meet policy and technological needs in order to successfully integrate renewable energy systems into the broader electrical energy economy?

2.2 Introductions

William Green: In this session the two papers discussed primarily electricity, and solar electricity, in particular, as a near term solution, and certainly decarbonizing electricity is a major goal, but in the first talks from Jane Long we heard about how every time we build solar generation we also end up building more gas turbines. So, maybe solar is not quite the panacea that one would hope. We never discussed at all the roles of needed fuels and in parts of the economy other than the electricity sector, which is at least the other half of the energy picture. We shall hear from Ross Koningstein from Google and from Francis O'Sullivan from MIT.

2.3 Presentation on near term strategies

2.3.1 The Google Adventure with Renewables: Why incremental advances are inadequate to Solving Climate Change: Ross Koningstein (Google)

My colleague, David Fork, and I published a paper in IEEE Spectrum in 2014, "What Would It Really Take to Reverse Climate Change?" This paper summarized a lot of our findings from the many years that we worked on this project. We investigated many energy technologies both technically and from a venture capital perspective. There were many things that different people knew to be obvious across the different sources of energy, yet those messages really weren't shared.

Figure 2.1 says that in California, many different ways can lead to breakthroughs in the renewable energy and current energy context in order to reduce carbon dioxide and ultimately climate change. You can see that if you push really hard with decades of technology introduction and cost risk you can change how much energy in the electricity mix that becomes zero carbon.

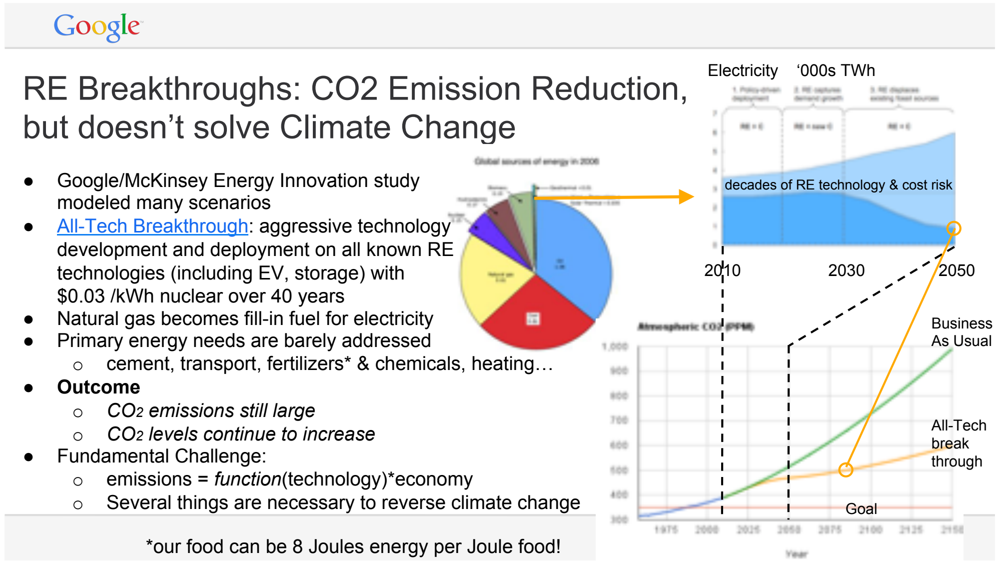

Figure 2.1 Impact of renewable energy breakthroughs

What is interesting is that the analysis concerns the effect upon carbon dioxide. We discovered that CO_2 actually doesn't even become stabilized. So, what some of us to be considered a major victory in fact isn't even really the start of the war.

As you push out intermittent renewables you discover that CO_2 emissions are still large, and CO_2 levels continue to increase. There is a natural coupling of intermittency with natural gas deployment, that's just hard to escape.

It also became obvious that the emissions that occur in a nation are a function of the technology in use there, multiplied by the activity of the economy. We have seen from our previous speaker a graph where the emissions dropped as a function of the dropping economic activity, and then they pick up again as the economy grows. The political system promises to grow the economy. So, if you want in the long run to change your emissions you need to address changing the technology mix.

Consider that 130 years ago you would think, "What is the best horse to power the future of flexible transportation? We have multiple breeds of horses. There are all sorts of things you could do." Of course we know the answer. The best breed of horse is engine horsepower. That's about the only relationship to horses that we have left in the energy economy. So, in the spirit of energy I like to think about well, "let's look at those things that would cause dramatic changes".

If we examine the atmospheric CO_2, we say that if reducing it is our design goal, and we consider things needing to be done we find that they're actually pretty difficult. One goal is getting the electric grid to nearly zero carbon emissions. Another is bringing a comparable amount of energy to be deployed in the zero carbon field replacement. A third concerns removal of a lot of carbon from the atmosphere and oceans.

Let's begin with the economically trivial case. When we performed our energy innovation study at McKinsey we needed many models, and found all sorts of ways by which we could not achieve the desired goal. The irony is that the trivial solution achieved the goal. The trivial solution is that of low cost power that is emitting zero carbon. I've been an advisor to Google Ventures, I've seen a large number of technologies in the course of going through the 'Google's Renewable Energy Cheaper Than Coal' effort, I've spoken with many people in the energy business. I'd like to think of this as the price that we need to pay in order to be able to think about what is going to be the equivalent of that horse a hundred years or 50 years from now that ultimately ends up crossing the finish line. It's going to be a very different horse from the horse of today.

For this work I need the business approach logical framework. So, if you have a company and you have revenues, and you pay some of it to taxes and operational overhead, and you've got this return on invested capital that must be earned. That is the money that shows up in your account because of the energy that you sold during the year before. You have a couple of choices of what to do with it. If you have an amazing product you can do 'closed box' reinvestment. You can just use the new cash to build a bunch of new things and then sell them, and you can scale that up at an enormous rate.

Some consumer electronic devices fit into that category, although really the majority of our highly scalable growth in the economy works because of high returns on businesses investments. Google would be one of them, but there are many others. The key to making those work is paying people a high return on their investment. In fact, the key to making any technology become adopted really quickly at scale is for it to be highly profitable for several different parties. So, if we want to go that way we ask, where are the price points that really define the kind of profitability that you need to either attract the needed capital, which you do by paying a decent rate of return, or, if you can, you find a closed box solution. That's tough.

When you're growing a business the time that it takes to grow to the needed size determines the needed profitability. If we have an energy business that can sustain itself at about $11 dollars a watt at a relatively modest six percent total return, when you factor in interest rates and other items you'll be paying maybe four percent for capital. That's OK. You can make some money, but it's not going to attract trillions of dollars a year in a growth market.

If you return on investment at 15%, this situation isolates you from ups and downs in interest rates. Then, you can attract a lot more capital, and that's where things get interesting in terms of building a highly scalable business. You can see that the cost per watt target of doing that is less than half of what it would be for an energy system that would deploy at a relatively sedate rate. If you want to do closed box reinvestment you can see that the rate is roughly even half of that. So, that is one dimension of looking how much capital you must attract in order to scale rapidly.

The other factor concerns how many years you're going to take to scale up. If you want to take 25 years to scale up, then you have a very steep scale up rate. If you are happy with scaling over 50 years then your number again is about twice as high. And if you're willing to wait a hundred years you can do better with a higher capital cost.

So, needs for both a short timeframe and capital put pressure on the cost per watt target. If I were a venture capitalist looking for the energy source of the future I would look at something that would come in somewhere between those two numbers, and I probably wouldn't pick 25 years to scale up, I would probably go for 50 years, and end up with somewhere in the five dollar to seven dollar range for the capital cost per watt, with other characteristics. This low capital cost makes it profitable for a large number of people, which provides rapid scalability. With all due respect to my friends on the policy side, policy is great for kick starting. It will get you tens of gigawatts, but if you want to move to an economy of terawatts, and you want to do it rapidly, then there is not really a sustainable role for subsidies.

So, if I were to summarize this, you can't just say that energy has a single price. It depends upon what you want to use it for. Diesel generator-set electricity, the top line in the chart (Table 2.1), has the highest price of electricity for a lot of people. If you want to create a disruptive energy source for that capital cost, that does not use fuel then you need to aim for somewhere around four dollars a watt. The distributed electricity situation comes in at around somewhere like two dollars per watt, large grid scale electricity at about 40 cents a watt. So we're talking about achieving zero carbon. That would be something like using photosynthesis or PV to hydrogen cells, or nuclear or something like that.

Table 2.1 Examples of cost/watt to scale in 25 years with / without financing

Examples of cost/watt to scale in 25 years with / without financing		**Not enough to ramp**	**Enough to ramp**	**Totally Disruptive**
Use Case	**LCOE tipping point (US)**	**Cost/watt @4%+2% IRR INT**	**Cost/watt @10%+5% IRR INT**	**Cost/watt organic growth(no investors)**
Diesel Genset Electricity	$0.20/kWh	$11.68	$4.67	$2.76
Electricity Distributed	$0.10/kWh (<retail)	$5.84	$2.34	$1.37
Electricity Grid Large-scale	$0.017/kWh (marginal coal)	$0.99	$0.40	$0.23
Fuel alternative	$5/MMBTU (NYMEX)	$0.49	$0.20	$0.11

These are tough targets to hit. I argue that incremental technology, in other words, technology that drives on a few percentage point gains here and there on current technology is not even close to being adequate, neither in terms of LCOE nor on the cost per watt. The blue items that I've highlighted in the table (Table 2.2) are for energy sources that provide zero carbon electricity. The challenge with these, like hydro, is that you can't build that much more of it. Many of the good sites are currently in use. Here in the U.S. we're even shutting down some hydro dams. Geothermal, it's great when you can get it, but it's certainly not cost-effective everywhere. And U235 power, using pressurized water reactors for nuclear, is arguably the safest form of energy that we have, but for several reasons there is not a lot of consumer demand for it. So, we're not going to see huge expansion of it.

Table 2.2 Cost and challenges for various energy sources

Energy Source	Cost	Challenges
Hydro	$1-$5/watt (hydro.org)	Can't build much more
Geothermal	$1-$6/watt	Few sources at low LCOE
Coal	~$2.00/watt	CO_2, pollution
U235 PWR Nuclear	~$5.00/watt ~0.025/kWh	Safety/security/waste/construction time, lacks end-user pull [Pandora's Promise]
Solar	~$2.50/watt (NREL)+	Intermittency CF≠1 => $?/W - storage/alternate adds to cost - seasonal variation requires alternate zero-carbon power source - more capital efficient to operate that year round instead?
Wind	~$2.50/watt (NREL)+	
Hydro Storage	$1-$5/watt (hydro.org)	Addresses daily but not seasonal intermittency; not a source of energy

If you look at the costs and you compare them with the costs of what you would want to scale up there is just not a good fit. Then, if we look at the intermittent renewables we can see that their cost per watt number on the nameplate doesn't look that horrible, but it's the capacity factor and intermittency that is the real problem with them. So, if you have a solar panel that bolts right to your air conditioner, and you only ever need your air conditioner when the sun is shining then your capacity factor match is pretty good and you would say, "Great. Score it for that solar panel."

But the reality is that a lot of the world has manufacturing industries that require baseload power. If you want good return on your capital investment you want to run it 16 to 24 hours a day. You don't want to run it just when the sun shines or just when the wind blows. You need it to run all of the time. And that's where the capacity factor problem really kills you with the renewables. Then, you must multiply this dollar per watt figure, and you have to add in the cost of some kind of storage to it. When you do that that's pretty punitive compared with the kind of goals that you ultimately wish to achieve. So, from a practical point of view if you look at these cost targets for capital and LCOE during time new energy technology would not include a steam cycle. You cannot afford it and still meet those targets.

So, I argue that if incremental advances to current technology are not going to satisfy you then you must invent new types of energy sources along the way. We need to invent new energy sources. There is just no getting around it. To do that what we need is to put money into R and D that will invent a highly profitable technology. There is a big difference between subsidizing an end product, continually at a global scale in order to change the infrastructure, and subsidizing research and development, which is typically an investment you make at the beginning.

A friend of mine once said, "If you want to see the story of any company just look at its balance sheet." If you want to look at the state of energy look at how we spend our R and D dollars. At Google we have this thing called 70/20/10, which is that we put 70% of our money into the current line of business, 20% into things that are related and new, things you would expect your competitors to do in the next couple of years, and then we put 10% into disruptive new businesses, self-driving cars for example. And people say, "Well, why would you do that?" And it's because well maybe there is a lot of money in that in the future and Google happens to know how to do it, so we try.

If we compare that with how research dollars are actually allocated in the U.S. government budget, you can see that 90 is definitely where we're putting our focus on our core business in energy. But in terms of new energy R and D we're putting surprisingly little amount of money into these things that are business related. We have many things related to what one would argue is the common good, in other words they're not necessarily of commercial value, but benefit the nation. So, that is actually a fair chunk of the budget. But from the perspective of somebody who is in the commercial world it looks to me like we ought to be putting a lot more of our money there.

So, we need a well-funded research program that can take us, as we're deploying the renewable energy and other things today; that allows us to invent new energy forms that will, through profitability, power its way and make us successful.

2.3.2 MIT Future of Solar Study: Francis O'Sullivan (MIT)

I shall speak about the MIT Future of Solar Energy study, a multidisciplinary effort the results of which we just published. This study is the sixth in a series of studies that we at MIT have published looking at important energy pathways and their roles in a carbon constrained future.

Of course solar energy will be important in that future. If we're going to address the carbon challenges that Ron described this morning we're going to have to look to pathways with very, very low to no carbon emissions, and solar is of course one of those. In our study we concluded that solar is one of the few technologies likely to be scalable to the needed extent, and it also has the very attractive feature that as a resource it's very broadly distributed.

If we look around the world today at where a lot of growth is expected to take place, China and India happen to have relatively abundant solar resources. So, it could be a viable option in those regions. If we even take our own current electricity demand here in the U.S., and we assess how much land area we would require given our average resource, it's really very small, less than 0.5% of the contiguous U.S. could land needed to meet all of the demand. However, of course, there are many technical and economic problems in the way of realizing a future based on solar.

Two pathways are really going to form the basis of our solar future. Photovoltaics will certainly dominate, for a long time to come. It's by far the most mature option available today, where 95% of all of the deployed solar is photo voltaic. As a technology it's beautiful in the sense that its technical efficiency is scale invariant, so a residential system--a panel--can be just as efficient as in a utility scaled system. Of course there are economies of scale in the balance of system that are important, as we'll discuss. These need to be considered in terms of tradeoffs, but the big drawback is that it responds immediately to changes in solar radiance. So, there is the challenge of intermittency. Concentrating Solar Power (CSP) is certainly less mature, and remains more expensive. There is a question of how expensive it is, because it's less mature, or perhaps because it is inherently more expensive. We don't know. It is a technology that scales with size. We require large systems in order to make it work. It also has the drawback that it requires direct irradiance, so that limits the number of attractive locations. It is a technology that can be integrated easily into the existing grid with dispatch-able sources.

For this talk, I focus on solar in the United States. The grid-connected photovoltaic capacity has expanded about 18-fold since around 2008. The graph (Figure 2.2) illustrates how it is distributed in terms of system scale. Most of the scale being determined today is the result of the installation of large scale utility facilities, but the residential and to a lesser extent the commercial sector of the business represents, the much more visual portion. Hundreds of thousands of systems are now being, installed on rooftops around the United States.

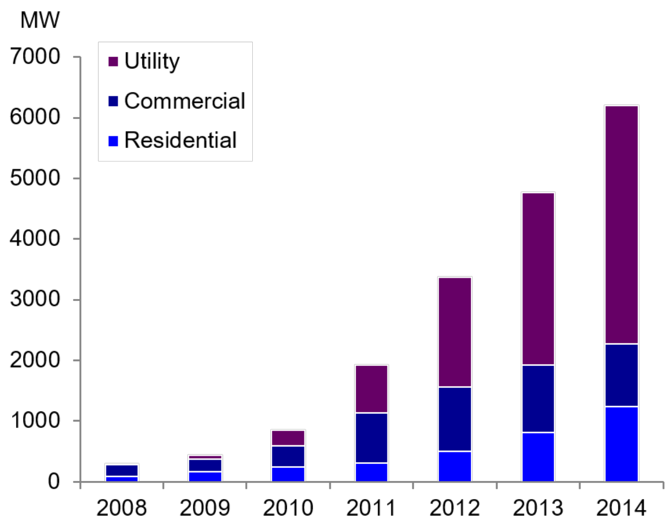

Figure 2.2 Annual PV capacity additions by system type

In terms of distribution California is, of course, in the vanguard. There are two reasons for that. California happens to have an excellent solar resource. However California also happened to have, and continues to have, a very favorable regulatory structure in place that supports and pulls solar into the system. That's also why Massachusetts is now an attractive place for solar, and where we're seeing a lot of growth. So, this balance of the actual resource and the regulatory structure is important in considering how this business and its industry is evolving today.

We're now at one percent of total global generation by solar. That's also about the same here in the United States. Now, for the future when we address the carbon reduction challenge the scale-up of required energy investments is enormous, maybe a multiple of 50 scale-up over the next three or four decades. Is this feasible, can we expect to see the growth rates that are needed? To begin to answer that question it's important to reflect on why we have seen the growth rates that we have witnessed to date. Let's begin with the costs.

Over the past half-decade the growth that we have seen arises from remarkable improvements in the economics of solar systems. I think that that's shown by the blue line (Figure 2.3) illustrating the drop in the price of a residential system, the average residential system price in the United States, and the green line illustrates how utility prices have fallen.

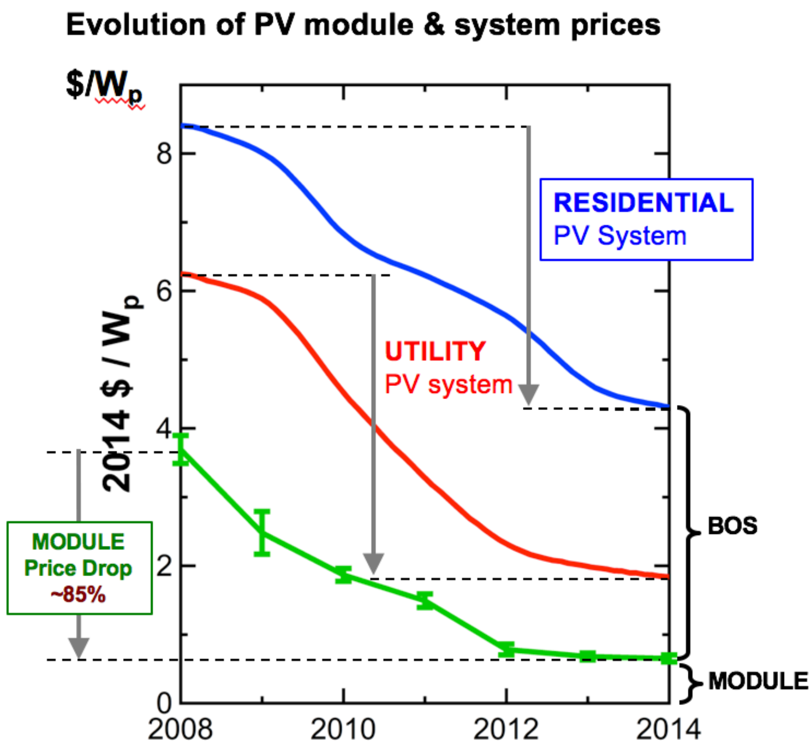

Figure 2.3 Evolution of PV module & system prices

These have been dramatic. Most importantly, the vast majority of these gains have come about because the module costs have fallen very dramatically. Now, we're approaching a plateau in price for today's technologies. Certainly there will be some incremental gains yet to be achieved with modules, but the dramatic decreases that we've seen are unlikely to continue. Practically speaking, we have obtained economies of scale now, especially in manufacturing.

Of course the system is made up of not just the module but also the balance of system, the bits and pieces physically required to install it and the costs of the software, labor and financing are important factors. Those costs have not been falling to the same extent. Gains are yet to be made, but certainly not to the same extent as recently. So, a question arises now of how much more we can squeeze out of the costs.

Germany has done better than we have, for example, the residential area. There is progress yet to be made there, but it is not likely to be transformative.

The other element stimulating deployment over the past half-decade has been the new federal , state, and local support mechanisms. The federal investment tax credit (ITC), for example, has been very important in supporting solar's growth. It is now due to expire at the end of next year. It's going to be reset to 10% for commercial systems. It's going to be eliminated currently for personally owned systems. So, it's unclear what that effect will be. There is also a degree of backlash beginning to emerge with regard to financing alternatives like net metering, which is an important subsidy where residential systems in particular benefit. For example, in Massachusetts you can own a utility scale facility, and benefit from net metering.

So, we are in a state of flux right now concerning how things are going to evolve. It's not inevitable that we shall be able to achieve the needed growth rates.

Let's reflect on where we are today in terms of the economics of solar energy. We have here an illustration of how the levelized costs of electricity (LCOE) of a variety of solar systems of different scales, positioned at different locations, compare to a benchmark of a combined cycle gas plant running at 85% capacity factor—maybe like some peaking plants. I should say that the LCOE is a terrible metric, but it is useful for understanding marginal penetration.

We are making progress. Today like California, for example, a utility scale facility is beginning to look competitive, as an investment in new combined cycle gas-fired unit. Since these numbers were established I think there has probably been an additional step forward. A California utility-scaled system now can be coming in with an LCOE of somewhere between $90 and $80 dollars per megawatt hour. That's impressive. In Massachusetts utility scale electricity is not remotely as attractive, and at the residential scale it's still much more expensive.

The Concentrating Solar Power (CSP) example for California illustrates the fact that CSP is less mature than the PV equivalent. Whether it can do better is unclear. It certainly needs more facilities in order to gain experience. We include Massachusetts here mainly to illustrate the point that CSP does not work very well where there are clouds in the sky.

This is a useful level set of results to show how alternatives for solar compares to its competition. What we have to worry about is not solar's economics today, but what they will likely be in the future especially, when it has much larger penetration into the energy economy. There is also an important nuance which I'm sure that most people here grasp, but that many others don't appreciate it concerns what happens when we move a lot of zero marginal cost generation into a competitive power market. That is what is going to have to happen if solar is going to win in the United States. Then, the result is that in the middle of the day when we have a lot of solar capacity coming online its low cost generation is going to push out of the supply stack those generation facilities that set a higher marginal price. That is going to suppress the spot price in the market quite substantially during peak generation times for the solar plants. It's going to mean that the price that the solar assets receive in the market decrease quiet considerably—and not only for them, but for all generators.

For the overall system there is a benefit in that, because it's going to reduce the average market price, as you can see from the red line in Figure 2.2. It falls as we move more and more solar into the system, but the price that the solar asset owners are going to see is going to drop much faster. In order to deal with this we are going to have to bring to bear much lower cost solar systems. That's simply a matter of fact. The cost of solar systems is going to have to fall significantly from where we are today in order for these technologies to be a competitive investment a few decades at the level of penetration that we are calling for.

So, this situation sets the context for the MIT study, and some of our main recommendations that flow from it. There are three main factors. The first is that we need to take a longer term approach to technology development. We need to appreciate that today we have made a lot of progress, and that the technology paradigms that we have have used have yielded gains that a decade ago we couldn't have imagined. However, we now need to be focusing on the next significant step. That requires focusing upon technologies that we're not investing in tremendously today.

The second issue is that we need to prepare for very large scale solar penetration into the electrical energy economy. As we move to using a lot of intermittent photovoltaic (PV) generation in the system we are going to have to contend with a lot of technical problems, especially intermittency and the need for storage. We also must consider changing our regulatory structures. If they're not managed effectively we shall hit some roadblocks.

Thirdly, we need to appreciate that subsidization of solar is very important. We're at a tricky point right now, where we need to continue to maintain our subsidies, but more efficiently. Today's structures need to be reformed to be more economically efficient.

Briefly, we must also consider a long term approach to technology development. Wafer-based PV technologies, particularly those using crystalline silicon dominate today, and they shall for a while to come. In many respects they are an extremely attractive technology. They are quite efficient. But, today's technologies are approaching practical limits of efficiency. They are very reliable, proven, robust. The materials are abundant and relatively nontoxic, but they have real disadvantages. When we say thick wafer, they're really much thinner than they were even five years ago, but they are still relatively thick. They're rigid and heavy. That has implications for the balance of system. Also, very importantly, crystalline silicon, as with crystalline structures, requires complex manufacturing processes, lots of vacuum, high temperatures, lots of manufacturing steps. That all adds to costs.

So, although today's technology has many intrinsic advantages, there are other drawbacks that make reducing costs to the needed level unlikely.

It's also just useful to reflect on where we are today in terms of overall system costs, and how the PV module plays into this. What you find is that the module cost is increasingly irrelevant, actually, particularly at the residential scale. However, if we could take a lot more cost out of it that would still be relatively useful, but we're still going to be left with a significant balance of system, where much of that balance of system cost, is driven by the physical form factor of the module. We shall ultimately need to address the balance of system cost in a transformative rather than incremental sense. Doing that will require using something that is likely much different from the crystalline silicon wafer-based modules that we have today. The obvious proposal is, of course, "Well, let's go with thin films." When I say that's an obvious answer. I mean that we're certainly getting some feedback with regard to the study at this point saying, "Well look, there is an alternative to silicon." And, of course that is true. What we're saying is that a transformative gain is going still to be required, and is likely not to flow from using silicon and thin films alone.

So why use thin films? Well, first they're very light and flexible; that is an inherent advantage. It may allow use of a different paradigm when it comes to designing the balance of system and the actual form factor. Importantly, they constitute a technology set that may provide a pathway to high throughput manufacturing, using lower temperatures, less incremental manufacturing stages, and less high vacuum equipment. That's important. And some of them, though not today's commercial technological offerings, offer potential use of an abundant material set as well.

But, they still have a range of current challenges. That's why we need to be investing in R and D on them. Low efficiency, at least the low efficiency, demonstrated at the module level remains a problem. There have certainly been some attractive results at the cell level with test cells, but we have a long way to go to make that into a practical product. They also have low stability, and they remain unproven at scale. We must respond to all of those challenges.

With today's thin films, there is a lot of excitement, but we're running into some roadblocks. Even if we could gain on some of the costs, this graphic (Figure 2.4) illustrates for a few technologies: crystalline silicon, CdTe, and CIGS, the scale of the multiples of current production needed in order to achieve five percent solar generation: These are 50%, and 100% by 2050, respectively.

What you'll find is that solar materials, are relatively abundant when we consider only a year's worth of total global production, or a little bit more, in order to provide us all of the silicon needed to deploy that capacity. But if you consider tellurium you are talking about requiring hundreds of years' worth, or more, of current production. And, all of these materials are really only produced as byproducts in a primary extraction process. So, the practicalities of actually expanding that production significantly, and of going to primary production will alter dramatically the costs of those materials. There is a feedback loop that we need to appreciate there.

So, these technological pathways will be challenged and scalable. Some of the newer emerging thin film technologies are still not proven practically, in the field, with other much more abundant options that are available. So, at least that hurdle can be overcome. The basic question, though, is that of whether can we actually make the technologies work.

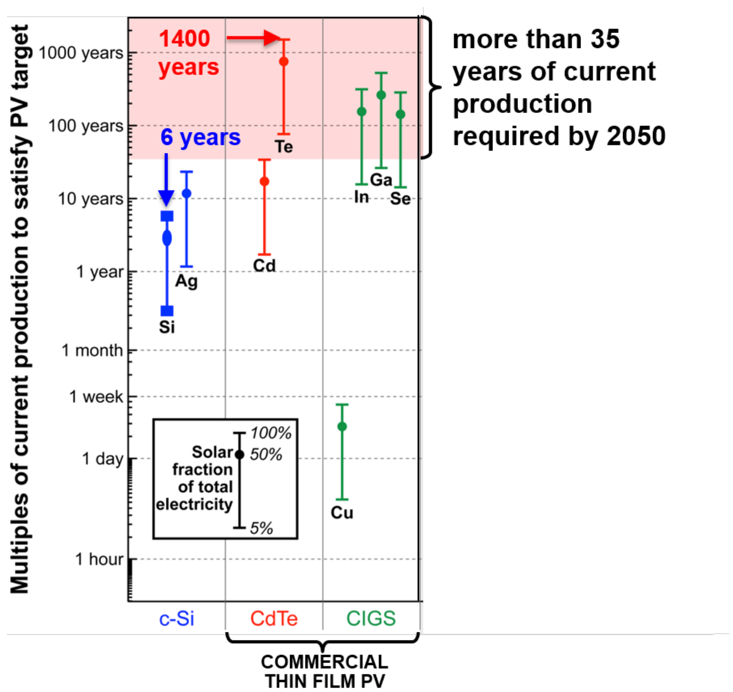

Figure 2.4 Multiples of current production needed to satisfy PV target

On the CSP side a couple of things are worth noting. Today, CSP constitutes a system where there are elements for which significant opportunities for improvements exist. That will help the economics of this technology. To begin with we can do a better job at capturing the solar energy, using more effective collectors. We can improve the power cycles, for example, by going to higher fluid temperatures. In combination these that might move the CSP technology from where it is today to where its economics may be a little bit more promising. But to do all of this requires a lot of work in the lab, and quite a bit of pilot scale operations in the field. To support that type of work also requires significant investments, investments that we're not seeing enough of today.

Concerning Figure 2.5 we have gotten considerable feedback on from the study. What it illustrates is a breakdown of how some of the DOE's solar R and D funds are spent and how this have varied over the past several years. The most important point is that there has been a general trend away from energy conversion technologies and towards focusing system integration, improving manufacturing competiveness, and reducing balance of system costs. In our study we acknowledged that all of this is entirely reasonable, entirely beneficial for solar. However, very importantly, this type of technological improvement (and the DOE's engagement in), it is not necessarily distinctively more transformative than that some of the commercial players who are today incentivized to address the balance of system, and who have, frankly, more experience in responding to these types of challenges.

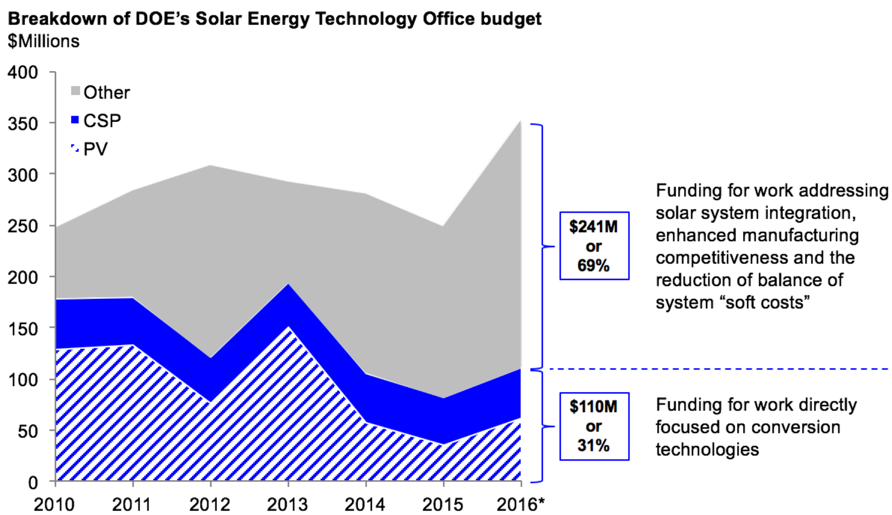

Figure 2.5 Breakdown of DOE's solar energy technology office budget

Where the DOE, and its unfortunately limited budget, can have the most distinctive effects is in investing in the types of technologies that no commercial entity is going to invest in. Emerging thin films need development, for example, and are crucial if we are going to improve economics to where it needs to be so that solar can be an important energy source in 2050. In fairness, the DOE is working hard to do as is much of that as is possible within this constraints. We are simply advocating that their work should become much better focused.

So, we make some recommendations for R and D in general, that are quite focused on the DOE. We have made great progress with silicon, but now it's time to shift our R and D focus, at the federal level at least, to the next great challenge, that of thin films and other technologies that potentially offer much lower cost systems. Doing that moves us toward environmentally benign thin film technologies. On the CSP side we need to examine what materials, and systems, are needed. We also need to investigate pilot scaling as an opportunity to do better with the limited available resources.

We must also support penetration of solar into the energy economy. We have seen the duck curve, showing at higher levels of PV penetration what we are going to face, and are facing it in California already, not even at enormous levels of penetration. This causes real challenges in operating the grid. These include grid capacity problems among other issues. Energy dispatching in a variety of forms, can help to address these, but we must recognize and respond to them.

If we examine the initial penetration of PV, at capacity levels that are required from the a system like ERCOT on a typical summer-peaking day what you'll find is that that the initial quantum of PV generation actually does help to reduce the capacity that is required from a more conventional fleet. However, because of the lack of coincidence between the peak in solar output and the peak in actual demand, as we push more and more solar onto the system we don't actually reduce the peak output that is required from the non-solar facility. So, that leads to the capacity challenge and to a need to invest in new future generating capacity, even if it's not being operated.

Then, as you push to much higher levels of PV penetration you also must contend with the fact that you have now introduced a very severe power ramping requirement on the overall grid system.

In order to address these challenges, we are going to have to have some form of energy storage. We are not going to use one single type of storage technology. One doesn't need to use a battery, although certainly they will play a role. This could also be done via virtual storage, as with through energy demand management. However, such storage would require a more dynamic system. Figure 2.6 is from our study. It illustrates the importance of storage for the economics of solar facilities, themselves.

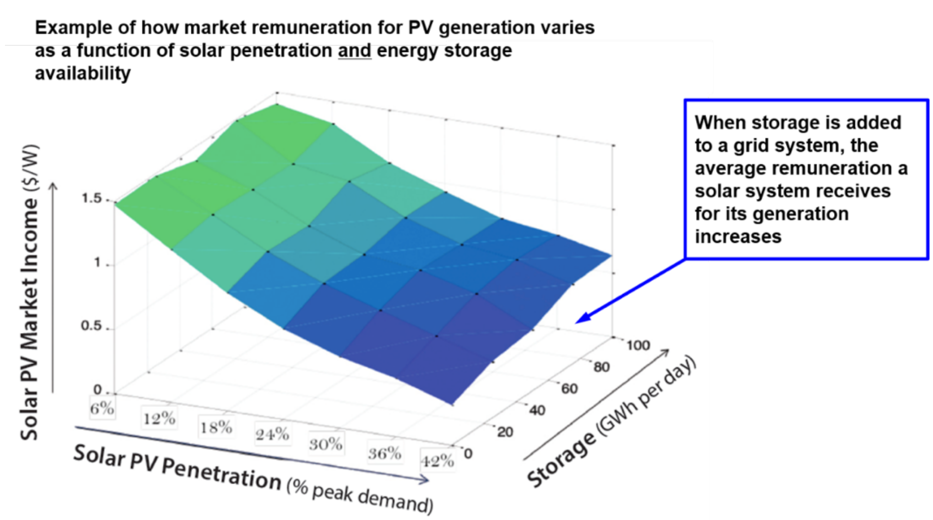

Figure 2.6 Impact of storage on PV revenue

What we see in Figure 2.6 is the effect of increasing solar penetration over time. On the vertical axis is a proxy for the return to the investor per kilowatt hour of generation. What happens is that as you move more and more solar capacity onto the system the dynamic that I described earlier, where a lot of solar pushes out of the generation dispatch priority stack, the higher marginal cost technologies. Thus, this suppresses overall market prices. That leads to a reduction in the average return that the asset owner will receive. The effect is quite substantial. This is why we need lower cost systems.

If you are fortunate enough to have access to abundant energy storage capacities, (note that we're not adding in the cost of storage to these economic estimates, as you increase the availability of that storage, that actually helps to shift some of that solar energy generation to the time of peak demand peak, or to when we need it most. Doing that helps to increase the average price that those asset owners can change. So, the availability of storage capability is really crucially enabling, for the large scale PV solar deployment that we're advocating for.

The other issue, probably the most contentious point from our study, has been that of distributed solar, and its relative benefits or otherwise. Solar advocates will rightly say that, if we have distributed photovoltaics we will be helping to reduce grid line losses of energy. This is absolutely true. But in the modeling carried out as part of our study over a range of systems, we developed a set of reasonably representative distribution grids. We pushed solar and distributed solar into those systems, and we examined the effects in terms of the overall costs of running the systems. We note that there are many types of distributed systems as many as there are distributed utilities, so this is not a universally applicable result. The universal outcome is that pushing significant levels of distributed generation onto the electrical distribution systems that we have today increases the cost of building and maintaining those systems. In that case, we must invest in those systems ultimately in order to provide the infrastructure needed to allow the distributed PV systems to function.

We are talking about significant levels of PV penetration here. As a result, we shouldn't necessarily believe, "Oh well, we are somehow reducing line losses, and bingo, we're in business. this is a win-win." It's actually not a win-win situation. You will reduce line losses, certainly, but in many systems you are going to require a lot of investments in order to manage voltage, for example. You are going to require investments to manage safety in many systems that were designed only for one-way power flows.

This is a challenge with distributed generation. It's not a fatal problem to any extent, but it is a problem that we should be aware of. Then, there is the other problem of net metering. Today in many settings in the U.S., in particular, you as an owner of a system will receive a net metered price for your electrical generation. It is important to appreciate how this system actually works. In the traditional utility world, we have many residential utility customers. For each of those customers, within the total price that they pay, per kilowatt hour, a portion of it is for the energy received and a portion of it, often half, is for the use and maintenance of the wires. Given the way that our regulatory structures have evolved this has led to the socialization of electricity. That's the way that it's always been, and that's reasonable.

Now, in today's relatively simple version of net metering let's consider a customer, A, who has bought a PV system and put it on his roof. Now he is selling a kilowatt hour instead of buying one.

Then, the utility will pay him for the energy that he produces, and will also pay him effectively to use the wires. That's how it works. So, the utility loses both that rent to pay for the wire that it has had, and it ends up paying the user for using the wires. Now, there are arguments for and against these effects, but it results in a shift in costs that ultimately have to be borne by other consumers who do not have PV systems on their roofs, and it all leads to increased costs.

That scheme works well with very small levels of penetration. Many utilities have said, "Look, we love net metering, because it was a very simple method for implementing the increased PV requirement." But, increasingly, and particularly with the distributed generation, some of these business models, that are now supporting much of distributed solar generation, are becoming problems for utilities. I'm sure that utilities could innovate around this, but many of them don't seem to have the capability to do that. So instead we're going to see more political challenges arising against net metering. Arizona has provided a prominent recent example of opposition, and it won't be the last one.

So, our recommendations concerning R and D are that it's crucial that along with supporting solar that we also support the development of energy storage, because these two technologies really have to evolve hand in hand if solar PV is to succeed. Then, on the financial regulatory side, our pricing systems for distributed customers, will ultimately also have to evolve. We need some evolution to allow the cost of running the distributed network to be appropriately allocated. I believe that the political challenges here are actually much more complicated than is developing the needed theory.

The final message concerns the problem of subsidies, and the need to reform them. Subsidies are crucial in order to support the growth of solar in the economy. We have seen them ramp up, but now is the time to ensure that we have a stable subsidy program in place, so that the gains that have been made can be fully built upon. Instead we have a fluid and fragmented subsidy arrangement in the U.S., at least, which is causing problems. Primarily, right now, the investment tax credit (ITC) is very important, and is about to expire. We think that it would be unwise simply to allow it to expire.

What we need to do is to shift away from an investment-based subsidy framework to one that is more focused on what really matters, which is not how many systems we have built, but how much solar energy generation we actually produce.

The weakness of the ITC and the investment-based subsidy approach is illustrated in Figure 2.7. It shows the situation of California, in terms of the levelized cost of electricity. In California today a utility scale PV system will receive about $37 dollars per megawatt hour in ITC subsidy if they can fully monetize it, although they rarely can.

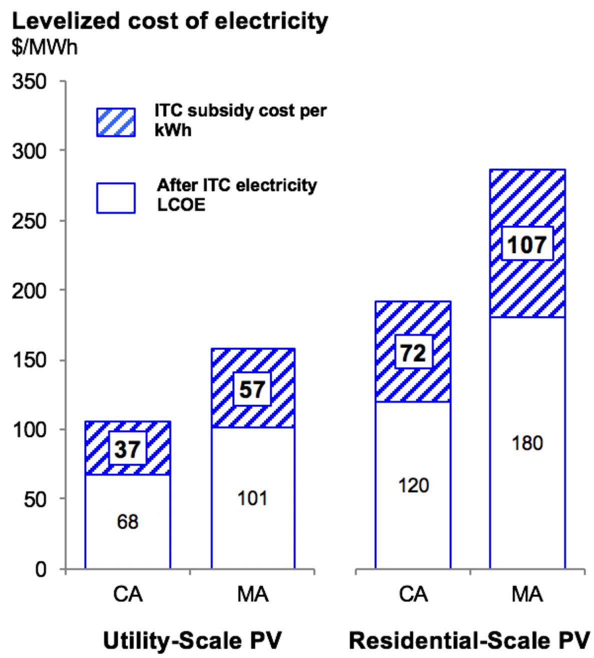

Figure 2.7 Levelized costs of electricity (LCOE) in different situations

In Massachusetts under the same system, that producer receives $57 dollars per megawatt hour in subsidy. That is because the system produces less electricity. This really doesn't seem like an efficient way of producing as much low cost solar generation as possible. Exactly the same problem exists on the residential side, except the subsides are much larger.

So this begins to open a philosophical discussion as to well as a practical one. We, in our study, certainly contend that what should matter is the reduction in the emission of carbon. We should be focused on having as much low carbon generation as is possible.

Since we're operating on the Chatham House rule, I'll speak freely. There is some fantastic action in developing business models lately, on the residential side, in particular. We are all familiar with the lease concept, where no money needs to be invested by a homeowner. In doing this one has democratized access to solar technology. However, that business model is based upon the ability of those that are installing these systems to value them, for subsidy purposes, based upon the income potential of the system, based upon the lease. Now, why does that matter?

That matters because the lease doesn't necessarily reflect anything to do with the actual cost of the system on the roof. What it reflects is the price that the utility is charging for power in that region. So, what you'll typically find is that lease rates will be pitched at about 15% below the utility rate. That's a compelling investment for many people. So, they'll sign up to lease systems. The owners of those systems will then take the net present value of that system, and they will claim that as the cost basis for ITC purposes.

Unless you have competitive markets for these leases, which we do not have, we end up with a situation where those valuations, are significantly higher, per watt, than the actual costs of putting those systems on the roof. This then leads to significantly higher subsidies for those systems than would be the case if the subsidy were based purely upon the cost of the investment. So, there is this subsidy amplification that exists in the residential sector today. It's a beautiful business, but it is not an efficient use of taxpayer dollars to support expansion of solar energy.

The final factor to discuss is the renewable portfolio standard (RPS). Today there are 24 states having RPSs containing explicit solar requirements. Almost all of them require the solar energy to be generated in-state. So here in Massachusetts, for example, we have a pretty strong, and it has recently been strengthened further, requirement for using solar technology. In our state RPS, that solar energy must be generated here in Massachusetts, not in New Hampshire, where you can generate the wind energy that you can use in Massachusetts or in New York where wind energy can be imported for Massachusetts RPS purposes. It has to be produced in-state. That is fine, but that is not the lowest cost way of providing for Massachusetts in helping out with this carbon challenge.

This is also a problem that will have to be addressed. In our report, we have naively advocated creation of some form of a federal RPS. Practically speaking, that's not likely to happen. But, it would be much better from a carbon emission reduction perspective, that is to say much less expensive, if the Massachusetts solar RPS could be met by a facility in Arizona, for example.

I conclude with some policy recommendations. The first is that any drastic cut in federal support for solar at this stage would be unwise. We really need to push on now, but we need to put in place a subsidy structure that is as efficient as it's practical. The current one is certainly not. We should not reward investment. We should reward generation. And we should try to step away from using tax credits if possible. Doing this is very difficult. Tax credits are politically useful, because they are somewhat hidden. The credit does not appear as a budget line item. But the reliance on an investment tax credit in particular, brings the tax equity investors into play. Tax equity investment is a beautiful business. There are some really big margins involved in that business today. We can do better, and we should do better

Finally, concerning state RPS programs, they really should be improved, but doing this is going to be very difficult. Certainly some of the siting requirements today are leading to relatively expensive outcomes.

2.4 Short term strategies discussions

2.4.1 Topic other than electricity

William Green: We never discussed at all the issues about fuels and other parts of the economy other than the electricity sector, which are very important.

2.4.2 Solar electricity and gas turbine

William Green: In this session the two papers discussed primarily, solar electricity, in particular, as a near term solution, and certainly decarbonizing electricity as a major priority. However, in the first talks we heard about how every time we build new solar units we end up building more gas turbines, too. So, maybe it's not quite the panacea that one would hope for.

2.4.3 Solar business model

Participant 3: The levelized cost of energy is a simplified metric, which historically was an aid to thinking about energy efficiency. It was a simplified metric that allowed us to compare investments in terms efficiency. It was never intended as an electricity system planning tool. But we have a systematic failure in the United States and globally to look at systems as systems. I think that one of the messages that could come out of this meeting is that we need to take systems, and examine them as systems, whatever that system may be. Doing that would be very salutary.

Francis O'Sullivan: We should use the wholesale market dynamic as a mechanism instead of simplified models. However, levelized cost is the least opaque of the mechanisms of analysis that was available.

Participant 3: There is a clear barrier between the engineering and economical parts in the solar business model that should be examined more seriously. Even in fully deregulated systems, the vast majority of power doesn't trade through the full scale market. Most sales are protected by bilateral contracting instead. Thus, the idea that the wholesale market is the sole economic determinant is flawed.

My last point on solar business models; the lease model is great as long as you can keep selling more leases and as long as nobody comes in to disturb the subsidy structure. One of the things we have to remember is that the entire deregulatory movement in the United States started with the disturbance of subsidy structures. We have done it in the past, and we shouldn't believe that some political set of forces will not come together and make it possible again.

Francis O'Sullivan: On the lease side of things, if you establish the subsidies using the lease mechanism, it will give you no more subsidy than used in the cost based method. This kind of immaturity is exactly what allows this to take place. One very positive aspect of that evolution is that it has shown that the distributed product can actually be securitized. By securitizing it you can do other things like issuing bonds and asset-backed security type arrangements. This will help us move away from ITC-based arrangement.

Participant 3: We should note that securitization isn't new. Just because something can be securitized doesn't imply that a lot of social good is going to follow.

2.4.4 Price depression problem

Participant 8: My question concerns the price depression problem with solar generation, and how to solve it. For example, we have experienced price depression problems with nuclear in 60s and 70s. But did we experience this kind of problems somewhere else and if so, how did we solve them?

Francis O'Sullivan: It's not clear whether we solved it, but certainly in some of the wind markets you see it as well. Considering that most of the solar today is being sold with long term Power Purchase Agreements (PPAs) instead of via trading in the market, this is not a serious problem.

Participant 8: However, there are still a fair amount of these contracts being traded in physical markets instead of in those financial markets.

Ross Koningstein: I argue that in some cases we are seeing this effect. So, for example, in the Midwest we're seeing deployment of wind that is making nuclear less effective. The nuclear plants are only able to sell fewer megawatt hours. So, the effects are being felt, just not by the wind industry.

Participant 21: As for the effect on nuclear what we are seeing may be a game of chicken. At least Exelon is threatening to shut down four nuclear plants, saying that they're losing enough money on them that they can't justify keeping them going. Essentially it's the result of a combination of the preference given to renewables, coupled with the dispatch order where the marginal price is very attractive for the solar assets. It's a real effect that may shut down real power plants.

2.4.5 Renewable capacity needed for low carbon future

Participant 9: I think that Ross Koningstein grossly underestimates and understates the problem of getting to a low carbon economy. He talked about installing 700 gigawatts of new electricity generating capacity using renewables in the U.S. This number is far below what it should be if real de-carbonization is to occur. The reason is that he didn't consider the lack of nuclear capacity that may occur by 2050, the efficiency problem of electrify everything, and the low operating capacity of solar and wind assets. Somewhere between 4000 and 6000GWe would be a fair number for what is needed.

Ross Koningstein: The 700 gigawatt number that I stated is approximately the size roughly of the electrical infrastructure today. I eliminated many things from analysis because I'm trying to concentrate on the most important factors that could have effects. I agree that 700 gigawatts is not the capacity that you will deploy, it's the capacity that you start planning with.

2.4.6 R&D funding

Participant 9: R&D is important. However, it's really important to mention that the progress that Francis O'sullivan talked about didn't happen mostly from R and D. The cost reductions in solar mostly are not attributed to the research dollars spent in laboratories, they came from the lessons of deployment.

Micheal McMahon: Building on the R and D comment, I think that both talks focused on R and D, and the allocation of it. We should emphasize more on the venture capital-driven development, concerned with how to allocate it on solar side, and where it should go. What are your ideas about how to have a more effective public/private partnership to harness R and D so that you can create the types of disruptive technologies that you don't really see yet? So, what are your ideas concern how to take the current system, take the best of the VC world and the best of the government world and have them come together?

Francis O'Sullivan: As for the R&D funding source, today we only have money coming from federal sources instead of from the private sector or even the VC sector. The topics involved here are too high risk for the latter two, but the potential is enormous. Only the Department of Energy, or the federal government is in a position to support that type of research where their effect could be distinctive. There are, of course, many opportunities for more applied R&D, but the federal government could play a very important convening role. This kind of activity could lead to follow ups from industry. However, most industrial companies don't have the money to throw into long, long term investments. It would help if the companies that do have the money would work together with government.

William Green: If we were to have a carbon tax of a thousand dollars a ton would all of a sudden the whole financial situation be different, and industry would be highly motivated to invest in R and D?

Ross Koningstein: I think if we had a thousand dollars a ton carbon tax, and we used that money to reduce carbon, then yes that would be very transformative to the business. How politically sustainable a thousand dollars a ton tax would be is an entirely different discussion.

I would really rather address one of the topics that you raised, that of public/private partnerships. I think these can be very powerful, because one of the things that I have learned in private capital is that there is just no substitute for the discipline of private capital. If you want to look at how people focus on the goals that are really important and take limited amounts of money and do that what they need to, it's the same as, when you put people in charge of a pot of money; they actually really tend to pay attention.

On the other hand, the place to fund and provide money for long term development, is from a government research program. Yes, you can have standout companies of the era, but they don't last forever, and some of these technologies will need to be developed at multiple places and possibly across different companies over time. So, I see the public/private partnership as the way to go.

Participant 21: International governments should play an important role in funding R&D if we are to meet the schedule that we need in order to decarbonize. However, most of the governments can't do that. In some less wealthy countries like China, the government has taken the mission to be transformative. So the rich countries should also do the same thing.

Participant 9: I think your characterization of the current state of politics is reflecting too much of your U.S. bias. I actually think there is quite a lot of effort in Europe.

2.4.7 International Policy

Participant 9: Considering that politics can flip a lot, it is unsafe to use current policy to project what will happen in the middle of this century.

Ross Koningstein: Having international government cooperation and focus on low carbon will be very difficult and unnecessary. I tend to believe that the next energy innovations will occur in the developed world, and the market will determine the rest of what will happen.

Participant 1: Thinking about global solutions might lead people to think or hope for global agreements. My view is that we should stop doing that. Let's try to make some progress expecting global disagreement, and noting that better manufactured goods are perhaps an area of opportunity. From the European/American perspective, we buy a lot of stuff, with a lot of embedded carbon, and that gives us quite a lot of power in affecting how things are done. For instance, my country, the United Kingdom, lives in the warm glow about how good we are in terms of conventional statistics about CO2 emissions until you factor in the embedded carbon of all the stuff that we now import, that we used to make. We're much worse than we were in 1990 by that measure.

So my question is why must we work with developing countries on this really difficult problem. So, why must we work with them? Well, it's because legally we have to. Legally we have to because of the point that Ron made earlier about trade. It would be illegal for us not to do this. We, the rich west, put up the WTO and we have spoken against tariffs. No, we also have to have a carbon tariff for that LED TV that I mentioned earlier. So, my view, is tax these bits of plastic that come into North.

Robert Bundniz: I want to observe what I think is a very negative trend in the U.S. in the last 25 years. In many of our states, the electric utility is the largest business in the state. They are very big and influential. However, they have found that the way that will make them the most profit is fund nothing for research. They haven't funded any long term research projects for many years. That is a tragedy, but it can be reversed. Coming together, and doing what the government should be doing is in their interest. The reason is if electricity is to be much more of the economy in the future, the electricity utility will have more profit. This is exactly what we want to be. However, this is not happening internationally. It's a terrible shame.

Participant 3: One of the consequences of the movement to deregulation electricity in the United States is that contributions from utilities to the Electric Power Research Institute (EPRI) have fallen through the floor. When Chauncey Starr started EPRI, and until deregulation happened utilities came to their regulatory commissions and having had a budget line for research. There was no instance ever of the commission saying, "We're not going to allow you to pass on the cost of your dues to EPRI to your customers. We don't see the value of the dues." Deregulation happened and deregulated states immediately eliminated those expenditures. Then, regulated states followed. As a result, EPRI then became the organization that had to go begging with individual utilities to raise its budget. That's one of the consequences of deregulation.

Participant 3: I want to comment on India's situation. India promises to develop wind and solar. However, they will only do this if the US and others will pay for it. They put expectations of significant multi-lateral international cooperation. I think that India's capacity for doing this on its own is very limited. India has been very clear about its intentions to develop and use its coal resources.

Francis O'Sullivan: There is no question that they would use the coal. The question was whether over the next decade solar energy will grows to at least get ten to twenty percent penetration in the electricity economy. Incidentally, India also has a huge advantage relative to Europe and the U.S. which is that most of India doesn't have any kind of reliable grid to begin with. Therefore, for a lot of Indians, the intermittency of renewables can be just fine, and can be better than what they currently have. India is beginning to realize that in fact new solar installation may cost less than with some of their coal installations. That's interesting, because it is so different from predictions of what is going to happen there in the next decades.

2.4.8 System Challenges

Ross Koningstein: There are difficulties with solar thermal systems. They come from various areas like system sustainability and cost.

Francis O'Sullivan: China can do it. They did it with PV.

Ross Koningstein: Yes, but the outcome depends upon who pays the balance of the expenses.

Participant 12: In addressing the intermittency problem what do you anticipate will be the importance of boxes with terminals on them versus systemic solutions?

Francis O'Sullivan: So, with regard to intermittency and the palate of available solutions, there is ultimately going to be a technological economic optimization. The ideal that the box in your basement will let you become a fully self-contained entity today seems unlikely. At least its economics appear poor relative to where they would need to be, compared to the alternative, which is to maintain your grid connection.

The reality is it's much more complicated and perhaps less compelling as an investment, but many people are talking about it. I think that there will be a focus upon trying to create a business. That can only be helpful for improving that option.

However, I think for the overall system, including transmission, the generator and down to the meter, the vision of the future that we envisage at least for the next three or four decades is one where you have a variety of different technologies providing a variety of different types of storage solutions.

Participant 12: It seemed to me what you have presented was a very US-centric view. Do you discount the idea that around the world we may see significant development of essentially off-grid electricity?

Francis O'Sullivan: Regarding to RMI and the off-the-grid vision, I mean we didn't really go after that question, because there was too big a gap between what we have today, and where one needs to be. However, I think that it's difficult to imagine, and I think for the remaining solar study group to imagine realistically a world where our grid is going to go away. What you will likely see, though, is a combination of using better storage technologies to lead to a looser aggregated grid, where you have a more of a meso-grid so to speak. One where you don't need as much hard transmission, and where you can rely upon more local storage to provide the needed grid reliability. So, I think that that's where the system is likely to evolve.

Ross Koningstein: I think that transmission grid expansion is particularly problematic, both from perspectives of cost and politics. As the population and energy consumption grow there will be pressure to create more local power sources. The costs of running a storage system, and the operational costs of actually using it are too prohibitive at the current stage of technology.

The other fundamental problem with energy storage systems is that they need to be financed primarily on a per-end-user basis. For many people that makes absolutely no sense. The second part is that if you are off the grid that means you have to deal with all your own capacity constraints. That can be very unpleasant, as when your daughter is using the shower at the same time when you would like to use the shower too. This extends to the TV and the stereo and lights. So, the typical average power use of your house compared to the peak power of your house may be incompatible. If you had to factor that into your own power plant you would actually not wish to pay for it.

Francis O'Sullivan: Just one final point on the utility death spiral. I think that we are in a situation where for distributed utilities that there is a lot of naïveté. The problems arise from a variety of reasons like regulation limitations, and the business administrative aspects of actually managing a distributed energy system.

There are many technical problems, where the actual rate of change is much slower than enthusiasts hope for. What needs to change faster is the regulatory paradigm that utilities today live with. I think that there is an appetite to be innovative, but I doubt that there is a capacity within many utilities to change. If they were unencumbered from their regulatory shackles they might then be in a position to be more competitive than they are now.

William Green: We have taken a very U.S./European-focused worldview about PV. But we're in a world here where we have a lot of natural gas, and where it's easy to do the grid load balancing using gas turbines. But most of the people in the world mostly live in Asia, and in China and India where they don't have much natural gas. So, how are they going to possibly handle the load balancing problem, or are they going to have to wait until we figure out how to make cheap batteries or something else?

Participant 13: I think one useful concept would be to fit into these kinds of studies the path-dependent nature of development. The available research today contains many uncertainties about the situation between now and the future. Their ideas are separated from the realities. I think it would be really interesting to develop some analytical work by working with decision makers and asking them what they need in order to support their decisions.

I think that the other problem that relates to the developing world is that implicitly a lot of the things that we say are based on assumptions that are contrary to the facts in many of these markets. So we should try to think about the broader set of requirements constraining technologies for bringing electricity to those countries. We must move beyond considering only to sell solar or wind projects there, or about using solar light bulbs. We really need to be considering the kind of infrastructural needs, their social and financial problems.

Although there is a lot of sun there, they also have very intermittent electricity already. So, they might not mind solar so much, and a lot of people use individual generators. Fuel costs three or four times the LCOE of solar today, but we don't see a lot of solar uptick there. Why? That's the biggest question. It is worth thinking over the fact that even though renewables are much cheaper than what the developing world is using today, they don't make use of much of them. Why?

Francis O'Sullivan: The investmentor only wants to get his money back. In order to attract him, you have to establish a risk environment that becomes compelling in the financial markets in order to attract the needed capital. We appear to be talking about the technology, but actually we are discussing the access to needed capital. You need to have incredible depth and assurance to enable access to that capital in order to attract it. Considering that the rate of return on capital investment has decreased incredibly, the current access to capital is much more difficult than a few years ago.

Participant 3: Just to answer your question about two recent studies, in one by the NDRC on China renewables, there is a high renewable penetration scenario for China-----adding 80%, entails retaining 800 gigawatts of coal also, in order to balance the system. About a year ago the World Wildlife Fund performed a similar study that includes using 1.1 terawatts of natural gas with no discussion of where the gas is coming from. For this case, the projected heat is almost two terawatts. In the first instance you could build a six terawatt system to serve it, and in the second instance I think you would build an eight terawatt system.

Participant 9: Nobody in this room or the world knows how we're going to manage really deep penetration of the renewables. But the time scale of building thousands of gigawatts of new capacity will need a lot of innovation. You can't get from here to there given what we have in the toolkit right now. By 2050 there will need to be some surprises.

Ross Koningstein: I would like to address the solar/diesel question. When you look at the developed world the diesel systems tend to power wealthy groups of people in apartment buildings. We have looked at why it is that you can't just add a whole lot more photovoltaic power to the grid to reduce at least offset some of the diesel consumption. It turns out there are a lot of really interesting technical and financial problems.

The first wall to be faced is the money wall, where the people who own the diesel resources would actually have to open up the power use to an entire new set of consumers, in order to reap the benefit. So, you need to create a market for let's say somebody who has a sewing machine type of manufacturing facility, where they need to be able to power their village by adding capital equipment needing the solar panels, the inverters, and so on. Actually in creating all of these markets and making them work, there is a lot of friction that arises, because you're trying to sell things to people who don't have money. So, even people paying for connection charges to even the simplest grid have a problem.

The other problem is technical. It turns out that not only is it hard to connect PVs to diesel, it's hard to connect diesel to diesel or PVs to PVs. There basically is no standard. The different ways that the generators regulate creates physical inertia that make them very, very difficult to interconnect. So, every job requires that you try to do something is completely custom designed. Until there is a standard way to parallel connect generators or to parallel connect inverters with generators there is not a cost effective solution available. You can put in a PV system, and have an auto-match to disconnection, which is what some people do. They just switch over to solar in the day time, and then they throw the night switch to run the generator set at night. There is no smooth transition.

SESSION 3: Nuclear Systems Performance Requirements

3.1 Session Question

What are the likely needed scale and products for new nuclear technologies to provide an adequate climate change response (variable electricity, heat, hydrogen, water?) What are the technological options, and requirements for supporting technologies, to allow nuclear technologies to increase its effectiveness?

3.2. Introductions

Robert Budnitz: The two talks in this session have to do with potential nuclear systems performance requirements and the two speakers with be presenting options for systems that they have been working on which may help to meet them.

3.3. Presentations on Nuclear Systems

3.3.1. Base-load Nuclear Power to Meet the Need for Variable Energy Output: The Value of Heat: Charles Forsberg (MIT)

I'm going to give a slightly different perspective on nuclear, and that is variable electrical output with baseload nuclear. The starting point is that we have to understand the challenge that we face of a zero carbon society. For roughly a half million years man has met variable energy demands by putting more carbon on the fire. The technology has changed a little. We have gone from cooking fires to gas turbines, but the basic philosophy has not changed at all. So, the real question that we have today is, "How do we replace variable carbon based energy production in a low carbon world so that we can match production to demand?"

The second observation addresses the totality of energy needs. The chart (Figure 3.1) Estimated U.S. Energy Use in 2013 shows various energy sources used meet various energy demands in the residential, commercial, industrial, and transportation sectors. We have to think of satisfying all of these end demands, not just one or two. Now the one important sector that is not shown on the far right is the electric sector where a lot of the initial energy inputs are converted to electricity, which then go into residential, commercial, industrial, and transportation consumption? Because of the central role of electricity, I am going to go into it in a further detail.

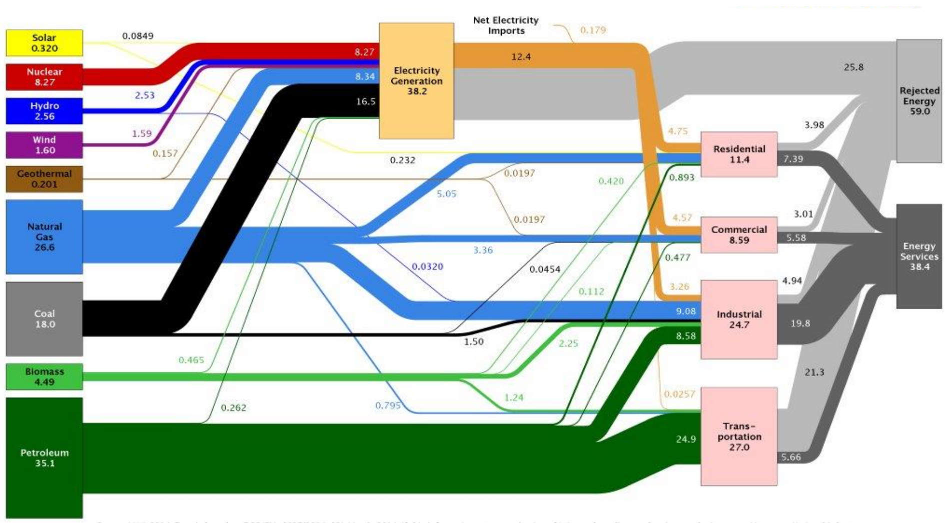

Figure 3.1 Estimated U.S. energy use in 2013

One observations are that low carbon and the future implies more situations of both low and high priced electricity. The next chart shows California electric prices in 2012. For each of these prices it tells you how many hours per year you could have bought electricity at a particular price. At $20 dollars a megawatt hour there are about 600 hours a year where the price was roughly there. This is a typical price curve for electricity in most of the United States today.

Now, what happens if you add a lot of solar or a lot of wind generation capacity? Well, if you add a lot of solar generation its output tends to show up mostly in the daytime with none of it at night, and mostly in June with very little of it in December. This means is if you install a lot of solar and all of the solar output appears at a particular time of day it's going to provide a lot of current to the grid and it will collapse the price of electricity. So, a lot of solar or wind input implies a lot of low priced electricity at times of high solar or wind production.

The other consequence is that you've got to have some other method to produce electricity at other times of the day, typically based upon natural gas. If those gas turbines run half the time rather than all of the time you're going to have to pay a lot more for them, so you're going to have more high priced electricity. So, going from today's fossil economy to a zero carbon economy changes the price curve from this nice sort of semi-Gaussian system to what may ultimately be a double peaked model of cheap electricity and expensive electricity.

Now, the price collapse challenge is for high capital cost, low operating cost systems, and it creates major problems for non-fossil generating systems. In the case of nuclear, operating at part load is very, very expensive. In the case of wind and solar, if you're going to have continuous power provided by the grid you have to pay for storage. Revenue collapse becomes significant when 10 to 15% of your total electrical energy is provided by solar, 20 to 30% wind, and about 70% nuclear deployment.

The last observation that I would like to make about challenges concerns economics. Energy is about 10% of the gross national product, and we cannot afford to double that cost. If you double that cost, I think that you will have a political revolution on your hands. It's as simple as that. What that means in the real world is that nuclear, wind, and solar are capital intensive, and you must maximize production in order to to minimize cost.

With that background let's take a look at these problems in the context of addressing the challenge of using heat from nuclear reactors. I start with a very simple observation. Nuclear energy is a low carbon, large scale, heat producing technology. It doesn't produce electrons as does PV; it produces heat. So, an important question is that of what can we do with this heat in order to meet variable demand? I look at it from three aspects. I start by discussing heat storage for providing peak electrical power for industry. I discuss two kinds of heat storage, nuclear heat–to-heat storage and grid electricity to heat storage. So we've got two intermediates systems under consideration here.

Now, here is a schematic diagram (Figure 3.2) of our heat economy. We have a baseload nuclear power plant. Traditionally we think of it producing electricity to meet electricity demands. Now in some parts of the world, (i.e., Russia and parts of Europe), baseload nuclear plants also produce heat to meet industrial demands. But there is another option. It is an option to add a heat storage mode between power generation and the customer. That heat storage mode can be in the form of heat obtained directly from the nuclear reactor, or in the form of electricity going into heat storage. That way heat storage can then go to industrial demands or be used to produce electricity using the electricity system. So, this could be our global system.

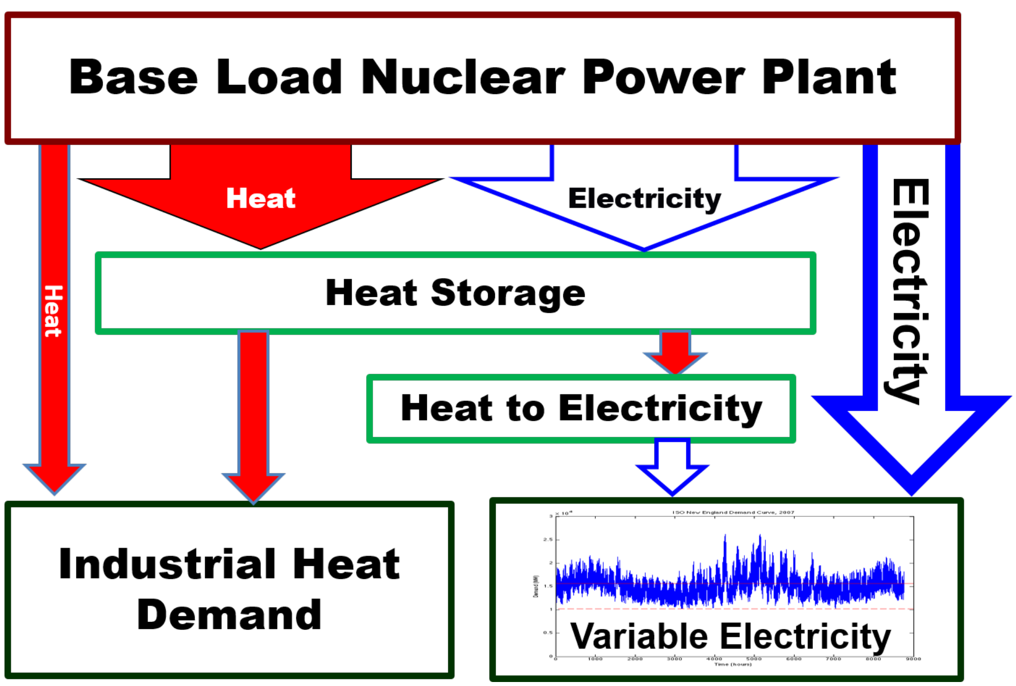

Figure 3.2 Schematic diagram of heat economy

If we examine heat storage technologies, there are many that couple directly to existing light water reactors (see Table 3.1). Examples such as liquid heat capacity, nitrate storage, and steam accumulators are heat storage technologies used in existing thermal, and solar thermal power plants. Most of the technology is available off the shelf and about a century old with a few minor

modifications. These are very well-proven technologies. There are other technologies that have not been
deployed, such as geothermal hot water and geothermal rock. Geothermal rock is what you get when you take hot water at about 250-300°C, heat up a cubic piece of rock, maybe 300-400 meters in diameter, placed a cubic kilometer underground. Thus, you create your own private geothermal heat source, that then can be used to produce peak electrical power for use at times of need.

The characteristic of these nuclear based heat storage systems is their scale. Here (Table 3.3) we show representative storage times. The first storage time is of the order of hours. For the example shown here the time scale is perhaps of a week. The nuclear geothermal system can be used for seasonal storage. Similarly, we can take a look at the size of these systems. These small nuclear systems are measured in capacity of gigawatt hours. When you talk about these seasonal storage options you're considering systems between 1,000 and 10,000 gigawatt hours of capacity. I'm not going to go into the technologies, except to note that technologies of these large scales require systems very large scale storage capacities. So we've got a set of capacities to consider.

Table 3.3 Heat Storage Technologies Coupled Directly to Existing Light-Water Reactors

Technology	Description	Storage Time (Hr)	Size (GWh)
Liquid Heat Capacity	Store molten nitrate or other material at low pressure	10	<10
Steam Accumulator	Store high-pressure water-steam mix	10 Fast Response	<10
Geothermal Hot Water	Store hot water 1000 m underground at pressure	100	100 to 1,000
Geothermal Rock	Heat rock to create artificial geothermal deposit	1000+	1,000 to 10,000

The reason why we want to think about thermal storage is quite simple, heat storage is cheaper than electricity storage. Take a look at the DOE cost goals for storing energy. In the case of thermal energy for solar systems, these are small systems, by the way, systems of megawatts and megawatt hours. The goal is $15 dollars per thermal kilowatt hour capital investment. For electricity, the goal is $150 dollars a kilowatt hour. In other words, the implied cost of storing heat is a factor of 10 less than for storing electricity. What this says is that if you've got a storage problem you don't want to store electrons, you want to store heat, for a very practical reason, it costs one-tenth as much. That implies that if you go to a zero carbon economy one of the things you may buy nuclear generation for is that it's got the cheap storage option. It's strictly economics, simply a factor of 10. That's a fairly significant number.

The other option for heat storage is to start with electricity and put it into heat storage using fire brick resistance-heated energy storage. When the price of electricity is low you heat fire brick. Notably, you can heat it up to a nice toasty 1800 Celsius using 1920s technology derived from open hearth furnaces. Then, of course once you have the hot fire brick you can use it as a heat source for industrial heat or as a heat source for peak electricity production. So, one can buy such heat whenever the price of electricity is low.

Well, what kind of a system does this imply? It implies low-priced electricity. We heat fire brick and blow cold air through it, creating hot air. We adjust the hot air temperature by adding cold air or natural gas, and we provide that hot air or mixture to industrial kilns or furnaces using hot air to heat them. It is a substitute for natural gas. That is a way of using low-priced electricity when it's available, put it into a storage system, and run it into the industrial sector on a large scale.

Now, let's take a little more look about the nature of fire brick storage. If we compare fire brick storage versus that of a Tesla, it takes a lot of Tesla batteries to equal the capacity of one cubic meter of fire brick. Another observation, which is perhaps more important, is that Tesla recently came out with its big news that they could provide home storage of electricity at $350 dollars per kilowatt hour. They must think people are made of gold. What does fire brick cost when you buy a railcar of it? Oh, it's about a dollar a kilowatt hour. So in these storage modes, we have a factor of a hundred in cost between storing energy as heat or as electricity.

What does FIRES mean in terms of the real world? I mentioned this particular price curve here (Figure 3.3) when you have lots of renewables and where you crash the price of electricity. If people build something like FIRES in their systems, then whenever the price of electricity gets below the price of natural gas, the people with FIRES will buy that electricity, store that electricity as heat, and use it for heat for their industrial systems. So what FIRES does is that it just kills off very low cost electricity prices and moves that energy from the electric sector to the industrial sector, and thus reduces the carbon dioxide emissions of the economy as a whole while improving the revenue streams for large scale use of nuclear, solar, or renewables. That's one example of heat storage.

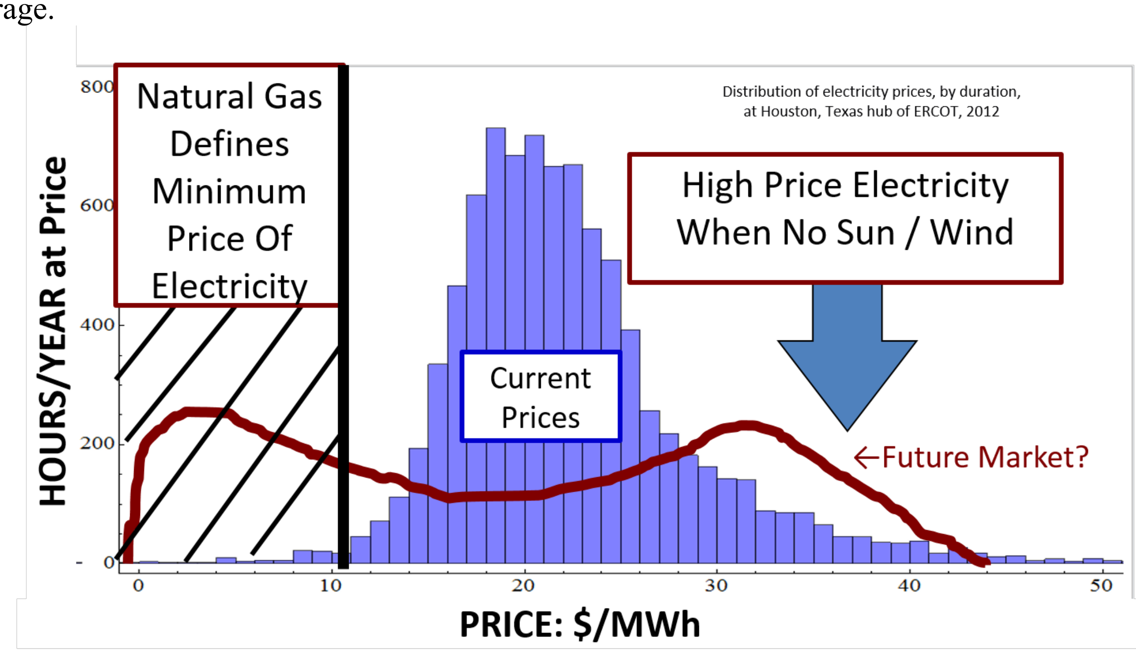

Figure 3.3 FIRES Stops Electricity Price Collapse

I would now like to take a look at a second option for heat storage, a second approach for nuclear energy to meet variable demand with a steady state reactor that operates in the most boring conditions, no up and no down. This option is the use of Nuclear Air-Brayton combined cycles coupled to nuclear reactors. This is a relatively new concept. It best couples to a fluoride salt cooled high temperature reactor, but it may also couple to several other types of reactors, including sodium fast reactors and high temperature reactors.

The first observation that we make is that advancing natural gas combined cycle technology enables high temperature nuclear reactors to be coupled to these gas turbines. This could not have happened 15 years ago because the gas turbine technology was not sufficiently developed. It is very important to understand this is a new strategy for nuclear energy, reflecting advances in gas turbines, and not to do with anything on the nuclear side. It suggests that the next generation of reactors may in fact couple to Nuclear Air-Brayton combined cycles, what we call NACC. I have supplied an example of a modified GE F7B gas turbine which could be combined with a salt cooled reactor (FHR).

Why do we want to couple a gas turbine to a nuclear reactor? Let's take a look at our Nuclear Air-Brayton combined cycle. Air goes in, travels through this big piece of machinery, and then goes back out the stack. Now, of course, we compress air in a gas turbine and can use the heat from nuclear to heat it up to 670 Celsius. If we're operating in baseload mode we can produce baseload electricity, let's say normally 100 megawatts, and the efficiency is 42%, nothing very exciting in any context. I mean it's exciting for the nuclear guys, but it's nothing unusual. But with this gas turbine, the warmer it becomes, the more energy that they produce and the higher is the resulting efficiency.

So, let's take this heated air to 670 °C and let's raise the temperature a little further to 1065 °C by adding natural gas or hydrogen or stored energy using FIRES. So we add some additional heat, and raise the temperature up to 1065, still lower than the temperature of top of the line gas turbines, that currently run at 1300 Celsius. If we do that we find out we can produce peak electricity, an addition 142 megawatts. But more important, the marginal efficiency of converting this incremental heat to electricity is 66%. That is because we are using a topping cycle on top of the low temperature 700 °C nuclear heat. What is so interesting about 66% efficiency? The best top-end standalone natural gas fired plant under the ideal conditions has a 61% efficiency. The efficiency of NACC is substantially better because of its topping cycle. That has several implications.

If you happen to build one of these plants successfully it implies that your revenue stream is 50 to 100% larger than with a baseloaded nuclear plant, because you can sell peak electricity and you are the most efficient user of natural gas. It also suggests that this type of arrangement of technology, nuclear with fuels, be it hydrogen, stored heat or natural gas, tells you where you want to go in the future. It's in this type of plant that you want to burn the last cubic meter of natural gas ever put into a peaking turbine, because it is the most efficient device on the planet Earth to convert heat to electricity.

Let's go a little further into details. NACC with FIRES enables baseload nuclear providing variable electricity to gain a place in the industry. We start with our boring nuclear reactor operating in steady state and direct the heat into a NACC scheme. NACC of course has air inlet, a gas turbine, where the exhaust from the gas turbine is hot low pressure air that goes to heat recovery boiler, where it makes steam that goes to the atmosphere. In this system we obtain electricity from the gas turbine, electricity from the heat recovery boiler, and we have the option of providing steam to the customers. All of this is operated in a variable output mode, depending upon how much variable heat we add and how much from our FIRES storage system or our hydrogen. So we have a system based on existing gas turbine technology, used in large chemical plants and refineries, where if we have a constant temperature heat source we can produce variable heat on the side, variable electricity, and variable steam to industry.

Last, I would like to turn to the third set of heat management options, hybrid energy systems. The objective here is to use excess low priced energy when available from nuclear, solar, or wind to produce a second product. It's enabled by heat storage, FIRES, and NACC, delivering steam and hot water for industrial purposes. These hybrid systems have the potential to be the lowest cost options by reducing storage costs. And if you can reduce storage costs in a zero carbon economy you can save a great deal of money.

But what is a hybrid system? There are many definitions and combinations, but we can use an example to give a flavor of the nature of hybrid energy systems as we look to the future. My example uses a nuclear renewable hybrid electricity hydrogen system, a system that produces both hydrogen and electricity. Now, the reason for using hydrogen is that producing hydrogen may constitute as much as a third of the total energy demand in the world in a zero carbon economy, and for a variety of reasons. It may be used as a direct fuel. However, if it's not used there it may be used also in biofuels production. It turns out that if you have hydrogen available you can roughly double the amount of diesel fuel that you produce per ton of biomass versus use of no hydrogen. So, if you have a limitation on biomass, biomass plus hydrogen can enable production of a whole lot more diesel. The second observation of course, is that it's used in fertilizer. All nitrates require hydrogen input. The third is we have a large industry that produces iron and uses hydrogen: steel, all of our metallurgical products. That industry uses coal as a chemical reducing agent. The alternative chemical reducing agent in a zero carbon economy is hydrogen. And last of course, hydrogen works perfectly well as fuel in a gas turbine. In short, for a variety of technical and economic reasons, a zero carbon society may use very large quantities of hydrogen, independent of whether it ever is used to power a vehicle going down the road. I would like to emphasize this. This is independent of whether we ever solve the vehicle storage problem for hydrogen. For a minor point of observation here, the U.S. currently consumes 10 million tons of hydrogen each year, we have pipelines all over Texas and Louisiana carrying hydrogen to all sorts of chemical plants and refineries.

This hybrid system satisfies variable electricity demand using a baseloaded nuclear power plant that generates enough power to guarantee our electricity demand. If we have cheap solar and wind on the system and put that into the electrical sector, then when we have excess electricity we can send it to a high temperature electrolysis system, where electricity plus heat produces hydrogen. This is the most efficient way to make hydrogen. If an electrolysis system is in operation we need steam from the nuclear power plant, so we get steam here and less electricity here. We get the electricity from the grid, all going into high temperature electrolysis to make hydrogen that goes into underground hydrogen storage or out by pipeline to industrial users.

A couple of features about this: The first is underground hydrogen storage. It turns out that the storage technologies are the same that are used for natural gas. In the United States we can store up to a quarter year's production of natural gas in underground caverns; the same would work for hydrogen. We can store hydrogen at dirt cheap prices as long as you want to store a million cubic meters of hydrogen. We have no idea how to cheaply store 10 cubic meters of hydrogen. It's a strange world. Storing a million cubic meters is trivial, cheap, easy, old technology; storing 10 cubic meters cheaply, way beyond our existing technology basis. The other feature about this is hydrogen pipelines. If you want to move energy, serious amounts of energy, 10, 20 gigawatts you can do that with one pipeline versus 10, 20 power lines. So if you were in the long distance energy moving game this is the way that you would want to do business. I use this example, but there are many others. The goals in all of these cases is to accommodate wind and solar generation and to let the nuclear plants run in baseload mode. They run at maximum output all of the time in order to minimize their capital investment and to maximize economic competitiveness.

With that, I'll conclude. I would like to emphasize in that conclusion, that the challenge is providing economical variable-energy upon demand. As I suggest here today, nuclear heat is a very major component of that, because it can access cheap energy storage, and it can access the use of Brayton power cycles, which have remarkable capabilities because of the incredible advances in gas turbines, and it enables use of hybrid energy systems.

3.3.2. Nuclear Cogeneration: Henri Safa (CEA, France)

In my talk I will be addressing how we can really use heat with nuclear power, using today's technology with current technology nuclear reactors, pressurized water reactors. Why are we dealing with heat? We have talked a lot about electric power, but electric power in France is already almost 100% decarbonized-94% decarbonized. So, it's not a problem to decarbonize electric power in France. The problem to address is that electricity is 40% of energy, the other 40% is basically heat for the non-transportation energy sectors, and the remaining 20% is transportation. So we have already completely decarbonized electricity, and we want to decarbonize the heat sector. This is the most important issue in the frame of the new law that is being discussed in the Parliament in France, that of how to decarbonize energy in 2050 more than it is now. Having already decarbonized electric power, we are already a country with a very low greenhouse gas emissions compared to the others.

If we look at a global picture in the world, heat is over 40% of the total energy, and 50% of this heat is low energy, low temperature heat. It's used for heating homes, commercial businesses, public services, etc. The potential for using this low temperature heat is huge. It's more than 20,000 terawatt hours, whereas the actual world district heating delivery is 2,500, so that is really a tremendous problem, that of using low temperature heat. If we look at the energy pathways chart from the IEA, energy sources are on the left, and final energy users are on the right, with the transformation of energy in the middle. In order to produce nine giga-tons of oil equivalent of energy to users, we have to burn 13.5 giga-tons of oil equivalent energy sources. So this means that the wasted heat is more than 4.5 giga-tons of oil equivalence. The question is, when we start from the sources with these losses of more than four giga-ton of oil equivalent and considering that more than 5 giga-tons are used at low temperature, can we recover the losses that we have already produced from our sources to fill in the final energy use at low temperature. So the question is, can we make this recovery with the current sources that we are using for burning from all kinds of sources such as oil, gas, coal, or nuclear, can we use these losses to fill in the final use at low temperature?

You can see that space heating in Europe, which is the greatest heat consumption in many countries, is mostly as a low temperature heat, below 120 °C. This is true also if you compare the electricity in France. If we exclude heating from electric heaters, 31% of primary energy is used for electricity, pure electric power, and 46% to heat. So this means that we have to address decarburization of heat and electric heaters for heat production.

If we try to look at more specifically what kind of heat and what kind of temperature is used in industry and by domestic users, we know that domestic users use heat for heating houses, buildings, and sanitary hot water. For industrial users we have to address different kinds of industry and look at which are the industries that may use low temperature heat below, let's say, 120 °C. We do that we see that 65%, two-thirds of our heat users in industry are at a final use at low temperature.

A short thing about cogeneration, this is for any electric power plant, it's not specific to nuclear, it's really the transformation of any source to electricity that makes waste heat, just because of Carnot's law, and the electrical efficiency can be from 34% for nuclear to 56% for combined cycle gas turbines. This means that two-thirds of the power is lost in heat for nuclear and about half of the power is lost in heat for the gas.

The idea is can we use this waste heat to recover or to make other energy products, either directly as heat or for producing fuels, steam, or water. I provide an example of recovery of nuclear heat. You see that two-thirds of the energy today is dumped into the environment, either in the river or in the atmosphere, so it's basically heating the birds and fishes. But what we really want is to recover this heat, for its final use. One very interesting application is recover of this heat for district heating. This means that we want to recover this heat, and, as nuclear power plants are far from cities, we want to use long distance transport from the nuclear power plants to the cities. So, this brings in the technology of the main heat transfer line at long distances.

Today's technology can transport heat in hot water transport lines. We can have very low losses in the modern heat transport lines, which can transport hundred kilometers with less than one percent losses. This was not available 20 years ago or 30 years ago, when we started building nuclear power plants in France. Now this is new technology that is readily available, and the nuclear heat can be recovered for this final use, which is the main use of heat in our country.

What is interesting in cogeneration is not only you get better efficiency, because if you add in the recovered nuclear heat plus the electricity produced the overall systems offers more than 80% of energy efficiency. This is very interesting from that point of view. It also opens new sectors for nuclear power beyond electric power because we can make better use of this energy by delivering this heat at the right temperature, and we can even match industrial application needs. It also gives you greater flexibility. Because in France we produce 75% of electric power from nuclear, we already have to deal with the need for flexible electrical demand. Therefore, our nuclear plants are all flexible. We have also much lower environmental impacts, because we have lowered the amount of heat dumped into the environment as a result of providing the additional heat sink.

Just a few words about the heat application in industry, of course I have talked about district heating, but one point which is very interesting in many countries is water desalination. This can be very easily done with the waste heat of nuclear power at low temperature. We have also gone through some medium temperatures applications of nuclear heat such as providing industrial steam, coal liquefaction, tar sands, biomass, and synthetic fuels, as well as the high temperature applications of hydrogen production. These last two groups of applications really need a new generation of reactor which does not exist today. For this, you must have high temperature reactors. However, district heating and water desalination can be done with the current light water reactors running in baseload mode.

There are three big advantages that we are clearly gaining on if we run in cogeneration mode: energetic, environmental, and economic. Transformation of plants can help to accomplish this. When you go from the nuclear reactor, which basically produces heat and electric power, to industry, you may also need other kind of energy vectors, energetic products that can be made in transformation plants. The questions are first, how to make the coupling between the nuclear reactor and the industrial use safe, and second, how to make it more efficient. So it really depends upon your industrial use and the temperature of heat that you want to use in the different processes. This is really resolved on case by case and resolved on industry by industry specific as to what is the best use of heat in from nuclear reactors.

One example is biomass to liquid production where we are trying to set up an example in France of this kind of transformation plant from biomass to oil to gasoline. You have a lot of processes where you can use cogeneration to produce either hydrogen or heat in the process and to try to enhance the overall efficiency of the system.

Regarding this we have to match the electric demand on the grid while it is constantly fluctuating. This means that today our nuclear reactors are matching the electric grid by running, in a non-optimal way. They have to reduce their power when the electric grid reduces demand. When you are operating in a cogeneration mode you can run the nuclear reactor at the optimum, at 100% of capacity mode, and whenever the electric grid demand is reduced you can increase the heat production as compared to electrical production; and go to the cogeneration product, which can be a kind of flexible use of electric power. Doing this will enhance flexibility, because it allows either fast switching from electric production to the cogeneration production or if you have storage capacity, and if your cogeneration can be stored, as in making synthetic fuels, gas or in water desalination. This provides you a coping mechanism for dealing with the variable demand for electricity without having to add anything more than cogeneration capacity. As an example, let's say that you have a nuclear reactor feeding a district heating network in a city, then you just have to change your control valve to change the electric power output going to the grid, and the system transport line. Here is a system that can cope with days of storage as compared to electric power which has to be matched to the grid every few seconds or minutes.

Finally, just a few points in conclusion. Heat recovery from today's nuclear power plants for district heating or for low temperature industrial applications is technically available today. It improves the overall energy efficiency of the old system, that of nuclear power plants up to 80%. Improvements in technology allow for the main heat transport line, which has been the key economic factor of competitiveness of district heating, to transport heat with very low thermal losses over very long distances. Of course, such nuclear cogeneration provides one way to address decarburization of energy, because we really can reduce CO2 emissions by using more flexibility and energy sinks.

3.4 Cogeneration discussions

3.4.1 An initial set of questions was asked regarding cost, efficiency, reliability, and scalability of current and future distract heating systems.

Robert Budnitz: In a developed economy like in France, the principle investment for district heating has to be that of putting in the heat system into residences. How much does that cost? Is it prohibitive? Is it reasonable? As opposed to all over the old Soviet empire, which is now broken up into a lot of little countries, the principle cities mostly had cogeneration everywhere. Of course Russia and all those places in Lithuania and Estonia, were cold to begin with, so they installed such systems. But if you had to do that from it start in Paris for example, is it very expensive? How does the main cost compete with the way that we're heating today? How efficient has this system been in practice and where is current research heading? How reliable are these systems? How do you design the turbine system to handle a wide range of heat extraction rates?

Henri Safa: District heating in itself is expensive, of course, but the heat network is just like the electric network. You have sources, production, transportation, and distribution. Today in France the heat network is very small compared to, for example, other countries in the north in Europe. In Iceland for example, they have 100% district heating. In France it's only six percent today. The heat network is very little developed. The main cost is the transport line from the nuclear power plant to the city, not the final distribution system for heating in the city. In the northern part of Europe, for example, almost all cities have district heating, and their sources are mainly fossil fuel sources like gas. Currently such district heating is not carbon free. If you want to have carbon free district heating we have to have carbon free sources, like renewables, geothermal, or nuclear.

District heating can be competitive if you have enough heat to transport, because we are recovering waste heat. So the production cost is almost equal to zero. You have to compare the heat transport cost to the cost of energy that you put, for example, as gas going into the cities in district heating. District heating gains its competitive edge when you can recover and transfer enough heat to a distribution hub such that the cost of the transport line per watt is less than the cost of gas. It will always be competitive above a specific amount of energy transported. If you transport very little power of course it's not competitive, but if you transport a high amount of power it becomes very competitive.

In practice, these long transport heat lines have been used in Russia with hot water at temperatures between 90 and 120 C, which is the optimal temperature for transporting hot water. Russia has a lot of nuclear power plants feeding cities with district heating with the longest transport line about being 64 kilometers. However, because it was built in the Soviet era, the line has very high losses because of old technology, so it is not very efficient from the energy point of view. We know today that we could build these systems with very low losses. In fact you may compare it to long distance transport line with electric power at this time. So it can be advisable today to revise this solution of energy systems, comparing electric system and heat system in the country.

There are some research questions still to be answered, but there are no fatal ones, because this is already technically feasible. What you want is demonstrate that you can technically operate such a system by switching from one energy source to another; from heat to electric power and from electric power to heat. The second thing you want to demonstrate is that you can survie failures. Of course you need backups, and you must show how you operate when you have backups? The third thing is improving instrumentation, because for instance when you have a leak in your system, then people need to go and to dig somewhere to find the leak. With modern instrumentation you can have much better immediate localization of your failure in the system and better operation.

As for reliability, with our nuclear power plants, they have two nuclear reactors, and generally you need only one to feed the system. There is a chance that both reactors could be down, but that's maybe an event occurring once every 10 or 15 years. For that, we need to have backup fossil fuel sources using low investment or storage means that is not cost prohibitive.

The wide range of heat extraction comes from the fact that you are always generating heat at your initial power source and you are recovering waste heat. So, even if you extract 3 gigawatts of heat from your reactor, you can still be producing 80% of the possible electricity. We are not extracting steam from the system, but raising the condenser temperature and getting the hot water from there. This adds an additional system, and does not replace the need for cooling towers when running at 100% electricity.

3.4.2 Where can district heating be located and how well can the industrial heat be used? This part of the discussion has to do with whether the technology can be used in warmer climates for district cooling, and if new non-co-located facilities can address liability issues that made negotiating deals for industrial process heat difficult in the past.

Participant 14: How is the system going to work in a tropical or warmer climate where you don't have the big heating load, but you have a cooling load? Also, when you went to these cogeneration facilities in the U.S. in the '90s we had, "Qualified facilities," which had to provide at least 10% of the power had to be used for something other than electricity. The biggest problem was finding sites where you could find a manufacturer who would take this heat. I was in this business myself for some time. One of the big things that we ran across was we had to sign liability contracts with these manufacturers that we would provide that power and when we couldn't we were liable to give them money so they could buy it somewhere else. So, it became really tough negotiating these deals. So now I've got nuclear plants that are fairly isolated in America, trying to sell to manufacturing. Is that connection going to be a problem?

Henri Safa: I see the tropical question as an industrial one, it's not a site for district heating. For me it's not a problem to be in either warm or cold temperature. The only difference is that the efficiency of the electric power plant itself which is slightly different. So the technology is exactly the same if you are in Saudi Arabia or if you are in Finland. It's the same nuclear power plant. District cooling is another issue. In Saudi Arabia you will do cogeneration not for district heating or cooling, you will do it for water desalination, because they need water and this is a big problem. And you can take all the heat for one nuclear power plant to yield two million cubic meters of water a day via nuclear desalination. This is on top of the electrical production, which is an added value, an immediate added value of your cogeneration options. You also don't really need to provide the entire rejected heat to the system. You don't really need to extract 3 gigawatts, for example you can extract only 50 megawatts and still use the heat for the customer. It's very flexible. You can have as much heat as you want from 0 to 3 gigawatts.

There are lots of things I haven't spoken about, of course, the chilled water, the preheating. You can do a lot of things with different technologies. I didn't speak about, the use of the gas network that we have in France. One use of it, for example, could be in the case where you are producing hydrogen. Even with low temperature electrolysis you can inject the hydrogen in the gas steam, and this is called power to gas. And this is one way to use the electricity from the reactor in off power mode, when the demand is lower, in order to have another energetic product. This is a cogeneration model, where you couple the electrical network to the gas network. And so, this is also one possibility which is being looked at closely.

For the other question with the industrial coupling, that brings us back to the reliability issue that you need to be sure that you can have 100% delivery to your customer. So, the first solution, of course, if you have two nuclear reactor power reactors at one site, then you can switch when you are doing maintenance of one power reactor and you can bring the other power reactor online. Doing this makes the frequency of the double failure low enough in order to have a cheap backup system.

3.4.3 How has the technology changed that enables transmission of heat of hundreds of kilometers and can it be used underwater?

Participant 35: Could you say more about the technology that enables transmission of heat over hundreds of kilometers. What has changed since a couple of decades ago? Is it just better installation or is there another trick that we should be aware of? Can it also be done underwater?

Henri Safa: What happened in the last 15 years is that now you have these pre-insulated-lined pipe segments that are factory-built with the insulation on them. You can send them directly to the site to be welded, and the welding also must be better welding for use in the systems. This has really helped a lot to have very good performance when the pipes are put into the soil. You also have sites where about 40 years ago you would have 10% per kilometer of losses. Now you have one percent over 100 kilometers, so it's a huge increase. It's a step-wise increase, but this is a huge increase. These can also be used under water. In Iceland they are putting these lines above the ground systems, even when it's minus 40 degrees outside, so it has very good insulation.

3.4.4 R&D on storage and gas turbines technologies are part of the key goals of improving the economics and rate of installation of associated technologies.

Participant 32: You have both talked about the ways that nuclear can start getting at some of the energy problem beyond just baseload electricity. If we think about trying to grow nuclear on a scale that would be interesting for getting to a low carbon or a no carbon future, and we look at the decade before Fukushima, we were adding globally about three gigawatts a year to the grid. If we wanted to have enough nuclear to be displacing a billion tons of carbon from the system by

2050 we would have to be adding about 30 gigawatts a year to the grid every year from now until 2050 worldwide. So we have to convince the people who decide what kind of power plants to buy that nuclear is 10 times as attractive as it was before Fukushima.

So I'm wondering what things might happen with nuclear that might contribute the most to that objective. Can we imagine dramatic capital cost reductions? One of the things you're talking about is that we're going to get more revenue out of our existing capital cost investments. Is it safety improvements that will change public perception? What are the key R&D goals or institutional and regulatory goals that we need to look for in order to achieve this dramatic change in the rate of nuclear installation?

Charles Forsberg: The first observation is that any significant installation of renewables is going to crash the electricity price under high wind and high solar conditions, and raise electricity prices when you have zero wind and zero solar. And nuclear, because you can access cheap storage, is the main benefactor of that. In other words, you can raise the revenues. Also, there is a transition time before people adopt new technologies, but if you have a lot of wind or solar you will collapse your revenue basis, which kills off wind and solar, but it also creates a great opportunity. The central observation here is that thermal storage is one to two orders of magnitude less expensive than electricity storage. You can't afford electricity storage on a large scale. You can't afford Tesla batteries, etc. They are too expensive by an order of magnitude or more. They're just not in the real world. This is a luxury item for well-developed countries, for people who earn $150,000 dollars a year. That's the world they're marketing for. There is nothing wrong with the Tesla profit margins, but if you're going to have serious solar or wind it means that you crash the market. That means that you create great opportunities for low cost storage, but it's got to be cheap. All the cheap storage technologies run through heat storage, big heat storage, not small heat storage. That's where you win. You try to find more ways to get revenue out of your existing capital investment allowing you to buy low and sell high.

Now, the gas turbine is a different game. It's a more advanced technology today, where the gas turbine technology has advanced so incredibly over the last 15 years in a stealth mode, where nobody is even aware of what those guys have been to. It's a different game. But, the storage game is clear-cut. To win you've got to be cheap. And the storage technologies that we are talking about will take out batteries, they will take out compressed air storage, they will take out everything except maybe pumped hydro, and that's basically because they're a whole lot cheaper. You've got to have better economics.

Participant 15: I agree with you in terms of the most efficient way of doing it, and I was glad to see that you, also, in your presentation, Charles, included electrical to electrical conversion, which is the purest way both for the energy conversion. By doing that I mean you're dealing, with thermal conversion, one to another, you're dealing in minutes. When you're doing electrical to electrical you're dealing in sub-second intervals. Now there is an opportunity for nuclear also to participate in the grid services market as well. By doing the electrical conversion with the recent advancement in power electronics, this becomes feasible as well.

Charles Forsberg: The interesting thing about fire brick heat storage, of course, is that you can vary the rate of heat input in a fraction of a millisecond. It's basically controlled by switching speeds, which means if you have FIRES on the system, that it takes care of all the transients by varying the power level input, and the heat going in, not on the way out. On the gas turbine options, the interesting thing about these kinds of gas turbines is that the power increase can start happening in less than 50 milliseconds. It's determined by the travel time between the gas burner and the first turbine blade. That response speed, by the way, of these Nuclear Air-Brayton cycles is way beyond that of a standalone natural gas turbine, and it is way beyond anything that the Air Force dreams of. It has to do with the system geometry and the structure of these systems.

The wild card in this game is with the gas turbines, because, if you look at gas turbines of 40 years ago the utility gas turbines were achieving 20% efficiency, today they're at 61%. This is a technology that has slowly, because of billions of dollars of R&D investment every single year, that incrementally keeps improving, and everybody ignores it. Then, you look back and you say, "My god, what have these guys done?" And it's extraordinary and most people do not appreciate it.

Now, I mentioned utility gas turbines, which are 61% efficiency. The other place that gas turbines are using combine cycle plants are in chemical plants and big refineries where you have variable steam demand that is going up and down like a yo-yo, electricity demands are going up and down like a yo-yo, as you're selling and buying electricity to and from the grid. Those gas turbines having this extraordinary capability to vary steam use and electricity production very rapidly to meet chemical refinery requirements are also directly applicable if you end up connecting them to a nuclear reactor. So, there is a whole gas turbine ecology available from the refinery guys, the Exons and the BPs, that most even utility gas turbine guys have never heard about. Rather, it's a stealth technology, it's so boring. We only improved a half a percent this year. But, when you do this steadily for 60 years it's astounding can happen.

Participant 15: Two challenges exist with the gas turbine though. One, it is in an integrative environment with renewables such that if you have a deficiency in energy production, they can respond very quickly. The challenge comes when, all of a sudden, there is too much energy and you want to absorb it you can't. Thermal energy storage will help solve that. The other important thing with the gas turbine concerns avionics. The operators know exactly what it will cost for them to vary the power. So, they know how to respond when there is no market for them to compensate for greater output.

Charles Forsberg: That's why I mentioned the refineries and the chemical plants. To keep the chemical plants running they have to be able to go all over the operational map very rapidly. In doing this, they're building up the experience base for gas turbines combined cycle plants that can do incredible things that you don't see in the utility industry. That's because if one of your process units goes down your steam demand collapses. If you're doing startup it goes up rapidly. And so, there is an entire part of the gas turbine industry that is simply invisible outside of the chemical industry, but they're developing the technology to do these very rapid power ramp rates for reasons that have nothing to do with the electric grid.

3.4.5 Hybrid Energy Systems

Participant 16: A National Alliance for Coordinating Energy Research think tank was created in France in 2009, and has been appealed to contribute to decarburization scenarios. In fact, decarburization has really been a concern or an objective in Europe since the first Climate Conference in the 90's. The Europe Commission sets goals for carbon reductions, especially in 2008. They expressed goals especially for 2020 aiming at 20% reduction in greenhouse gas emission, 20% of renewable energies, and 20% reduction of energy demand by 2020. They have already been working on setting new goals for 2030.

In all of the scenarios there have been sources of inspiration for some national energy policies. I mean all the ideas that have been presented this morning for California have been considered, even to the extreme, such as in committing ourselves to cut greenhouse gas by a factor of four by 2050, or we are aiming at reducing the energy demand by a factor of two by 2050, with energy savings having been put to the extreme of acceptability, and electrification has been considered up to let's say the maximum electrification for cars. What I want to say is that in hybridization of nuclear systems, and we had two very good examples or matters for thought along this line, that are very important. Having an energy source that can make two different energy products, electricity plus something else, or having a combination of energy sources that could just augment the production of either appears to offer indirect solutions that could not be achieved using a single technology. I think that this is really a very attractive subject for further inquiries, not taking for granted the pictures that have been presented here. I think that hybridizations, combining energy sources in better ways, is a very attractive field of research to achieve decarburization without sacrificing too much of energy access or things like that. Of course the economy is the judge of what is achievable. So I'm very supportive of Charles Forsberg's work, for example, over the past 20 years, and we strive to take inspiration from it for some of the work we are doing in our think tank.

Participant 4: I wish to clarify that we don't need to have high temperature reactors in order to make hydrogen. We have shown that the high temperature steam electrolysis, carried out at 850°C, has plenty of heat to recuperate from the products, the hydrogen and the oxygen, in order to super-heat the incoming low temperature steam to get it up to about five percent of the temperature that we need. So you only need to provide a little bit of topping heat to sustain the electrolysis. This means that high temperature electrolysis can be done with anything that can produce steam, to just above saturation temperature. So whether that's from the back end of a natural gas combined cycle unit or a pulverized coal plant does not matter.

When you electrolyze water you obtain oxygen. That's a great source for oxy-fired combustion, so it opens up yet another market of clean energy, which is a natural gas combined cycle. This excess capacity that's in the system gives us an opportunity to set up a negative carbon source when we capture CO2 and convert it back into fuels. Three examples, co-electrolysis with steam works well, putting it through dry reforming with methane, so that without steam, we still must take care of the coking and the carbon dusting. This works quite well and would require those higher temperature reactors. However, the third is then using CO_2 to make methanol which opens up the entire world of chemicals.

3.4.6. What needs to be addressed in order for nuclear to succeed? This section focuses on advanced nuclear and uses the FHR as an example in addressing safety and risk, deployability, and regulatory and licensing concerns.

Participant 4: What do you think about reducing the risks of the high temperature reactors, and in particular the salt-cooled reactor? I know one small modular reactor being developed, a pressurized water reactor is about three orders of magnitude safer according to the company's calculations, via the conventional light water reactors. So will that go a long way in terms of addressing risk?

3.4.6.1 Safety and Risk

Charles Forsberg: First, the specific reactor that we're working on connects to an Air-Brayton cycle is a fluoride salt cooled reactor. It uses fluoride salt cooling and high temperature gas-cooled reactor fuels. A little history is required here. Salt, as a reactor coolant, was developed during the aircraft nuclear propulsion program in the 1950s, with the goal to build a nuclear powered bomber. So, the coolant was designed explicitly to couple to a jet engine. That was its goal. Now, the catch is, that jet engines used for power production were absolutely terrible in the 1950s. It has taken 50 years of gas turbine development to get a gas turbine that actually can couple to the 1950s salt cooled technology that was developed for reactors. So that's why this FHR concept has come up only recently. Salt coolant is not new. HTGR fuel is only 30 years old. What is new is the Air-Brayton cycle improving the performance.

Now, the economics, of course, are based on this ability to produce variable power and the most efficient device on the planet to convert heat into peak power. The safety case is relatively extraordinary. We think currently that we may be able to design a reactor where it's not possible to fail the fuel. The reasons have to do with materials, as usual. The fuel fails at 1650 Celsius. The coolant boils at 1400 Celsius. To give you a point of comparison, iron melts at 1600 Celsius. What that means is that with a medium sized reactor if everything goes wrong and everything turns into a pool of reactor materials, at the fuel still stays intact, in that case you conduct the heat out through the walls to the environment. You have over a thousand degrees Celsius temperature difference to drive heat to the environment. So you have a situation where the fuel survives the accident, even though the reactor is complete trash. Its safety case is based on a fuel with a failure temperature of 1650 Celsius. This gives you enough of a temperature drop to push the heat through the containment to the environment. So, it's a radically different safety case compared to any system that has previously existed.

Robert Budnitz: Let me try to make the case stronger than that. I spent some time studying, a homogenous fluoride coolant using the TRISO fuel pellets that GA developed for its gas cooled reactor. I still can't figure out how to engineer a radiation release. That's a really nice reactor, isn't it? If you can't figure out how to engineer a release, then you've got a really safe reactor. Even in a terrorism scenario you can't figure out how to get much of the radioactive material out, and that's great. The probability of release is not just orders of magnitude lower than those of existing reactors, it's close to zero.

Now, the question is whether you actually build such a reactor that will work, and can the cost make sense? We don't know either of those answers, and there is a lot of engineering to be done. But to start with a concept like that is a remarkable change compared to any other concept that we are now struggling to develop, like the advanced water reactors that you mentioned. Sure they're safer, but I can engineer a release pretty easily. But you can't do that with the FHR, right? So a system that I cannot figure out a way to engineer a release would be a major advance.

3.4.6.2. Deployability

Robert Budnitz: The next thing is to get something that has this ability to follow the load. The reactor itself doesn't follow the load, but the energy used can follow the load. Those together could make a qualitative difference. Finally, nobody is going to deploy a dual product reactor like this again, without having the industrial users deployed next to it. This isn't the case in our country, nor is it in France.

We only had one example of such a system in the United States, and it failed. In the '70s Dow Chemical Company in Midland, Michigan was going to build a nuclear plant—it never got built; that was intended to feed its chemical facility right next door. This was all part of the economic case. That's the only case we've only had in the United States of an actual executable plan, and then it failed for other reasons, which weren't related to what I just discussed.

In Russia they have a joint venture that would run the smelters, and the Canadians have talked about deploying CANDU reactors in Saskatchewan in the Tar Sands area. None of that has happened yet, but one could envision it. It's hard to believe that if we're going to have a lot of deployment of nuclear facilities around the world, that we're not going to deploy reactors near industries that are built for them.

Charles Forsberg: Oddly enough I grew up in a town having a cogen plant. It was coal, not natural gas, fired. A one noteworthy feature about it was that about half the town was district-heated from it. The other feature is that about three-fourths of their steam is now sold to industrial customers. What has happened over the years as part of the industrial recruiting program is that the plant has half-priced steam, because it has this cogeneration capability. So, what happened over time is that the plant's complex has evolved into an industry of low priced steam. So, people and companies moved there because of the cheap steam. And, of course this is in the rural Midwest, which basically means evaporation of milk, a couple of million gallons a day of milk. Doing this requires an awfully-large amount of low temperature steam. But it's agriculturally based. If you have low cost steam for many industries they will come if the price is right. There are several cases in the Midwest where people who had cogen plants since 1910, 1920 have built up a local set of industries based on "We have cheaper steam than you can generate." So, there is a model out there that people have used and can imitate.

3.4.6.3. Regulatory and Licensing Concerns

Participant 17: Going to your points that you just made about the safety aspects of the TRISO-coated particle fuel, and that you could not engineer a release from it; that fact is currently causing us some difficulty, because the licensing basis of all reactors licensed in America right now is focused upon how to protect against a massive meltdown of the fuel. Here we present the regulator with the case of a reactor that will not melt under any known circumstances, and where we have yet to come up with a good design basis accident by which the NRC will allow us to license it. I think that this goes to the previous question as to what types of original breakthroughs do we need in order to move forward with nuclear energy. This is the sort thinking that we need in order to advance further concerning these advanced designs. They present us with not only opportunities but challenges that we have not considered before.

Robert Budnitz: I have no doubt that a principle impediment to some of these advanced reactor designs coming true is going to be regulatory. It is an impediment, not an intellectual impediment, but a practical impediment in terms of time, schedule and actually doing things that could help rather than hinder the cost of management. There is no doubt in my mind that this is true. I also have no doubt about the following very sad fact. There isn't a single regulatory agency in the world, including ours, that is taking that challenge seriously. The French aren't. We aren't. The British aren't. The Russians aren't. Nobody is. The general approach is to try to license those plants by using the current scheme with some small exceptions, and that is sadly going to be an impediment to the deployment of all these advanced reactors. It's a terrible thing to say, but I'm convinced of it. It's ultimately a question of having the will to get out in front of, rather than waiting for the designs to mature and then responding to them.

Participant 18: I take a very different view on this. The NRC is not funded to look at advanced reactors. That's simply a fact of life. The NRC does have a program on developing the licensing basis for the light water SMRs. It's when we go to the advanced non-light water that there is very little activity. The main reason is that the NRC is funded 90% based upon fees. Those fees are derived from the operating commercial companies, and the companies paying them frequently remind the NRC that it is important to reduce those fees. The companies are not, at least up to this point, interested in the NRC pursuing advanced reactors.

The current legislation requires that 90% of the NRC's funds be recovered from those fees. The remaining 10% is used for homeland security activities. To me, the answer to what Bob said, is that there needs to be a change in the funding formula from the Congress. The Congress needs to tell the NRC that advanced reactor licensing is part of their job, and for them to be paid to do it. However, until they're paid to do it I don't think it's going to happen.

Robert Budnitz: I agree with you 100%. I wasn't blaming the NRC, but I am going to blame them a little because the initiative could come from the NRC more strongly than it has. By the way, it's not just a problem with the NRC. This is true in each of our countries. In all of the countries where this is going on, none of them is working along these lines sufficiently. It's a sad tale about chicken and egg, and who has got to do something. Do you lay the chicken or lay the egg? It's really difficult. I understand the dilemma.

Participant 19: I would agree with your comments, but I have been recently interacting with the nuclear regulators in Canada, and there the situation is a little bit the opposite. They have a whole team that is working on preparing a licensing methodology for modular reactors. There the problem is that they have no modular reactor vendors who are interacting with them. I know from my discussions with the head of that team that they're considering canceling the program, because there is nobody interacting. It's an unusual case, but it shows that the problem is on both sides. The Canadian program is not restricted to LWRs, but still they don't have somebody knocking on their door saying, "Hey, let me go through the licensing process." So if anyone is developing a small reactor and looking for a place to license it, go there.

Participant 20: I agree with the remarks defending the NRC. The industrial focus right now, is on reducing the fees, the regulatory burden from the NRC. The nuclear industry though, is interested in advanced technologies. There is an advanced reactor working group at Nuclear Energy Institute (NEI). However, the NRC is not in a position right now to license in a reasonable timeframe, a commercial advanced power reactor. But, NEI is looking at ways of licensing through the NRC, a demonstration machine, possibly using the research and test reactor route at NRC.

The utilities are looking at this in terms of maybe having a demonstration reactors operating in the 2025 timeframe, one that doesn't generate electricity, with commercial deployment occurring in the 2035 to 2040 timeframe. We are beginning to think about how the regulatory process needs to change for enabling the broader commercial machines, addressing the issues that have been brought up here. A phrase that I've heard before from some folks is too safe to license. That's a real challenge.

Participant 3: I'm struck by the fact that the conversation is all prospective, looking about what could be done, when in any realistic look at the U.S. particularly, the relative role of nuclear in a low carbon economy is more likely to decline, not increase. So, with the licensing issues the nuclear cliff is very real. If you look at most of the economic projections, they show that plants will be shutting down at a faster rate than they will be coming online. So, the total net production of nuclear energy will go down. That's the nuclear reality concerning carbon. One must deal with that reality first. In fact, nuclear's role in society will likely be that of increasing the carbon challenge, not mitigating it? What are the steps that could be taken to actually reverse that? It seems to me that the amount of effort being put towards maintaining and extending the existing fleet as well as licensing advanced designs is small compared to the scale of what is required. It may be a little better in China, but the relative global prospect is not much better.

Participant 18: First, there is a strong national program in reactor sustainability in the DOE. There are several companies that are at least exploring the possibility of licensing beyond 60 years. And we have been developing, at the DOE together with the NRC and EPRI, a far better understanding of what it would take to go beyond 60 years of operation. At least I hear rumors that by 2018 we may start to see companies applying to go beyond 60 years. The other point is that the light water small modular reactors are extremely important. We're looking towards the first license application to be filed next year, and targeting 2023 for deployment. The importance of maintaining the existing fleet is not lost on the current political administration. Their climate action plan recognizes that the loss of any zero carbon power source only complicates the global climate change problem of the country. So, these are activities in process. It remains to be seen if we'll be successful. I don't think industry would view those as small efforts at all. Those are quite substantial. And, the interest of industry through EPRI in the light water reactor sustainability program has been substantial. It's a cost-shared program between the government and industry. I don't view it as a small program; I view it as a very successful program.

Participant 21: Basically, I think that if nuclear and the renewables are to coexist then some way such as the hybrid systems illustrate has to be found and made workable. This is true more for the renewables than it is for the nuclear plants. The real question for the renewables is would you like to try to save the planet without nuclear? Some people will gladly say yes. Others might wish to hedge their bets. But that's what it really comes down to.

On the question of regulation and acceptance of the nuclear ideas I submit that, this is a social decision. Basically, as long as saying no to nuclear is a low cost decision, then people will say no to nuclear. They have been doing it for quite some time. The way to think about a renewable and nuclear combination responding to climate change has to be within the context that society really cares about their effectiveness, and that it's going to protect them as options.

One thing that you learn eventually is that you're almost always wrong about the future, but at least it makes some sense that people could begin to care. If they do, then the way in which these safety questions are faced and the way that the regulatory system is supported to function could also change quite a lot. Should that happen the good news is that the regulatory paralyses problem will have largely been solved, at least conceptually. The NRC itself has experimented with the technology neutral regulatory framework, for example, using risk concepts, so the basis for improvement exists. There is work that has to be done to make such change a practical reality, but in the context of an acute international problem this is something that can be dealt with.

SESSION 4: Strategy for Synthetic Liquid Fuels / What Are the Options for Liquid Hydrocarbon Fuels with Zero Net Carbon?

4.1 Session Question

What are the energy markets for which synthetic hydrocarbon liquid fuels are likely to be essential? Are there more than three options for zero-carbon hydrocarbon fuels (biofuels, fossil liquid fuels with atmospheric CO_2 recovery and sequestration, CO_2 from atmosphere or other sources with conversion to liquid fuels)? Are there any credible non-carbon zero-carbon transport fuels (NH_3, etc.)? Can biofuels meet the needs?

4.2 Introductions

Michael Pacheco: The two talks today are primarily on biofuels, but in the remarks introducing this session (above) there is a wider set of options—some that we will discuss later. Those other options, including hydrocarbons from carbon dioxide and ammonia, can use stationary energy sources including nuclear for fuels production. With that, I introduce our speakers, Lee Lynd and Bruce Dale.

4.3 Presentations on Liquid Fuels

4.3.1 Biofuels and Climate Change Mitigation: Need, Land, and Development: Lee Lynd (Dartmouth College)

I focus upon biofuels. If you want a source of zero-carbon or near-zero carbon hydrocarbons, you want to look at nature's income (biofuels), as opposed to capital (fossil fuels) with respect to hydrocarbons. Biofuels provide a low-carbon liquid fuel option because CO_2 is extracted by plants from the atmosphere, converted to liquid fuels, burnt, and returned to the atmosphere with no net change in atmospheric CO_2 levels. In the case of biomass one needs to consider need, land, and development.

There are five fairly prominent low-carbon energy scenarios (Figure 4.1)—the International Energy Agency Two-Degree Scenario, the Global Energy Assessment Efficiency Scenario, compiled scenarios from the IPCC, the ECOFYS World Wildlife Fund Scenario, and the Greenpeace Energy Revolution Scenario. On average in these low-carbon energy scenarios, 25% of the primary energy is provided by biomass in 2050. That amounts to about 140 exajoules per year.

Most people who look at trajectories that would lead us to a low-carbon future find it extremely difficult to do so without biomass—even though they start with the goal to run the world on everything but biomass. These scenarios generally assume large-scale use of batteries (electricity) and hydrogen in the transport sector, but end up with about half the transport demand met by biofuels. If you decide to meet this demand with fossil fuels rather than biofuels, you produce about twice the allowable greenhouse gas emissions that would meet the 2°C limit in global climate change.

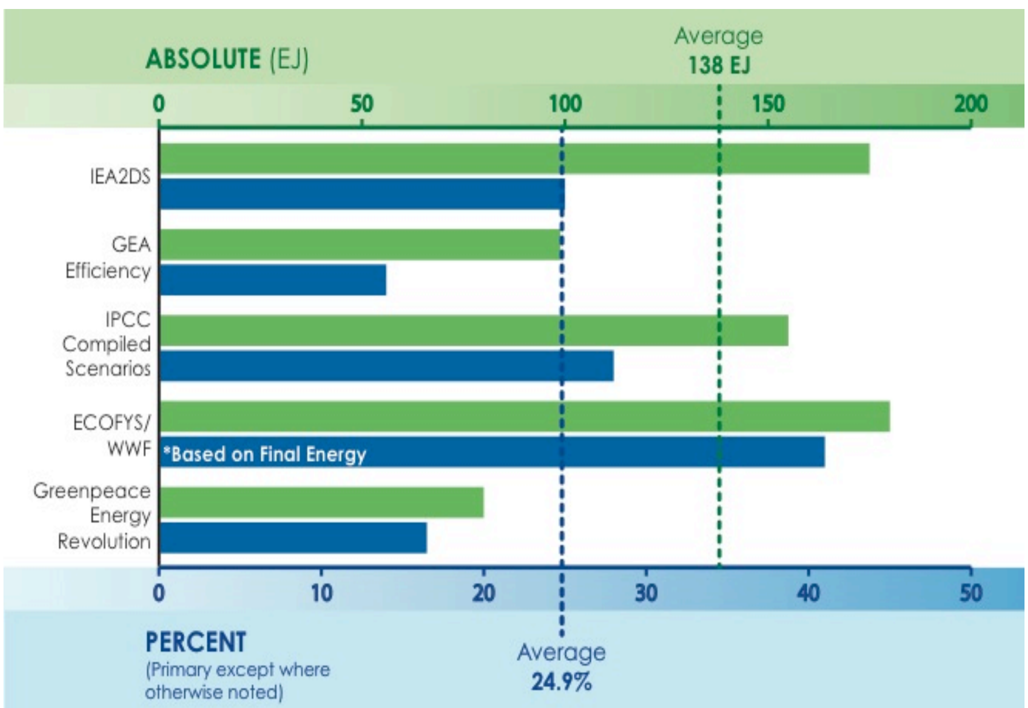

Figure 4.1. Potential Contribution of Biomass to Meet Low-Carbon Energy Needs Based on Five Independent Studies[16]

Global sustainability is dominated by two big systems: energy and land. If one thinks that one can solve the climate challenge by looking only at energy, they are probably wrong. The largest lever

[16] Bruce Dale et al., "Take a Closer Look: Biofuels Can Support Environmental, Economic and Social Goals," *Environmental Science and Technology*, **48**, 7200-7203, 2014

is diet—it's actually not the amount of meat that people eat but the kind of meat. Soil and biomass are massive carbon storage sinks. Thus, land use directly impacts atmospheric carbon dioxide concentrations. Not surprisingly, if you add bioenergy into the middle of that system you can get both positive or negative outcomes. I believe most people would agree with that.

The good news is that the cost of lignocellulosic feedstock ($20-100/ton) is sufficiently low that biofuels are potentially competitive with fossil liquid fuels (see Figure 4.2): However, there are conversion costs where there are many options. While conversion costs are competitive with sugar and starch feedstocks, they are not currently competitive with lignocellulosics or algae.

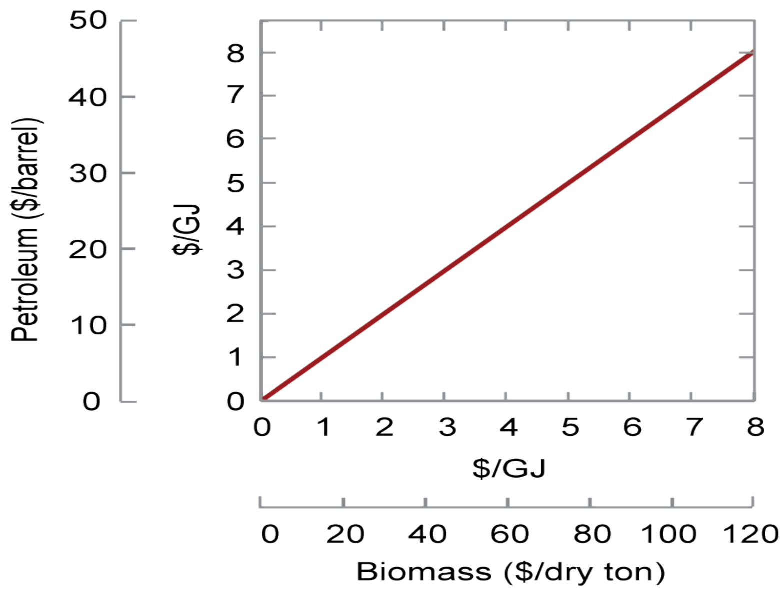

Figure 4.2. Cost of Biomass Feedstock vs. Price of Petroleum

There is a widespread consensus that biofuels and bioenergy will be needed in substantial amounts—on the order of half of the transportation demand in a low carbon world. There is plenty of land for food and large-scale bioenergy—but there are important issues concerning whether we will use the right land for the right bioenergy. The climate change impacts of land use, including diet-driven changes, are of comparable and perhaps larger magnitude than are those of biofuels. Measures are necessary to make land use part of the solution to climate change; e.g., placing a value on agricultural emissions. It is reasonable to assume that we can develop cost-competitive biofuels; but this will require R&D-driven innovation and investment. Finally, perceived risks of action have prompted the world to turn away from biofuels and bioenergy to a significant extent in the last five years. However, the risks of inaction appear, at least to me, to be substantially greater at this point than the risks of action in light of the anticipated need for bioenergy and biofuels in a low-carbon world.

4.3.2 Biomass Fuels Imply Rethinking Agriculture (Bruce Dale, Michigan State University)

I would like to start with an observation. One of the reasons that I think we do not get much traction within this U.S. political system about climate change is the fact that, whether we as scientists recognize it or not—the person in the street understands very well that if you cut off their access to energy, they're going to be poor, a lot poorer. Imagine yourself, or ourselves, without abundant energy. Without it life changes. The rate of energy use, which is the rate of work done, largely determines both national wealth and opportunities for human development (Figure 4.3). This is very simple, it's basic physics.

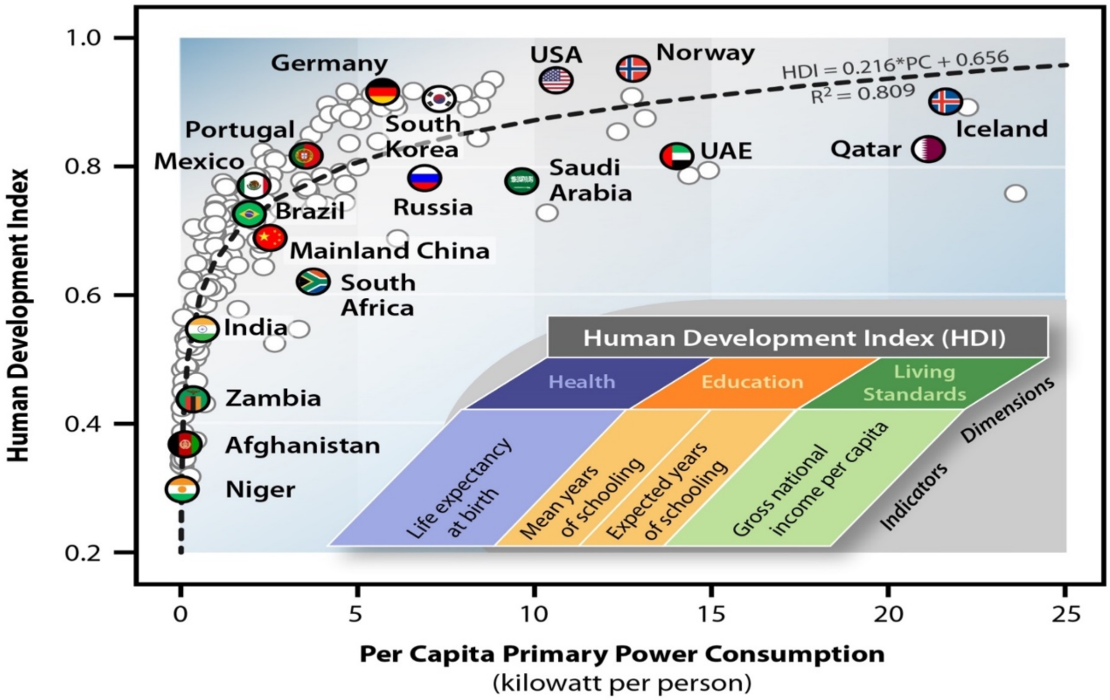

Figure 4.3. Human Development Index by Country vs. Per Capita Power Consumption in 2010

Ninety-three percent of the variation in per capita wealth production can be explained by per capita energy use, work being done. And yet, this is almost not part of the discussion, how important the use of energy is to the rate of wealth production, to prosperity. Do we become more prosperous, better off with the more energy we use? To a point the answer is yes, and then no. Consider Figure 4.3, on the Y-axis is the human development index (HDI), a composite measure of life expectancy, health, education, and standard of living. On the X-axis is the per capita primary power consumption. There is good news and bad news. The good news is that our lives get better and better with the more energy that we consume—up to a point. The bad news is that it levels off at about four to five kilowatts per person. So, do a little math. For a world of 8 billion people we will need 32 terrawatts—about twice today's energy consumption rate. It also implies a large demand for transportation fuels—can that demand be met with biofuels without major impacts to food production?

I have never obtained a good answer to a question that I did not ask correctly. The question that is traditionally asked is can we impose a really large new demand for biofuels on the existing agriculture system that doesn't otherwise change? Do we want it to keep doing everything that it's always done, and give us a terawatt or so of liquid fuels? That is not a realistic expectation. We designed our agricultural system to do something else. What we designed it to do is provide animal feed—as I discuss later. To assume that we do not have to change agriculture is tantamount to saying I am going to take by gulf cart and enter the Indianapolis 500 race and expect it to compete. A gulf cart's perfectly good for getting around a golf course. It's not good for winning the Indy 500. Likewise, your Indy 500 car would not be welcome on a golf course. Not because it's not a vehicle, it is; but because it was designed for a different purpose.

I am one of those who believe that agriculture should change, it must change, and it needs to change. Farmers are the key to that change. Now we have a big opportunity to change agriculture for the better, and provide much more sustainable fuels. We call this *Biofuels Done Right*.

We do not primarily grow food for human consumption—we grow animal feed that uses about 80% of our total agricultural land (Figure 4.4). About 56% is pasture, range, and pastureland—that is unarguably feeding animals. Human beings do not go out and graze that land. We send out a cow, goat, sheep or some other animal to graze that land.

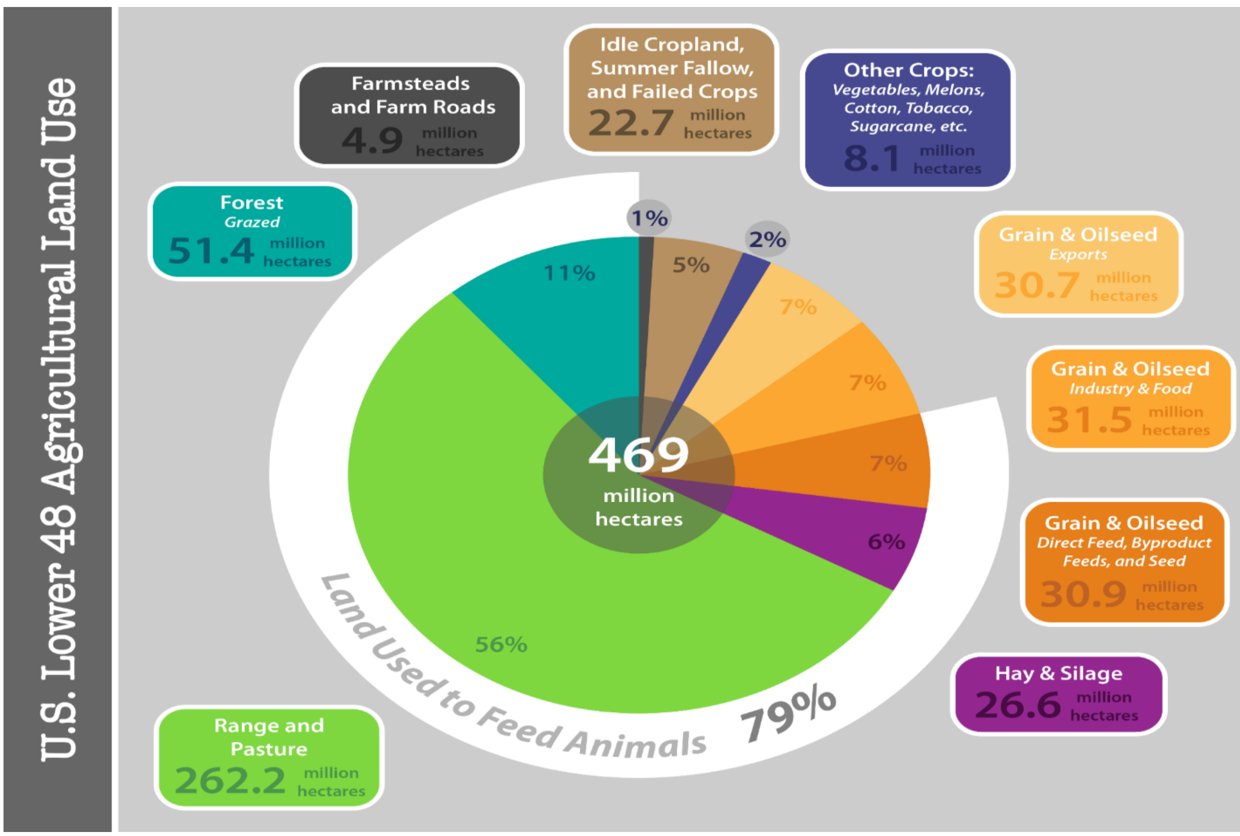

Figure 4.4. Land Use Patterns in the United States

As Lee stated, it's really the kind of meat, not the amount but the type of meat that determines how much land is used. It's primarily beef cattle. Like human beings, animals need two primary food macronutrients—protein and calories. If you add it all up, U.S. livestock consumes almost 12 times as much protein as humans and 5 times as many calories.

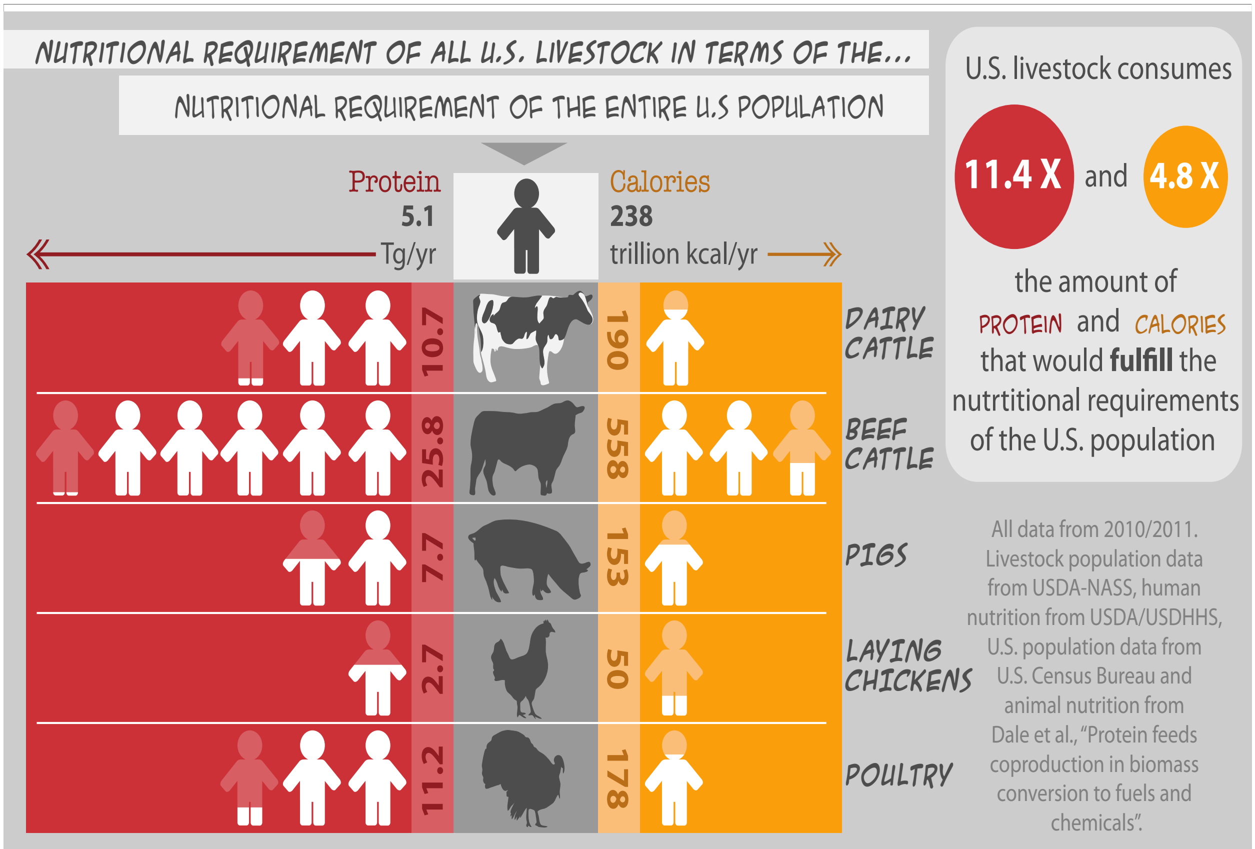

Figure 4.5 Nutritional Requirements of Humans and Animals

We do not primarily grow food, we grow animal feed. So if we want to integrate biofuels production and food production to their mutual benefit, we have to approach it through this lens of feed. We need to think about how to provide the same amount of feed, or change diet (and we should do that). So five years ago we published this article called "Biofuels Done Right" with the subtitle "Land Efficient Animal Feeds Enable Large Environmental and Energy Benefits"

A major part of changing agriculture is the use of cover crops and double crops. Much of U.S. agriculture is producing corn for animal feed—a warm weather crop that does not do well until the weather really warms up—like late May and early June, It grows and matures by late August/early September. So it's useful for solar energy collection in June, July, and August. There is a big photosynthetic window before and after that crop—the idea is to use that time for a second crop—double cropping. So why aren't farmers doing a lot of double cropping? The answer is that there is no market for it. If you drive through the Midwest in winter you will see the weirdest ecology in the world. All of that land brown—just dirt or stubble. Planting a double crop would help increase photosynthetic production, hold onto soil, provide additional carbon in the roots, scavenge nutrients, and maybe reduce spring flooding. If we used about 30% of the cropland for double cropping, it would reduce atmospheric carbon dioxide by 700 teragrams per year (10% of U.S. emissions), increase soil fertility and reduce nitrogen and phosphorus losses by 75%--with food production remaining unchanged.

There is an example of this. About five years ago the Italian government passed a feed-in tariff for electricity that allowed farmers to make an economic case that they could take to their local banker and get the economics to work for them. They now have about 1200 biogas plants with a total output of about one-gigawatt of electricity capacity and 12,000 new jobs and use a quarter-of-a-million hectares of Italian cropland out of 6.5 million hectares of farmland. Each plant has a capacity on the order of one megawatt.

Here are the principles they follow. Grow your regular crop for food or feed—same production as before. Then grow a double crop to feed their anaerobic digesters—their energy crop. They add manure and other locally available waste materials—all that generates biogas to typically fuel 1-Megawatt generators. The waste heat from electricity generation is used to keep the digesters at 37-40°C—optimum temperatures to maximize production. They take the liquid after digestion (typically 70 days) and put back on the fields to reduce fertilizer demand. They till in the solids residue resulting from digestion. They have seen rising soil carbon levels and something like 20% increase in the productivity of the fields they have treated. It's all about improving profitability—partly by reducing expenses.

If the incentives were for liquid fuels, systems would be modified. The central need is the need to start incentivizing and involving the farmers to produce bioenergy but do it sustainably.

4.4. Liquid Fuels Discussions

4.4.1. Biofuel resources are potentially available and competitive relative to crude oil because the feedstock is cheap. The question is whether we will develop the required technologies and policies.

Lee Lynd: There was recently a paper by Creutzig, et al. Felix Creutzig was part of the IPCC discussions, which were very contentious. The authors, Tim Searchinger and André Faaij said there was strong consensus that up to 100 exajoules of bioenergy could be produced globally. The scenario that I presented had about 50 exajoules for transportation fuels, which is clearly one of the areas that's the hardest to meet in a low-carbon world with non-biomass sources. So from a resource point of view, biofuels is doable. From an economic point of view, the raw materials are very advantageously priced compared to crude oil. We haven't talked about the conversion technology, but, given the time, I'm certain that it can happen.

Bruce Dale: We have the land to make all the sustainable biofuels that we want and most of it is under cultivation. It's a matter of using it more effectively and more efficiently. Add to that diet changes that I think we need to make anyway, I think that we can have all the sustainable biofuels that we need.

Bruce Dale: What I think is new in the biofuels area is using part of your land to provide feed for digesters to produce biogas. Most of the anaerobic digestion systems that I'm aware of are used to treat manure and other wastes with biogas as a byproduct. Farmers don't actually grow anything deliberately for conversion to biogas.

Participant 3: So what's the net added value to doing that versus using the manure directly as a fertilizer and a cover crop?

Bruce Dale: One way of expanding biofuels production is to start growing crops specifically for the anaerobic digester. But this is done as part of an integrated system where you take the digestate back and put it on the land to reduce the amount of fertilizers that have to purchase. It is a method for efficient recycle of plant nutrients and a way to build up the organic matter in your soil.

Participant 3: There are millions of farmers in India and China that are doing that today. I mean, there are well-established systems for doing that, getting biogas, bringing it back.

Bruce Dale: From the time a farmer decides to install one of these anaerobic digesters on a farm, it takes four months to have it up and going. That's the quickest installation for a renewable energy system that I'm aware of for large scale use. It's the farmer's land. If he chooses to do it, he'd get it done in about four months. But it gives farmers an incentive to use their existing land more sustainably, because they plant the double crop, the cover crop, and that benefits the whole system.

Participant 3: The main point is that I don't think it's as radical, which is good, as you suggest. Rather, it's a question of looking at past patterns and recognizing that.

Bruce Dale: Here among this group of people, I would hope it would affect your thinking more. I hope all of us would think more about why it is, why it's so important to have energy to use.

4.4.2. How should biomass be used? We have choices in how we use biomass: transport fuels, production of electricity, heat, and sequestering of carbon dioxide to enable continued use of oil in a low-carbon economy.

Participant 3: Today the largest use to bioenergy is not for liquid fuels or for electricity. It's for processed heat (paper and pulp, etc.). It's the single largest source of renewable energy in the US. But the conversation at the highest levels of government and industry hasn't been of the three different ways you can use it, of how you balance it and how you make it into a portfolio that's sustainable with time. I do think that the industry has missed it—a lost an opportunity to see it as having three different uses. You should ask how do you balance it geographically.

Michael Pacheco: If you look at the amount of energy produced by biomass today, including the small uses, it exceeds the sum of all of the other renewables put together. It is almost equivalent to the sum of all the other renewables put together, plus nuclear. It is in the order of 95% of other renewables and nuclear combined. It is something that happens, softly and quietly and unrecognized.

We have ample supply of biomass for transportation. The big strategy question is, does it make more sense to use it for electricity or for transportation fuel, or possibly what's the right percentage and combination.

Participant 22: Biomass can be converted to liquid fuels or into electricity that is used to electrify the transport system. Both options are viable, but which is better? At this point, we don't know.

But what the market's starting to do is take us down toward a path with more electrification of the transport system. Once again, economics will come into that and tell us what is the best use is. There are some things in the transport sector we are not going to electrify. We're not going to electrify airplanes. We shouldn't draw the box around too close in terms of biomass and how it can help us.

Lee Lynd: A reasonable estimate for the amount, the fraction of mobility in a conservation-intensive scenario, for the difficult-to-electrify parts to the transportation sector is about half. At this point that's a reasonable estimate. We recently published a paper in *Proceedings of the National Academy of Science* that looked at how far you can drive on a ton of biomass converted to electricity, versus liquid fuels. That's not the only metric, because economics comes in, as has been pointed out several times.

The short answer is for light duty vehicles you can go about the same distance, although it will probably cost you more to store the energy electrically than as a liquid fuel. For heavy duty vehicles, it's much better to use a liquid fuel than batteries. All arrows point to liquid fuels if you're going a long way or you have a heavy vehicle, it's just much easier—but all transportation is not the same. There's a lot of scope for things other than bioenergy for many transportation modes. But for some of them, the alternatives are very difficult and expensive. And there's a huge risk that we'll simply not use low carbon alternatives because diesel's such a good fuel.

Participant 7: We examined the costs of vehicles using biofuels or electricity. If you think that $25,000 is the average price for an internal combustion car that can burn ethanol, and a Chevy Volt costs $40,000, that extra $15,000 allows you to spend a lot more on fuel. We look at and say that electrification increases the cost of a car by 30%. But you can increase the price of fuel a lot more and still be economical and not pay that extra capital cost needed for electrical solutions.

Economics really favor biofuels if we reward the options similarly. We're subsidizing batteries and other such options now. But, you have to bring the cost of batteries down to $3,000 or less in order to be competitive. So, you could easily double the price of fuel, and be competitive. I think biofuels are easily in that sort of window.

Michael Pacheco: That comparison doesn't even include the work that the original equipment manufactures are doing to get the weight of the vehicle down in order to improve the efficiency—in addition to a roughly a 30-40% improvement on the thermodynamic efficiency of the engine. Those advances favor biofuels relative to electricity for vehicles.

There are many people who really don't believe that it's a good use of biomass to produce electricity. I'm not saying that that's been decided, but I can tell you that there are two strong camps on that. There are those who think that it would be a tragedy to convert biomass to electricity when we haven't yet solved our transportation problem. But I also view this sometimes as a physicist's bias in the whole energy business. The energy discussion is mostly dominated by people from a physical background, and agriculture is viewed as something over there that tends not to use high temperatures and high pressures and fancy gizmos.

There is possibly a fourth option, synthetic liquid fuel that could be made from that very low value electricity that's being produced during the peak periods when there's low cost wind, low cost solar, and when we don't really want to shut down the nuclear plants or turn them down severely. It's a very intriguing challenge for the technical community.

Participant 22: If you were going to design a fuel from scratch, you'd end up with diesel fuel. The other consideration for biomass is processing costs, which I think is a big difference. However, if you convert to electricity first, you can capture the carbon and have negative emissions while you're doing that as opposed, in the transportation sector to putting the CO_2 back into the air. Doing that can make a big difference in the overall cycle of the economics.

Lee Lynd: There is good evidence that fuel production can be a better business economically in terms of conversion cost. You are right, that if you do stationary combustion, you have an opportunity to capture all of the carbon. It's also true that if you do fermentation of biomass to fuels, you have an opportunity to capture pure CO_2. The cost of carbon capture and sequestration from fossil plants is very high because of the cost of capturing and separating the CO_2 from the off-gas because normally you don't get pure CO_2 out of a combustion process. Some of the biofuels processes are the low-cost option for capturing CO_2.

Participant 23: There are many schools of thought in the United Kingdom about biomass as a fuel versus burning it for electricity. Their big idea is to burn it, to put the CO_2 under the ground, to take the credit, and then to burn diesel fuels in cars.

Participant 24: Participant 23 made a key observation. If you have any biomass system that allows CO_2 sequestration, you may end up pumping oil out of the ground for the next 500 years, and burning it as diesel if you've got a method to take the CO_2 out of the atmosphere. It may be that the biofuels business is not primarily a bio*fuels* business. It may be a CO_2 removal business, so that you can burn diesel fuel, the good stuff that comes out of the ground.

Participant 3: Changes in land use can have major impacts on atmospheric carbon dioxide levels. In the U.S., land use shifts that occurred in the 19^{th} century are providing a 13% conservative offset to fossil fuel emissions today as farming has shifted from the east to the Midwest and early farmlands have return to forests. Land use is not static—how we use it can have big impacts on atmospheric carbon dioxide levels.

4.4.3. A central question is U.S. staying power in research, development and policy

Participant 14: If the climate problem is looming out there at the level that we think it is, and given the statement that was made this morning that we should have started this 20 years ago, and that we've got, 25 years to scale up the smaller, very exciting, interesting first steps, do we have time to take a lot of little first steps, given the clock is ticking on this issue?

Second, what's the big research question? The thing I keep coming back to is, we have no staying power in terms of R&D in America. I've seen five or six different technologies come and go. In biofuels, everybody embraced it in 2007. This was going to be the answer to everything. There was absolutely unanimity among the different stakeholders. Today, that consensus is gone. And there are discussions about getting rid of or amending various incentives to use biofuels. So all the momentum saying biofuels was an answer is dissipating. And we're going to have some other new answer in a year or two, and we're all going to embrace that for three years. So how do we convince our political system that it takes a sustained 10-, 15-, 20-year effort if we're really going to make some inroads in these technologies we've been discussing today?

Michael Pacheco: It's not coincidental that 2007, in addition to all of that interest in biofuels, was the first time when we broke the century mark on the cost of crude oil. It's not so surprising that this year, when we got oil prices back below $50, that all of the major oil companies started to immediately cut back their investments in that area. So I wonder how much luxury and how much flexibility does a large energy company have to stick with a technology that's probably not going to impact its bottom line for the next 20 years.

Participant 23: BP has been arguably the most forward and engaging large energy company in biofuels and in renewable approaches, in general, and has been investing a lot of money. It is in the order of $12 billion over the last eight years—so what's $12 billion to a company like BP?

Two things happened. One of them was the big accident five years ago in the Gulf of Mexico, which has been an existential problem for BP that has cost about $42 billion. What really happened is that BP got out of LC ethanol recently because of the fall of prices from $110 to $45 per barrel of oil—its major product. If you're a big oil company, you've got a large capital expenditure list and you are always throwing things out at the bottom. You throw more things out at the bottom when you've taken a threefold hit in your business.

Lee Lynd: We need a sustained R&D effort that spans innovation. Instead, we've had a real attention deficit disorder collectively. Sometimes we'll emphasize R&D and then we'll cut it. This is not very effective. Industrial scale operations require learning by doing.

We tend to allocate money very unrealistically. Someone mentioned public/private partnerships before. I don't think we've done a very good job in the bioenergy area. For example, in the case of ethanol, it already works from easy substrates. So, the obvious next thing is to do lignocellulosics. In the case of non-ethanol products, none of them works very well from even easy substrates now. So, from a commercial point of view, if you want government and innovation to cluster around something, you focus on the molecules that you don't know how to make yet from easy stuff to work with. You can't do too many new things at once. So, you focus on the molecules that you know how to make, and have a market for. You tackle lignocellulose. Actually, the US has largely abandoned that approach, after we had gained the world's leading position in it. Most companies will tell you that if you want to do lignocellulose, you should go to Brazil today. You should not waste time working on this in the United States, for all sorts of reasons. So, we're throwing away a leadership position.

In terms of policy, we need to recognize realistically what does and does not motivate industry. The renewable fuel standard, whether we change it or not, doesn't move industry's needle. I've had this conversation with many people, and investors saying, "Let's see, in order for this to pan out, I have to have ten years of constant government policy." That's discounted to a fare-thee-well. But that's the current idea of how to drive this from a policy point of view. It's not taken seriously by the people whose investment that this approach is trying to motivate.

Participant 36: If we want to look at a consistent government policy on funding R&D, the shale oil and fracking developments have been a tremendous success. But one good question to ask is, why can't further innovations in the biofuels or in the zero carbon energies be based on the type of environment where that was created. Consider the Aerospace Board in southern California. This is another example of a private/public partnership that has been fairly successful for over ten years. These things can be done; it's just that you have to create the environment that makes them work.

The large abilities for industry to handle fuels are in the form of the liquid hydrocarbons, the diesel, the gasoline, and the more portable natural gas versions. If you want to create something that people will adopt right away, that is by far the best set of molecules to synthesize.

And it's not like we haven't seen any companies that are able to do that. I don't know if you're familiar with Cool Planet Biofuels. I've seen their apparatus working and it's very interesting. From the point of view of creating a company, create a company based upon something where people can buy the product right away. It just makes for a happier company.

Participant 3: One of the challenges is that there's been an overpromise, and there's now a reaction to it. If you look at the history, there have been so many outlandish claims made about the role that bioenergy can play. Then you've seen the pendulum swing back. I encourage those who are in the field to be more moderate in the predictions and accepting of incrementalism.

I've been in meetings at the highest levels of government where big claims for biofuels get made, and it ends up, of course, failing. Rather than seeing biofuels as a Pacala and Socolow "wedge", or a half a wedge, instead of saying this is an important contribution, and we can make it, I think the whole biofuels issue has just been polarized by making extreme claims. And then, you have all of the secondary effects, whether that be land use issues or competition for land, et cetera.

***4.4.4. Conservation across the board is underestimated as a method to reduce energy consumption and biomass for fuel and other purposes*.**

Participant 11: If you go back to the global energy demand curve that Bruce Dale spoke about, the most terrible thing that could happen is if all those developing countries were aspiring to use 4 kW per person-as is much current in the western world. They don't need to get to four; they only need to get to two. This is because as we're using it; half of the energy wasted. Half of what I do at home is wasted, compared to what we would do if I were building my house anew.

Bruce Dale: Yes but the U.S. is at about 11 kW/person on that scale.

Participant 11: No, I'm not arguing that case. I want to try to say something important. My house is a sunk investment, and it's much more expensive for me to improve the energy efficiency of my house than if I were building a new one. These people are going to come into the world's energy economy for the first time, billions of them. It'd be insane if the world as a whole were to let them waste energy the way that my house, which was built in 1900, wastes energy. The same thing is true with my cars and how I design cities.

In most cities nobody walks. They're designed to use cars. That's insane. We have two missions here. We've got to get to zero carbon, but we've got to do it in a way where our energy is used efficiently rather than inefficiently. We haven't talked about that yet here. It seems to me that at the center of being able to get to zero carbon by 2050 or 2070, is having those people have the prosperity that we have. I don't know anybody in the world that wants to consume energy. I don't. I want the services that energy provides. That's a lesson I learned from Art Rosenfeld. We can get those services in a much more intelligent way, by starting anew. And many of these places are starting a new.

Michael Pacheco: That's a very good point. I think that many of us, I agree that efficiency is certainly the first step. And Art certainly made a tremendous contribution in buildings efficiency.

Participant 11: It's actually the cheapest thing we can do, and has negative costs.

Michael Pacheco: I think it's also probably less known in this audience, but even in the food system, most of our society really could live very well on about 2000 calories a day, and yet our society in the United States produces about 6000-7000 calories, the last time I checked, of human consumable food. So a similar percentage of waste exists there, too.

4.4.5. Research Priorities

Lee Lynd: I would list three research priorities, and they're not necessarily prioritized. One, we have to look at lower cost ways to overcome the recalcitrance of converting cellulosic biomass to fuel. Two, although it's a major challenge, can we make an affordable gigajoule with algal light harvesting? We look too much downstream; we don't look enough upstream. But that's a fundamental issue. Three is related not just to whether is there enough land, but of whether we can develop environmentally, socially and carbon-beneficial land management strategies. I really think that the third one is a part of the equation.

Bruce Dale: Lee Lynd and I have actually been involved in this our entire careers. The key technical problem is what's called recalcitrance. That means that the sugars in biomass plant materials don't yield up their energy very easily. You have to beat on them to make them do that. But, there are a lot of ways of approaching that problem, including pretreatment, using less recalcitrant plant materials to start with, cheaper enzymes, microorganisms that do both at the same time.

There are a lot of attractive fuels that we could make. The most attractive fuel right now is to make ethanol because (1) it conserves such a high percentage of the energy in the sugar in the fuel and (2) there are nice strategies for using ethanol in both diesel and gasoline engines in order to improve the efficiency, to yield the octane and the torque that we need.

There is another challenge. The biorefining system offers us two parts – the part that grows the crops, the farming system; and the part that converts the crops. What we don't have, per se, in biofuels is a logistics system to connect those two. You can order a million tons of corn and grain and it'll show up at the front end of your plant if you put out the right contracts. You can't order a million tons of almost any plant material, except wood chips, in the Southeast. I can't order a million tons of corn stover, and have it show up. You can't do it. So, there's a whole problem of how you're going to establish that supply chain.

What I suggest, an appropriate area for policy would concern the technologies, or ways of commoditizing biomass. Some folks at INL are working on this. But how do you convert basically fluffy, low-density, combustible plant material coming off the field into something that's a good feedstock for a biorefinery. It needs to be dense. It needs to be stable. It needs to be easily shipped, easily stored. It would be nice to have it be able to be blended so that it can have consistent properties.

What that implies to me, strongly, is you need some sort of an intermediate facility between the farm and forest and the biorefinery that gives these properties to plant material, that makes it a commodity so that it can start being traded. It would need to be dense and stable. I would like to see the farmers own part or all of that facility so that they can capture part of the added value.

I would like to see policy designed so that if the farmers were to abide by certain environmental criteria they would get some type of incentive, a $10-20-a-ton incentive for following sustainable production practices—things they can do, like double cropping, like using no-till or low-till activation, like not planting on steep slopes. We know that those things will give us big environmental improvements. Also, they can be monetized that all the way through the system to the biorefinery. So, we can start having a large-scale logistics system to supply the biomass for a sustainable biorefining system. We largely don't have that now.

That would be my highest priority answer, to try to incentivize the creation of sustainable supply chains that benefit the farmers and that provide stable commodity-type materials for the biorefining part.

Lee Lynd: One of the places where this technology needs to go is to lignocellulose. If you want to do lignocellulose biofuels, from a commercial point of view, I'm convinced that the next step is making ethanol. But, I think that you want to work in a place that has room for it. That's not the United States. It would be a very inexpensive policy simply to mandate that all vehicles be fuel-flexible vehicles. That is unlikely to happen mostly because the air's come out of the biofuels balloon. Today there isn't any sort of the incentive to do it.

It's interesting, think about this. How many times have you heard recently about transportation being based upon electricity or natural gas or hydrogen? Every one of those takes a much larger infrastructural change than using ethanol does. So, it's really the case that we've lost faith in ethanol and biofuels, in general, than with many other options. This is not global. This is in the United States; it's one reason that we're poised to lose our lead.

Once you give up on biofuels you cease to lead, Yes, we could do great things for hydrogen and natural gas. But we need much smaller infrastructure changes using ethanol. However, somehow those options are now off the table. That's kind of odd.

Michael Pacheco: Ethanol is only one of the possible options when you look at biofuels. Right now, across the planet, there are at least six fundamentally different technologies making different products, not all ethanol, that are being commercialized. I think at this point that it would be safe to say that it's an open question in terms of which technology is going to turn out to be the most cost-competitive. It may not be the technology that has the best carbon footprint. If those two are not coincident, which as we all know is very highly likely, that's going to continue to challenge society as to how to deal with biofuels as a response to climate change.

Michael Pacheco: You were making the point about Cool Planet, and you were also talking about the market accepting bio fuels. Some of those here may not be aware that for the last four to five years, we've been up against what's called the blend wall—a limit on the amount of ethanol in gasoline. What Lee Lynd is referring to is one of the barriers here in the United States. It is that there's 10% ethanol in essentially every drop of gasoline being sold in this country.

So, to blend it at a higher level creates some real challenges for the industry. It's a challenge in many dimensions, not the least of which is technological. We now know from working with the original equipment manufactories (OEMs), that there's an optimal way to use ethanol in a blend with petroleum stocks. It turns out to be quite a bit higher than 10%, but nowhere near 85%.

Right now in the Department of Energy, with about nine of the national labs, is working together with the Secretary's office to put together a large national program that would figure out, how could we leapfrog to that optimally designed fuel and corresponding internal combustion engine system.

Michael Pacheco: I'm sure, as you're probably aware, the other challenge that the oil-producing countries, particularly, say, Saudi Arabia are facing is that they're burning enough oil just to air condition their homes to fill the largest two refineries in the United States with crude oil. It's a very interesting situation.

Michael Pacheco: With the oil industry we see a product that from 2003 to 2012 basically captured 10% of the market share– it went from nominally two billion gallons of ethanol in 2003, to 14 billion gallons of ethanol in 2012/13. Then it hit the (blend) wall. The only reason that it stopped growing is because it hit the wall. I would say that there were some very challenging dynamics, what some refer to as the battle of the barrel. It's still a very challenging dynamic that's holding back the biofuels industry right now.

So you have companies like Cool Planet and UOP and Ensyn that are developing entirely new technologies based on pyrolysis that may not even be as effective as ethanol, simply because there's no other way to get around the ethanol blend wall. Then, they're going to sell their feedstocks to the refiner. In fact, that's already being done today, all just because of this complicated free economy working. It's a very tough situation.

So I think that biofuels were not oversold. It's that we grew much faster than expected. I never thought that we would hit the wall that much faster than expected. We grew much faster than anyone in the industry thought that biofuels could grow.

4.4.6. *Economics and Business*

Participant 1: So we've heard discussion about how the low oil price is killing a move into biofuels. This reminded me of some thoughts that I heard that predate the US fracking revolution, and also was said by somebody who knows the nuclear power and electricity industries and not the oil industry. It's Sheikh Yamani's quote that the Stone Age did not end for lack of stones. So, it's about exiting or transitioning from oil and gas. I'd always assumed that the end game for oil and gas was going to be something to do with expensive fossil fuels. And this person looked at me like I was foolish. And he said, "You clearly don't understand our industry, do you?" And I said, "Well, no, I don't." He said, "No, no, if there's ever going to be an exit by the international oil companies, it's in a world of really low fossil fuel prices."

The logic goes something like this. Until a few years ago, West Texas Intermediate and Brent crude was at $110 a barrel. International oil companies own about 15-17% of the business. The residual is all in the hands of national oil companies. It's the phrase "national oil companies" I want to get into this debate. They're most of the oil business.

So oil comes out of the ground in Saudi Arabia at $10 a barrel. The international oil companies don't have any oil like that. They have to melt things or make it out of plants, or something. All of those ideas cost $45-50 a barrel, for the sake of argument. That's fine when oil trades $110 a barrel. The international oil companies have really good ideas at $46, $47, $48. However, things get scary when they're at $40, then $39 and falling.

Mazda used to make light bulbs; now they make cars. It's in that world that the national oil companies are just fine. And, I'm not really implying they are fine, but they're much better off than the international oil companies. Their situation prompts the plan, "Let's have North America and Europe go to using biofuel. Let's have them go non-fossil. Also, let's throw up barriers to our market for the people whose oil comes out of the ground at $10 a barrel."

Participant 23: I agree with all of that. Life is better at the higher oil prices. And it's also true that if you look at the history of the international oil companies, the forerunners of them helped open up all of the fields in the Middle East. Then, the governments realized they were getting 10% of all the proceeds, so they nationalized the oil fields. Thus, the big oil companies are now doing crazy things like going 200 miles out in the middle of the water, in a mile of water, and four more miles of rock to get to their oil. At the same time in Saudi Arabia, it's still just bubbling right up. This is problematic.

Now there's starting to be some use of electricity in the transport sector, and 10% ethanol has arrived. The great untouchable liquid transportation fuel market has now shrunk to 85% of what it was. So, we're using less oil now in America than before. In the future, as low prices will cause the international oil companies that are still the holders of most of the technology – less so than they used to be, but still the holders of most of the technology – to look at other things. I think that two areas where international oil companies have a disproportionate advantage in are biofuels and carbon capture and sequestration. The first is because of their downstream system knowledge, and the second is because of their upstream understandings. I look actually for the international oil companies to play a major role in large-scale biofuels production and carbon capture and sequestration

4.4.7. How to Transition to a Low-Carbon Economy?

Participant 25: So, what's the best plan for the transition? Is it a low price? Well, we have a low price right now. And what's happening is that gas is beating everything else out of the market. So it's not a simple question to answer at all.

Participant 1: But the transition that I was referring to occurs when the international oil companies perceive an existential threat to themselves. We are not there yet. Maybe they think that good times will come back, in which case they can say let's just cut all R&D hoping that we can go back to business as usual. But what if business-as-usual is dead.

A parallel is that of Philip Morris. However, that company is still in the tobacco business.

Participant 25: Much of the challenge could be solved or addressed if we had a price for carbon. I believe that every single one of those companies has a business plan for that. They have a hidden price for carbon. They understand what kind of businesses they're going to be in. And the sooner that we establish a price, the better, because the companies need to be part of the solution, not part of the problem.

Participant 23: We would love for there to be a price for carbon.

Participant 25: Remember that these companies are not monolithic. At the moment you've got juggernauts in Washington stopping establishment of a price for carbon; whereas, the engineers in the field are saying, "We can respond to one." I think that a part of the whole issue here is the Citizens United decision by the Supreme Court.

Michael Pacheco: I've certainly heard similar thoughts in the last seven or eight years. I was at a meeting at Georgia Tech not too long ago. Where a man from Exxon saying the same thing, that what you really need is a predictable, steady, gradual ramp-up on the price of carbon. Then the companies can start making good decisions about investments for the future. I certainly agree.

SESSION 5: Nuclear Fuel Cycle and Proliferation Prevention Requirements / What Technologies and Institutions for Sustainability?

5.1 Session Question

What are the effective performance requirements for global proliferation control? What are attractive potential international fuel cycle arrangements, including those for nuclear waste disposal and fuel provision?

5.2. Introductions

Scott Kemp: Our speakers are Frank Carré from the CEA, France and Matthew Bunn from the Harvard Kennedy School. The two talks in this session have to do with the nuclear fuel cycle and proliferation requirements.

5.3. Presentations on Nuclear Fuel Cycle and Proliferation Prevention Requirements

5.3.1. Challenges and Issues Associated with the Nuclear Fuel Cycle for Sustainable Growth of Nuclear Power: Frank Carré (CEA, France)

I start by covering the conditions to be met for a satisfactory nuclear deployment across the world. I mean satisfactory, in terms of a secure and safe framework for operation of nuclear power facilities, and for taking full benefit of what it could really bring to decarbonization, including electricity generation, but also extended applications. We currently have about 440 nuclear power plants operating, most of which are light water reactors, and there are about 70 nuclear power plants under construction. Most of these plants are being constructed in Asia where China is building 25 of them, India 6, and Korea 5. The Western world has typically been building less and only 4 are under construction in the US and 6 in Europe, including Central Europe.

Current global projections anticipate growth by a factor of two to three by 2050, which is a reduction from the anticipation that existed at the time of nuclear renaissance, before the Fukushima accident. There are also some really serious mature nuclear countries that have signed a nonproliferation treaty and are betting strongly on nuclear for the long term. Some have also been connecting research on fast neutron reactors in closed fuel cycles. There are a few newcomer countries such as Belarus and United Arab Emirates as well some others that are considering the investment into nuclear, but have not made a decision yet.

In brief, this shows that the current construction of new build projects in fact is being pursued mostly in mature nuclear countries that conduct research for the next step, fast neutron reactors in closed fuel cycle. Almost all of them are signatories of the nonproliferation treaty with the exception of India. The actions of international agencies – the IAEA, International Agency for Atomic Energy, as well as the NEA or Euratom that conduct safeguards; verification checking of how the facilities are being operated, and checking of how the nuclear materials are being managed are really vital in this. It is vital that the activities of these international agencies proceed onto the verification of how the nuclear facilities are being operated in relation to other very beneficial actions, such as sharing good practices or sharing visions on the future nuclear concepts. It is also important that the IAEA's activities supporting newcomer countries in building appropriate infrastructure for a safe, secure, and peaceful use of nuclear energy proceed so that countries that decide to invest into nuclear have the appropriate framework to do so.

Now, just a short word about the security aspects and the nonproliferation treaty, which at its core, is a bargain between countries that do not have nuclear weapons and those who do. The former agree to never acquire nuclear weapons, and in return those countries that have nuclear weapons agree to share the benefits of peaceful nuclear energy. This means an obligation to assist those countries that signed this treaty in getting the technology necessary for the operation of nuclear power plants. This treaty is extremely important in this period of time. However, experience has shown that in fact some countries could take advantage of being a signatory because a country could have clandestine or secret facilities, especially regarding fuel cycle enrichment and spent fuel processing. Even so, this is a vital agreement that currently frames the nuclear cooperation between members of this treaty.

In addition to nonproliferation, there are other conditions to be met for advanced light water reactors to be successfully commercialized. Security is extremely important and safety, of course, is another core feature, especially given the lessons learned from the Fukushima accident. One important way to improve safety is by progressing towards harmonized safety standards, for instance all Generation III type reactors have taken lessons from accidents that have occurred: Three Mile Island, Chernobyl, and Fukushima, putting a different emphases on whether to correct a cooling accident or whether to correct a reactivity type of accident. Currently we have a diversity of technologies offered in the market with no clear view of what is really Generation III-relevant. Harmonizing safety standards could help steer us in the right direction towards facilitating the commercialization of these advanced reactors.

Economics, of course, is very important as more and more decisions to invest into reactors involve private interests. It's extremely important that future nuclear energy systems be competitive with other energy sources as well as that some adapted or customized funding schemes be put in place to facilitate access to nuclear technologies. Sustainability is also a key aspect because having nuclear technology that minimizes the waste burden or minimizes the impacts on the environment is also important. All four criteria are interwoven into an integrated vision of long term sustainability that is an essential requirement in order for the public to accept nuclear power. This condition, having the public accepting nuclear power, is vital for government support and future investment into nuclear power.

Regarding nuclear security, we have one of the experts here today. I simply quote him, reminding us that nuclear power will be unable to gain the support it needs for large-scale growth unless nuclear facilities and nuclear stockpiles are seen to be safe and secure. Effective security is a key enabling factor for nuclear energy, just as safety is. Regarding the methodology for assessing proliferation resistance and physical protection, I have borrowed some information from the Generation IV International Forum that give an overview of threats to be considered, for which provisions should be made to minimize their importance.

Proliferation resistance comes in many flavors, and has to do with making provisions to minimize the risks of nuclear materials being diverted or misused or having states that are signatories of the NPT break out from this contract or develop clandestine facilities. Physical protection aims to minimize the risks of theft and sabotage. The measures that have been imagined so far are of two different natures. One is investing into intrinsic resistance protection which has to do with dealing with nuclear materials that are easily detectable, that necessitate a larger radiation protection burden, or that might not be appealing for proliferation activities. The other activities, extrinsic really, relate to specific measures for inspection of facilities or accounting for nuclear materials. Those two are really the basic actions taken so far to safeguard facilities and nuclear materials. They have to be updated as the technologies advance.

There have been regular attempts at establishing a global framework for successful deployment of large water cooled reactors in the coming decades. In fact, two parallel initiatives were taken in 2006 that were betting on installing a global international framework that would be based on international government agreements where some states would operate nuclear fuel cycles and that they would offer guaranteed services for nuclear fuel cycle to some states that would be interested only in operating nuclear power plants in order to get energy from them. The vision at that time was to have these multinational nuclear fuel cycle service centers that would offer fresh fuel to those reactor countries, and they would offer the service of retrieving the spent fuel from them to avoid having creating dormant stockpiles of spent nuclear fuel that could contain transuranic materials. Therefore could be used as raw material for proliferating activities. A separate vision was also developed in 2006 of having a two different parts of the nuclear world. Reactor Nations would operate only reactors while leasing and returning fuel and Fuel Cycle Nations would operate both nuclear power plants and fuel cycle facilities while offering fresh fuel at market price, uranium fuel exclusively, and offering the service of retrieving nuclear spent fuel.

The difficulties with these approaches arose when questions opened up the legality of retrieving the nuclear spent fuel, and also what to do with this retrieved nuclear spent fuel in the nuclear country that would host this international fuel cycle center. At that time, it was even imagined that those fuel cycle countries would operate fast neutron reactors in transuranic burning modes so that in they would burn up the transuranic materials in the retrieved spent nuclear fuel from reactor operating countries. The difficulty was that the technology wasn't available, at least at a commercial level, to proceed with such an operation. I note that there is still debate today between whether to encourage the retrieval of the nuclear spent fuel from reactor countries, or to encourage them to have national or regional storage of nuclear spent fuels.

There are difficulties on both sides of these global nuclear strategies. On the side of the retrieval, it is illegal in most of the nuclear countries to host the nuclear waste from other countries. It could also be a matter of public acceptance for the country hosting this multinational nuclear center to accept waste from other countries. Even gaining public acceptance for strategies regarding domestic spent fuel policies has been difficult for many countries. Another difficulty is that it would imply the shipping of nuclear materials, so the spent fuel, and possibly the ultimate vitrified waste, would be transported back to the source country. On the other side, the difficulty is in creating national or regional storage facilities for an indefinite period of time with an unclear future for the spent fuel that will be stored under these conditions. There is a risk of having repositories created in some more or less controlled manner that could ultimately become mines of transuranic materials. That could be one way, even though it might not be so straightforward, to get nuclear material for proliferating activities.

So in summary, I try to cover a number of conditions to be met for the successful commercialization of light water reactors in the near term, and important issues regarding safety and security. Other aspects that are different, such as having nuclear comply better with viable renewable energy sources or with extended applications come in addition to that. Another factor that I do not expand on relates to the perception of the necessity for a country to have an endpoint for the spent fuel. In France, for example, there is a necessity to successfully implement a geological repository in order to open a future for nuclear energy. Whereas, it's not the same in other countries, or at least the timeline is different.

Looking further into the future, we can see what types of reactors we might be expected around the middle of the century from what the Generation IV International Forum identified as likely future energy systems. There are some that could operate with low enriched uranium such as the very high temperature reactor or the supercritical water reactor, which could be viewed as some advanced version of light water reactors operating at temperature above 500 degrees Celsius, and having an excellent conversion efficiency. These reactors for either domestic use or for export would be more or less to be considered in the same terms of those for light water reactors today. The situation might be different for the fast neutron reactors with a closed fuel cycle. Sodium cooled reactors are the only available fast reactor technology today, but they need research to become commercially available, and alternatives such as lead or gas cooled fast neutron reactors will require longer terms for development.

Fast neutron reactors are attractive because they are believed to be able to fulfill two missions that light water reactors cannot do. The first is to convert uranium-238, which is over 99% of natural uranium, into fissile plutonium in order to make more efficient use of natural uranium and to release an additional 80-90% its energy content. Whereas light water reactors, whether they are operated in the open mode or limited recycle mode, mainly use uranium-235 which constitutes only 0.7% of the natural content of uranium. Consequently, light water reactors make use of half of a percent of the energy content of natural uranium.

Typically, in order to produce one gigawatt for one year, you have to mine 200 tons of uranium and to fission one ton. Whereas, if you consider fast neutron reactors with a closed fuel cycle, with plutonium as fissile fuel, then you just need one ton to make up uranium-238. And those nuclear countries that are operating nuclear power plants today have plenty of stockpiles of depleted uranium or reprocessed uranium. It is believed that during the 50 years operation of one light water reactor, enough depleted and possibly reprocessed uranium is stockpiled that would make it possible for a fast neutron reactor of the same power to operate for 5,000 or 10,000 years. So, it’s understandable that for uranium-poor countries and energy-poor countries such as France, Japan and others, aiming at this technology is a strong matter for energy security, provided that it is appropriately made safe and secure, including the security of the closed nuclear fuel cycle.

The other benefit is that the physics of these reactors might allow for burning transuranic materials and optimizing the nature of the ultimate waste to be directed to the geological repository. Reprocessing could remove plutonium and uranium and leave vitrified fission products with only traces of actinides as ultimate waste packages. This would greatly improve the ultimate nature of the high level wastes by greatly reducing its decay heat and radiotoxicity as well as its volume and actinide content in terms of volume, and in terms of radiotoxicity. I borrowed this viewgraph (Figure 5.1) on options for management of domestic SNF that was prepared by DoE that compares the different fuel cycles.

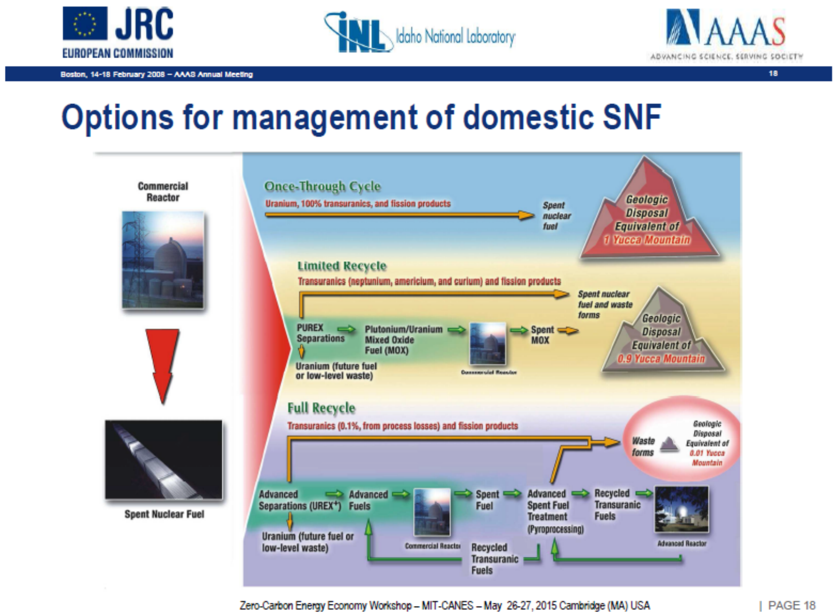

Figure 5.1 Options for management of domestic spent nuclear fuel

For a uranium-rich country like the United States, the mission that such a fast reactor could provide, at least in the medium term or maybe over the 21st century, could be this burning of actinides, either for minimizing domestic waste or as a way to deal with the retrieved light water reactor spent fuel from a country that has leased the uranium. And if the US were to retrieve it and operate a fuel cycle service center, then a burner reactor could—be used that would optimize the transformation of the spent nuclear fuel into this vitrified waste that is optimized for going into the geological repository.

In France we have made an intermediate step along this line by reprocessing spent fuel and recycling plutonium once in light water reactors, and this has been a practice in our country since the '70s. So, we, of course, are working and doing research and development on more advanced processes that could be implemented for closing the fuel cycle of fast neutron reactors. And, we are very eager to share some of the experience with fuel cycle countries to work towards the visions of closed fuel cycles that would be acceptable from the point of view of security.

I have provided a chart showing the world experience in sodium fast neutron reactors that shows the current countries that have had in the past, or that currently have programs on fast neutron reactors and nuclear fuel cycle. It's striking to see that Western countries, both the US and in Europe, have no fast neutron reactor anymore. The program that was started in the US in 1978 through the Nonproliferation Act was later cancelled, and political opposition to fast neutron reactors in France in the late '90s led to shutting down of Superphoenix. We were authorized to operate Phoenix until 2009 for research purposes, but the Western world doesn't have fast neutron reactors anymore. Russia and India are the champions of this technology today and are planning to put an 800MW reactor and a 500MW reactor on the grid this year, respectively.

China is really striving to catch up with the development and has aggressive plans to develop nuclear power and to switch to this more sustainable, more efficient nuclear technology. Japan was one of the developers of this technology, but there have been technical and legal difficulties in restarting their fast reactors. The fast reactors Joyo and Monju had experienced some non-nuclear technical problems, but because of the nuclear situation in Japan, this objective is of second or third priority at the moment.

Having this transuranic burning technology available, the question becomes, when is it best for the waste? Is it for the spent nuclear fuel, either for the domestic nuclear spent nuclear fuel or for the spent nuclear fuel that'd be retrieved from reactor countries? There are pros and cons. For burning, there is the minimization of the waste and the waste burden, but the difficulty is the fact that the reprocessing, the separation technology, is a sensitive technology, and that of course this operation would call for safeguarding. Diversion could be more difficult in some way considering that separation would allow group management of actinides that would be easily detectable and not so appealing for proliferating activities. If you had such a technology available in the international centers, then you could think of returning the vitrified waste to the reactor country. Doing this would comply with the legal disposition so far, but certainly would not minimize the transport of radioactive materials.

If you advocate for national or regional repositories, then a difficulty is due to some indefinite future with uncertainty about what will happen ultimately. This could leave some repository, national or regional, with the difficulty of having to deal with a type of waste that has decay heat and radiotoxicity, and that could be considered as a mine of transuranics that could be exploited for proliferating activities.

I was requested to make a comparison between the once-through cycle in light water reactor and the full recycle in fast neutron reactors, but I'm not sure that a fair comparison can be made because both need to be considered at different time scales. The once-through cycle in light water reactors is the option that most nuclear countries have today. What could be considered as sensitive issues include enriching uranium that is needed for these types of reactors, as well as possibly that a large amount of spent nuclear fuel could have accumulated as a stockpile. Safeguards are essential in this matter. Whereas, for the fast neutron reactors in a closed fuel cycle, the sensitive issues include the need for separation technology as well as the refabrication of the transuranic fuel. Again, possible countermeasures are safeguards, appropriate instrumentation to really count the material, to detect the materials, and some ways of combining actinides that would make them less appealing for the proliferation activity.

One word about a specific approach that is being considered in the US, which is the low-enriched uranium fast neutron reactor with a long lifetime-the traveling wave reactor from TerraPower. This is a type of breed and burn fast neutron reactor that can eliminate enrichment and achieve high burnup without reprocessing, but it doesn't say what will ultimately happen with the spent fuel of this type of reactors. However, the vision is that it would need quite a significant amount of mined uranium to constitute the initial core made of 20% enriched uranium. When you consider the amount of natural uranium that is needed per unit power energy that is produced, then, for light water reactors you have to mine about 200 tons, of which you finally fission one ton. For this type of reactor, you need about 40 tons of natural uranium to operate for the 60-year lifetime. So, then, this is a vision that would escape difficulties associated with the sensitivity of a central repository. But at the same time I don't think it would fit with the plans of energy-poor countries or uranium-poor countries that really bet on fast neutron reactors to cut by two orders of magnitude the amount of uranium needed for their operation.

Now, just a few personal comments about what innovative concepts that could be considered as game changers. I've already commented on the situation for the traveling wave reactor. So the question is whether the small-/medium-sized reactor that is transportable is really a breakthrough for controlling proliferation risks. In one sense it is, but I think that the weak point is economic, not only because the specific cost of this small/medium reactor will be high, but I think the investment into the initial low enriched uranium is likely to be high. I don't expect this type of reactor to be really competitive with light water reactors of the same unique power levels. There is also the possibility of building nuclear systems which have co-located the reactor and spent fuel processing facilities or repository. You could think of either the integral fast reactor-based concept with the use of the PRISM fast reactor and co-locating the power processing device, or you could think of some futuristic vision of the molten salt reactor. Those types of reactors might have the advantages of just being fed with fresh uranium fuel and delivering the ultimate waste to be readily disposed in interim storage or ultimate storage. So, you could think that it would really eliminate the difficulty of transporting spent fuel, reprocessing it on another site, and then bringing high level waste back, so it certainly has advantages. However, if you consider exporting nuclear technologies, then you can have questions regarding exporting some compact separation process that would be operated in another country, and whether misuse of it could allow the extraction of some interesting nuclear material for proliferation activities.

I conclude by presenting an overview of the challenges and issues for a sustainable growth of nuclear power that I have discussed. I want to say that while nuclear energy has been a vital component of the world energy mix, I think that it has really a great future towards contributing to decarbonization. It can be important not only through electricity production, but also by extending its application through the production of a synthetic hydrocarbon fuel for diverse uses, especially transportation, as well as for delivering heat, either for district heating as process heat. In the short term, advanced light water reactors can be safely commercialized under a number of conditions for which meeting upgraded requirements for the safety are a must, as well as establishing a secure framework for the circulation of the nuclear materials that are needed for the operation of these reactors. Sometime thereafter, which might be in the second half of the 21st century, I think that fast neutron reactors will be needed with some version of a closed fuel cycle because they will be necessary to make nuclear power durable, not only for a few decades, but several centuries or thousands of years. Fast reactors could also be vital in burning actinides and therefore in optimizing the ultimate waste to be disposed of.

I believe that international cooperation is really key at all steps in preparing the future, not only for sharing the cost of research and development for new reactor technologies and of large demonstration reactors, but for advanced fuel cycles as well. One should be cautious, of course. This would be the type of cooperation between fuel cycle countries only. I don't bet that there will be only one fuel cycle process available. I think the situation will be different, but I think that it is important that such cooperation could contribute toward establishing consensus on the criteria for a process that a closed fuel cycle should meet in order to be recognized as secure enough. Ultimately, I think that it is necessary to establish an intergovernmental framework for securing the circulation and use of nuclear materials worldwide through appropriate safeguarding measures.

5.3.2. Avoiding Nuclear Proliferation in a More Nuclear Future: Matthew Bunn (Harvard)

This talk covers, from a little bit more of a policy perspective about avoiding proliferation in a more nuclear future. What I really discuss are two kinds of worries, one is state-based proliferation and one is non-state-based. In both cases, how does it affect the picture if we go to a much larger global nuclear energy infrastructure than we have today?

I argue that large-scale nuclear energy growth implies nuclear weapons spread. If we're going to make nuclear energy so attractive that the countries already operating it want to have hundreds and hundreds more, it's going to be attractive enough that other countries are going to want to have it, too. I've supplied a viewgraph (Figure 5.2) showing just the most serious of the newcomer states with advanced plans for nuclear energy development at the moment. If you were to add everybody that the World Nuclear Association claims is considering in some way, there would be many more countries included on that map. Some of these countries are probably not ready for nuclear energy. I've supplied a list where I've coded in red the countries that are in the bottom fifth of the World Bank Governance Indicators for either control of corruption or regulatory effectiveness; and then in yellow, the countries that are in the next bottom fifth. I just note that there is a fair amount of red and yellow on that page. This is more of a safety and a security problem than a proliferation one, but there are quite a number of countries on that list that would raise at least some proliferation questions as well.

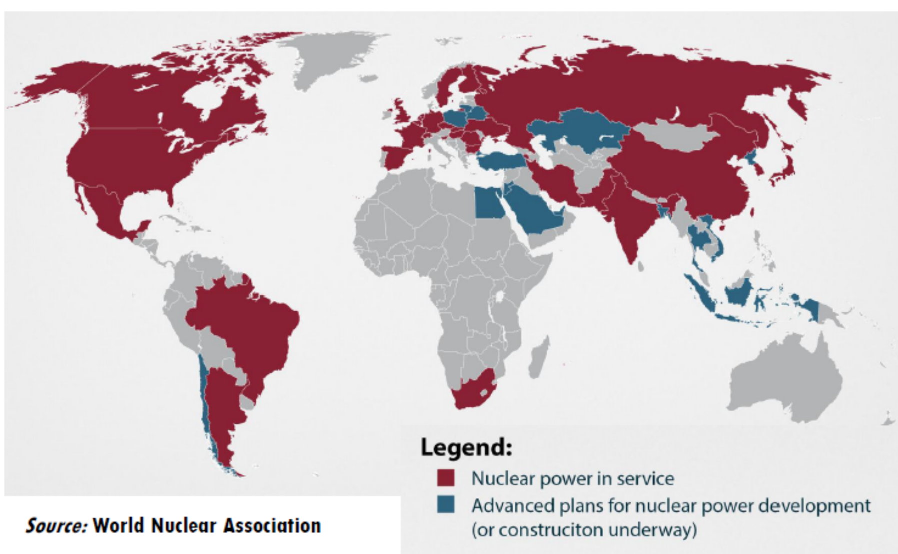

Figure 5.2 Nuclear spread worldwide

However, I argue that just having a nuclear power reactor under international atomic energy safeguards doesn't create much proliferation risk in a country. More broadly, I would say the civil nuclear energy system does affect proliferation, but it's not the big driver. Nuclear weapons programs are really driven by state security concerns, prestige desires, domestic politics, and bureaucratic imperatives. So if you're a leader of a country, and because of the civil nuclear energy system or for other reasons, you can convince yourself that getting into nuclear weapons is going to be quick, cheap, or easy, it is more probable that you will decide to go to that direction than if none of those things are true. So nuclear energy can facilitate nuclear weapons programs, but there are two considerations that are both true. Nuclear energy advocates often point out that no state has ever built a bomb with material from a safeguarded nuclear facility. At the same time, it is also true that every nuclear weapons program established since civil nuclear energy became broadly established has had important, and in fact crucial, contributions from the civil sector.

In the civil sector, there are very few cases where states either considered, planned, or attempted to accomplish the actual diversion of nuclear material that is so often raised in proliferation resistance discussions, but it's much more often that the civil nuclear energy system was a source for either overt or covert acquisition of technology. A few examples arise, as when South Korea says, "I'll buy a reprocessing plant from France," or Pakistan steals centrifuge technology from the civil nuclear energy system in Europe, or it can be a cover for purchases whose military purpose would otherwise be obvious. So Iran says, "Oh, we're building enrichment plants because we need them to fuel our civil nuclear energy system." In the case of Iran in particular, they acknowledge that their centrifuge program began in 1985. Think about Iran in 1985. They had no civil nuclear energy. Their plant had been bombed and the Germans had pulled out. They had no hope of having civil nuclear energy at any time soon, but they were locked in a desperate war with a country known to be pursuing nuclear weapons. So, I argue that, at least in its origin, that program was military, not a civil program. But they claim it's always been a civil program. Even so, a civil program can provide the buildup of infrastructure and expertise.

There are some bottom lines worth mentioning before getting into more detail. First of all, the proliferation risk of a country just having a couple of light water reactors under safeguards is modest, though not completely equal to zero. The key factors to worry about in the civil nuclear energy system are enrichment and reprocessing in all their various forms. Enrichment is not likely to go away soon, even if we move toward using fast reactors. On the reprocessing side, the difference between processing spent fuel and not processing it is much bigger than the differences between the various technologies that people have envisioned to process it. In the Bush administration, when they were pushing the GNEP (Global Nuclear Energy Partnership) idea that Frank Carré talked about, the National Nuclear Security Administration in the United States performed a really complicated, in-depth, and I think reasonably good assessment of the proliferation risks of all of the different kinds of spent fuel processing that were being talked about. Their summary was: If you consider the overall proliferation risks on a scale of 1 to 10, where 1 is not processing the fuel at all and 10 is separating pure plutonium, then the best one we’ve looked at is, if not processing the spent fuel at all is considered at one end of the scale and separating absolutely pure plutonium is the other, then the best one we've looked at is at about 8.9. So it's a lot closer to 10 than it is to 1.

When judging fuel cycles, it's not just the diversion of material that’s important. There's far too much in the proliferation literature where you have engineers wanting to use a single criterion that they can shoot for. For example it could be that my material is always more radioactive than X, or as long as I've got at least Y-percent of plutonium-238. But, that's not the right way to think about the problem. The right way is, if it were deployed at the scale that its advocates want and with the distribution that would be likely, how much overall the materials, technologies, facilities and expertise would reduce the time, cost, uncertainty and detectability of acquiring nuclear weapons. You can then make engineering estimates by answering those questions and comparing them to a once-through system of producing the material for a nuclear weapon. It really is the material production that is the most difficult part of making nuclear weapons, and that is the part that the civil nuclear energy system would contribute to most significantly. This again emphasizes the point that with safeguarded LWRs, the risk is modest. Yes, there's material having 4-5% low-enriched uranium, as we've seen in the Iran case, that would shorten the time to HEU if you have an enrichment plant. If you don't have an enrichment plant, then it's more or less irrelevant to a nuclear weapons program. You end up, as Frank Carré pointed out, with spent fuel that contains plutonium. It could be used if you have a reprocessing plant, but it's more or less irrelevant if you don't.

I would argue that facilities overall make a minimal contribution, and that expertise is more important. You can have hundreds of trained nuclear experts. When the United States was attempting to prevent Russia from selling the Bushehr reactor to Iran in the 1990s there were very few people in the government who believed that Iran would use the Bushehr reactor to produce plutonium. What we were most worried about was this flow of hundreds of Iranians going to Russia, studying at some of the universities where Russia trains its key nuclear weapons people, and making personal contacts and friendships. So we were concerned they would get all sorts of technology other than that of the safeguarded light water reactor. What we didn't know at the time was that they already had a direct channel from Pakistan for exactly the technologies that we were worried about.

In order to use nuclear power, there must be the supporting fuel cycle. There's got to be an enrichment plant somewhere if you're going to run an LWR. That's where the real proliferation risk is. But that may be in a nuclear weapons state, or in some state that has had it for a long time. It may also be a bureaucratic power base, but that can actually cut both ways. There are cases where the sort of Atomic Energy Commission-like entity pushed for nuclear weapons. There are also cases where they pushed against a nuclear weapons program because they were basing their efforts on imports of technology from other countries for the civil sector, and feared that that would be cut off.

For enrichment and reprocessing the key things are similar to real estate: location, location, location. Is the facility in a non-nuclear weapons state, first of all; and, is it in a non-nuclear weapons state that you worry about, second of all? Now, is it a state that you're worried that can change over time? So, the United States was seriously contemplating transferring enrichment and reprocessing technologies to the Shah's Iran once upon a time. Imagine if that had been accomplished by the time that that the Iranian revolution occurred? We might be in a very different situation with respect to Iran today. So, I am not one who thinks that what we ought to be doing is transferring all the technology that we want to states that we trust, because the situation can change. You're really talking about decades to a century of commitment when you're talking about building and operating a nuclear power plant, because then you're eventually going to have to do the managing of spent fuel and the decommissioning, and so on. New enrichment technologies are probably only going to make a modest difference, because the technologies that we've got already are so bad. Centrifuges are small, use very little power, and are easy to hide. New technologies might make things smaller and easier to hide. And they would make a difference if they were much easier to make and operate than centrifuges, which is certainly within the realm of the physically possible. There's no physical law that says that nobody's going to invent a really, really easy way to do uranium enrichment. But nobody's done it yet.

If you have an enrichment plant, then you have the option that you could try to divert. However, there's not a lot of great stuff to divert. It's mostly low-enriched uranium normally, in a civil enrichment plant. So, what you would probably do is try to begin producing HEU, but that would probably involve the inspectors noticing. So, you're probably led to a breakout scenario, where you kick out the inspectors and just start making HEU from LEU. Or, it would give you the expertise in the supply chain to build a covert plant. So, I'm much more worried about Iran doing something covert than really trying to race to the bomb at the declared facilities where we're negotiating about how many centrifuges there will be. At the declared facilities, inspectors will notice what's happening, and those facilities will cease to exist before they make enough HEU for a bomb. There are several non-nuclear weapons states that operate enrichment plants today. A couple of them are in URENCO, so they're operating as part of an internationally controlled organization, which may reduce risks a little bit. In the near term, there's not much incentive for other states to go into the enrichment business. It's an oversupplied market and the dominant companies in that market have a lot of investments made over many years in making efficient technology. It's pretty hard to imagine, if your incentive were really fully civilian ones, why you would want to go into that part of the nuclear business. On the other hand, most countries are unwilling to sign away the right to enrichment.

Reprocessing is more or less the same story in that there is a real risk if you have a domestic reprocessing plant. But there's arguably even less incentive for countries to establish one. Reprocessing plants so far have proven to be extraordinarily expensive. Even in France, the official studies have concluded that they've spent many billions more than they would have had they not gone the reprocessing direction. In addition, dry cask storage, at least for the interim, provides a safe and cost effective alternative for spent fuel treatment. Most countries operating reprocessing plants that were in the merchant business have found their foreign contracts are drying up. South Korea is the only new non-nuclear weapons state seriously interested in going into reprocessing. I should also note that China is seriously considering going into reprocessing, and also building fast reactors in a big way. China is already a nuclear weapons state, so I'm not especially concerned that they'll have access to a lot more plutonium, but given how many nuclear reactors they're building, they will be the nuclear energy leader of the future. If the nuclear energy leader is saying that reprocessing is essential to the future of nuclear power, it will become more difficult to prevent the spread of reprocessing, because other states will look to them and say, "Well, that's the way you're supposed to do it if you're a serious nuclear energy state." I think that new reprocessing technologies help, but only modestly. All of them look likely to be more rather than less expensive as studies that the US labs have done show. I think in general that nuclear energy's future will be best ensured to the extent that you can make it as cheap, as safe, as secure, as proliferation-resistant, and as simple and easy to understand as possible. Reprocessing in all of its various forms, points in exactly the wrong direction on all of those counts. I think there's plenty of uranium to last into the 22nd century. As a Russian colleague of mine, who is working on one of these fast reactors lacking reprocessing, put it, "I refuse to worry about what people in the 22nd century are going to do for energy." We know so little about what the technologies of that time will look like.

So, what are some of the steps we could take to reduce the proliferation risks of civil nuclear energy? First of all, the politics of reducing demand are actually very important. That influence has been much more successful than people realize. There are today more countries that started nuclear weapons programs, and agreed to give them up than there are countries having nuclear weapons. So our efforts to talk countries out of it succeed more often than they fail, even in the relatively modest number of cases where countries have started down that road in the first place.

Today, there are nine states having nuclear weapons. A quarter century ago there were nine states with nuclear weapons. So that's an amazing public policy success story. We added North Korea, but we lost South Africa, which admittedly, was a terrible trade. But to have no net increase over a period of 25 years is really remarkable. Of course, past performance is no guarantee of future success, and the world is changing; but people have the idea that any dictator who wants a nuclear weapon can get one, and that's not correct. We need to secure all the nuclear materials and facilities, minimize the spread of these sensitive facilities to additional countries, and beef up controls on illicit procurement. One of the things that's happening on a large scale today is that countries like North Korea and Iran are buying technologies illicitly.

Now, there's a question as to how important that is. Scott Kemp has written a terrific article on international security that I commend to all of your attention, making the argument that actually a lot of what I'm talking about is not that important because states have shown that they can build centrifuges that are good enough in short periods of time, using small groups, without buying a lot of equipment internationally, and that almost any state would have the ability to do that. To the extent that you believe that, you should be more worried about nuclear proliferation in general, but less worried about the impact of the civil nuclear energy system, because they can acquire nuclear materials anyway, even if they aren't getting equipment from the civil nuclear energy system. International ownership and control of key facilities can be, I think, important and worthwhile, but I don't think it is as much of a total answer as it sometimes made out to be. Finally, improving the technical proliferation resistance I don't ignore, but I put it last on my list of priorities.

As far as terrorism is concerned, you don't necessarily increase the risk of terrorists getting a nuclear bomb by having a lot more nuclear energy in the world. Once-through LWRs use low-enriched uranium that can't be made into a nuclear bomb, and the plutonium that they produce is in these massive and intensely radioactive fuel assemblies that would be really hard for terrorists to steal and process. Now, on the other hand, if you're separating plutonium and shipping it all over the place, and so on, then you may increase the theft risks somewhat. Expanding nuclear energy, though, would create more targets for sabotage. Also, there are groups that have planned attacks on reactors, and I think that they are continuing to do so. I think that Fukushima probably highlighted to them just how much terror and disruption you could cause via nuclear means. But, as we move toward more advanced reactors, we're moving toward more passive safety concepts. As Robert Budnitz said yesterday, he couldn't even think of how to engineer a big release from the fluoride high temperature reactor. I think that this increases the value of having these passive safety concepts, and of having effective security everywhere. There are, by the way, still countries who believe it's a bad thing to have any armed guards at all at their nuclear facilities, even in some cases at facilities with highly enriched uranium or separated plutonium. So there are a number of things you can do to improve terrorism resistance, but basically it's comes down to minimizing the number of places with highly enriched uranium or plutonium, having good security, and increasing passive safety.

Finally, I want to return to something that Charles Forsberg mentioned, which is the importance of economics. The reality is that governments are not going to force the nuclear industry to do all sorts of things that are way more expensive because it might be somewhat more proliferation-resistant. Nuclear advancements will only help on the proliferation front if they're the kind of nuclear energy that's widely deployed. They will only become the kind of nuclear energy that's widely deployed if they're the most economically attractive kind of nuclear energy. Asking how much more we willing to pay for proliferation resistance is the wrong question. What we ought to try to be figuring out is, what can we do that will be economically attractive so that lots of people will deploy it, and that is also proliferation-resistant.

5.4. Nuclear Fuel Cycle and Proliferation Prevention Requirements discussions

5.4.1 What is after the GNEP? This question explores what might be next regarding multinational agreements comcerning repositories and technology transfer.

Scott Kemp: On this issue, in order to balance between Matthew Bunn's and Frank Carré's talks, the question is what's after GNEP? GNEP had a vision for controlling technology, and having of the dream of a closed fuel cycle that was efficient. Many people signed up for technology transfer, but a lot of people didn't sign up to give up their rights to technology. Now that we are looking at advances in computational chemistry, what does that means for extraction of uranium from seawater? Do we still need a GNEP-type international framework to manage the fuel cycle facilities? Or, can we use the traditional LWR once-through fuel cycle for a while longer?

Matthew Bunn: I think that there're really two aspects to this. One is, do we want to leave spent fuel sitting in a lot of countries, or do we want to try to figure out ways to take it back? The other question is, do we want to process it? I think those questions are often assumed to be a single question, but I think that they're actually two questions.

If you look far enough forward into the future, it's got to be true that there will ultimately be multinational repositories. It just makes no sense at all for every country that has even one nuclear power plant to have its own Yucca Mountain repository.

Now, the politics of that are very difficult. As Frank Carré points out, some countries actually have legal bans saying "I'm not allowed to import other countries' spent fuel." But my guess is as soon as one country goes into that business and starts making enormous piles of money, as they would, that then other countries will start scratching their heads and thinking "is there a way for me to overcome this political obstacle?"

My guess is that by 2100, we'll probably have four or five repositories in the world that are accepting either spent fuel or wastes from other countries on a commercial basis. I think that this would be positive for nonproliferation and for nuclear power. I'm a believer in the notion of fuel leasing or even reactor leasing, if we get to the point of factory-built reactors, and then of taking them back, at least on a modest scale for countries that are using a modest amount of nuclear power.

There's been a lot of talk about creating fuel banks and things like that to give countries fewer incentives to have their own enrichment capability. I think that the market works well enough that. Except in a few cases like Iran or India, countries aren't really going to be worried about being able to obtain enriched fuel. There has never been a nuclear power plant that shut down because it couldn't get enriched fuel.

If, on the other hand, you said to a country, “Go with me and you never have to develop your own Yucca Mountain facility,” that's an attractive deal. And that's why the Russians are being so successful in the international market, now. Rather than France or Britain which say, “Well, we'll reprocess your fuel for you, but then you have to take the wastes back,” Russia says, “You buy our reactor, we'll take the spent fuel back; you never have to hear about it again.” That's a good deal. But I don't think that necessarily reprocessing is essential to that vision. It's not contrary to that vision, but I don't think that it's essential.

I do think that that idea of taking back spent fuel was sold in GNEP in the most negative possible, unattractive way from the point of view of non-nuclear weapons states. Essentially, the Bush administration came in and said, "We're going to draw a new line between haves and have-nots. We've already got a line between states with nuclear weapons and states without them. Now we're going to have a line between states with fuel cycle technology and states without that too. And, we're going to try to prevent everybody who hasn't already got fuel cycle technology from crossing over that line."

That position, provoked a hullabaloo among the non-nuclear weapons states, including the biggest explosion of expressions of interest in enrichment ever in the nuclear age. There were about nine countries that suddenly started saying, "Oh, whoa, we're going to build our own enrichment plant." They wanted to make sure they were on the right side of the have/have-not line before it got drawn. Fortunately, most of those expressions of interest went away.

The exact same policy could have been presented in a much more positive way. They could have said, "I'm going to give you more Article IV rights than you've ever had before. I'm going to not only guarantee you all the fuel you'll ever need for every nuclear reactor you ever want to build. I'm going to guarantee to manage your spent fuel for you." That would have been, I think, greeted in a very different way.

Frank Carré: I agree with Matthew Bunn that concerning both issues in the GNEP approach were really to retrieve the nuclear spent fuel, and then of what to do with it. At the same time, I think that it provided an interesting vision of having multinational centers that could offer fuel cycle services, especially the leasing process.

For nuclear exports, I have no definite position. I'm not going to express any preference between retrieved nuclear fuels or national or regional interim storage. I strove to put forward the pros and cons of either situation. One might say that offers were made at the time of GNEP where the technology did not exist, at least at industrial scale, that could really offer the services that were claimed. There was still a long path to go.

I also acknowledge that Russia at that time had made offers of retrieving spent fuel and then keeping the waste. Then suddenly it became the country most likely to do this, if it could be made capable to do so. However, let's say with the time, I think that this policy could create some reluctance even for Russian population to dealing with nuclear energy than with the knowledge that the nation was really hosting other countries' nuclear wastes. At sometime it might be come counterproductive to do so. Such offers also could have been denied by some countries. I believe that the European Commission encouraged Finland to not accept leasing offers from Russia.

So, those are for the nuclear exports. Now, one could speak about domestic nuclear and regarding reprocessing, or not. So, I understand all the questions, all the visions that ended up being expressed, especially as developed here in the United States and that Matthew Bunn has expressed extremely well.

The US and countries like France are in different positions in terms of access to uranium and energy poverty. The significance of nuclear power differs, therefore, as does the concern for energy security. Therefore the effort that we are making towards a sustainable nuclear enterprise also differs, at least with this vision of fast neutron closed cycle. At the same time we are doing research and development, and having cautious international cooperation with other fuel cycle states to proceed with research and development, and some demonstrations not intended to define an ideal type of reprocessing mean, but at least to do experiments that could bring a scientific basis to developing consensus for some recycling modes that could be acceptable from the point of view of security, if used domestically in nuclear countries. Possibly this could be used in nuclear international fuel cycle services when the time comes, but this would be a different step.

I acknowledge the vision of GNEP and maybe the similar vision in Russia at the time, where there was a new whole comprehensive set of integral environmental agreements to really establish an appropriate framework for the world to develop a safe, secure, and peaceful nuclear energy. The form of that has yet to be negotiated. Negotiations are proceeding. The IAEA is really developing visions for that. I think that it has to proceed.

Matthew Bunn: I should just mention that while the word, GNEP, died, some of the concepts didn't, and that there are still now, both France and the United States participating in this International Framework for Nuclear Energy Cooperation, which looks not only at the fuel cycle, but also at things like financing and other aspects of building up an international cooperative framework for nuclear energy.

I'm 100% of the view that the United States and other countries should continue to do R&D on reprocessing and fast reactors to see if some of these difficulties can be overcome. But it’s less urgent for the U.S, I'm maybe more optimistic about the availability of uranium, perhaps in part based on the MIT Fuel Cycle Study[17].

Frank Carré: I agree with most of your presentation, and especially the last statement saying that things can help with nonproliferation if they can be made economically attractive and can be effectively used in other countries. It's of little use to be extremely virtuous in one country and avoiding any sensitive technology if the rest of the world is progressing along other lines.

5.4.2 How much will limited water availability affect the spread of nuclear technology?

Participant 6: I have two questions. One is, to what degree do you view the potential limitation in water availability for cooling reactors to be a limitation for the spread of the nuclear technology. All energy technologies use quite a bit of cooling water. To what degree do you see that to be a limit, particularly given the size of the heat output.

Participant 11: Jane Long talked about a study yesterday about California. A piece of that study, "How to Decarbonize California," was a chapter in that report, which asked the question, could all of California do everything it needs in the energy side just with nuclear energy? In doing this, you'd have to electrify everything, except perhaps jet fuel.

And the answer was, no problem. You'd have to build 70 to 80 reactors for California. And then you could electrify everything. We're not discussing economic feasibility; but it's at least technically feasible. Then the question arose, how could you build 70 or 80 reactors in California when you don't have enough water? We certainly don't have enough ocean available, even though we have 600 kilometers of ocean. This is because no one would let you use it.

The answer is, no problem at all. You can build reactors that use almost no water. You would just have to pay a little less than 10% penalty on the output. In fact, we had one such plant in California at Rancho Seco and a few more in the rest of the country.

So the answer is, technically, if you're willing to absorb a 10% efficiency penalty you can do this, it's not a problem of using water, either ocean or fresh. Now, no one is proposing building 70 or 80 reactors in California and electrifying everything. However, this was the extreme question being asked, that indicated what is at least feasible. So the answer is, don't think that water's the issue. It's not.

5.4.3 Can nuclear provide a future that is free of resource conflicts?

Scott Kemp: Thank you, Robert. Let's actually try to keep the questions focused more on proliferation for this session, if we can. There was a general question about whether nuclear promises a vision for the future that is free of resource conflicts. This is an argument for nuclear power that runs opposite to proliferation concerns. That's a very lofty question.

Matthew Bunn: I think that it's extraordinarily unlikely, at least in this century, that we're going to have enough nuclear energy to have a major effect upon resource conflicts. As Frank Carré

[17] Kazimi, Mujid, et al. "The future of the nuclear fuel cycle." Massachusetts Institute of Technology, Cambridge, MA (2011).

noted at the very beginning of his talk, we might have two to three times nuclear energy growth by 2050. That would be keeping about the same nuclear contribution to total primary energy demand that we have now.

Even that would require roughly 3 to 30 gigawatts a year of new construction. So if we really want nuclear, not just for California, but for the world, I mean, you're talking about a completely unrealistic number of reactors being built any time soon.

5.4.4. Reprocessing

5.4.4.1. Proliferation Concerns

Participant 26: Concerning reprocessing, I have two comments. Matthew Bunn mentioned that long term scarcity of natural uranium is the driver for the fast closed cycle. DoE sponsored an evaluation screening of fuel cycle options, where we looked at all the things people generally care about. Then we put together a spreadsheet that lets you ask what would be your favorite option based upon performance goals? For example, reducing uranium resource mining by two orders of magnitude has many benefits unrelated to the availability of uranium. If you have good, environmentally sound technology, it probably doesn't have much heavy mining.

We should note that there is a fuel cycle technology that doesn't require reprocessing and enrichment and is generally not consider to be the most proliferation-resistant technology, that's the CANDU and its variants.

Matthew Bunn: You're absolutely right. It doesn't require either of those things, but it's still not very proliferation-resistant, in part because the basic reactor design has online refueling. So, you have to safeguard it all the time, as opposed to inspectors keeping an eye on when you open the pressure vessel, as you would with a PWR.

With the CANDU, you also have the lower fuel burnup, so that the plutonium is a little more attractive from a weapons perspective.

5.4.4.2. Reprocessing for Energy Security in France

Frank Carré: For domestic use the main impetus for us in France is really energy security. We are interacted in technologies that will be commercially viable, or that could be technically and economically viable. But in the next generation. At the same time, we are seeking a format for ultimate wastes, conditioning this waste for being placed into geological repositories.

Also this is a more sustainable nuclear power in the sense of avoiding throwing away nuclear materials that have 99.5% value of energy that could be used by the next generation of reactors.

So, as you said, the prime driver is, for an energy-poor country like us or uranium-poor countries, is really energy security. But at the same time–this process is aiming at saving reusable materials and optimally conditioning waste, for the time when it will be put into the repository.

So there could be side effects that could be beneficial, one could argue, but they are secondary. But this also merits asking questions regarding health effects. There could be concern that maybe dealing with nuclear material in the short term might expose people to harm. Currently in the nuclear fuel cycle most of the dose really comes from mining. And then, recycling nuclear materials that have been accumulated at stockpiles, depleted uranium or reprocessed uranium contribute. Just drastically diminishing that necessity can have beneficial aspects.

Scott Kemp: Right now, France is reprocessing, but only has a thermal MOX fuel cycle in which to utilize its reprocessed fuel. I understand your concern, you don't want to throw away good fissionable material, material that can be converted to fissionable material. But why not save it in dry cask? Save it for the day that you do have fast reactors and then you can really utilize it. Also, it's economically sensible to do this, instead of spending the money up front for a technology that doesn't really justify itself economically. Would a dry cask hold the fuel for 100 years?

Frank Carré: I think that history has much to do with it. I think that energy security has always been a concern for France. And that plan for fast neutron reactors originated from the beginning. Also, these applications that could have defense application at the same time. I think that there were plans in the '60s for a fleet of fast neutron reactors to be in operation by 2020. Implementing the spent fuel reprocessing was meant to prepare for the advent of this fleet of fast neutron reactors. However, nuclear energy did not develop as it was anticipated because of the nuclear accidents and economic competition from other energy sources.

So, we had initiated development of this technology. We had implemented in the '70s this spent fuel reprocessing plant of La Hague. One way to make efficient use of it, even though it's of limited benefits with limited recycling, was to reprocess the spent nuclear fuel from the French nuclear fleet and to have the benefit that I just described. I mean, to partition between ultimate waste, and to put it in a robust form, ready to be disposed into the geological repository, and to have stockpiles of unattractive nuclear materials. So, depleted uranium or reprocessing uranium is being accumulated – for the time when other types of reactors that can make efficient use of it will be ready.

So, we went this way. That was interrupted at the end of the '90s. I mean, the industrial development of fast neutron reactors in France was interrupted by political decisions, So that in '98 there was a political decision to stop the operation of Superphoenix. Then we were authorized to proceed with the operation of Phoenix, which was an earlier reactor, for the purpose of research. And now we are in the process of having no fast reactor as well.

The interesting thing is that the Parliament acted similarly to when it took an action that helped resuming the process for creating a deep geological repository. They put one paragraph into an act that was promulgated in June 2006 that is primarily dedicated to implementing a deep geological repository in France. This paragraph says that research should continue on optimizing the waste form, and that CEA, our national lab, should work with industry partners on a prototype of a fast reactor that would demonstrate feasibility by the end of 2020 – that's too early – and should proceed with demonstration of advanced recycling that would demonstrate, achievable progress toward the ultimate waste form.

There was an indirect signal that we could restart research, and we were mandated to work on the project of a new generation of fast neutron reactors that would operate in the 2020s, and would of course meet the goals of this law. At the same time, we should give an opportunity to improve the reactor part of the system, and therefore to come back into the international research on this subject with some advances, compared to the large commercial-sized reactors that India and Russia will connect to the grid this year.

Matthew Bunn: You don't have to make a decision today. You can put the materials into a dry cask. You can put some money aside for whatever it is you're eventually going to do, and let technology and economics develop over time. The reprocessing that's been going on has been occurring because of contracts that got locked in and facilities that got built. Then, the fast reactors didn't come along as people had expected. But one thing that we should be aware of is that as a result of all that, and as a result of the recycling and light water reactors not keeping up, we now have more plutonium separated from spent fuel in civil stocks than in all the world's nuclear weapons combined. This all just happened by mistake; I mean, nobody intended that. So there's an enormous stock of plutonium already separated. In Britain, it was one of several factors that destroyed the company that built the reprocessing plant.

The other thing to mention is, from the MIT Fuel Cycle Study, the key takeaway was that there's enough uranium that it opens the option space a lot. You could have fast reactors that have a breeding ratio of 1.2 or 1.3, or whatever. But you could also have reactors having a breeding ratio of 0.8 or 0.9 or 1.0. So uranium availability doesn't drive you to only a single system.

Frank Carré: Two comments: Regarding the separated plutonium. It's not exactly a stockpile of separated plutonium. It is in the form of spent MOX fuel.

Regarding the other aspects, the breeding gain really is an issue for newcomer countries to nuclear which do not have a plutonium resource. This is the case of China and India. Those countries do not have the stockpile of plutonium needed to start their fast neutron reactors. They are eager to have high performance in terms of breeding gains so as to shorten the doubling time. By this I mean, the time that you need for a reactor to breed enough nuclear material to really have another unit of the same power start operating. Therefore, they are interested in some metallic fuel, and technology that can achieve this high breeding.

For a historically nuclear country like France, there are stockpiles, and the current vision is that at least over the 21st century, they would aim at breakeven breeding. They would certainly not make use of breeding blankets. That certainly could be a positive view of making use of sensitive technology regarding nonproliferation.

5.4.5. Nuclear Security in Libya

Matthew Bunn: In a couple of respects, one could argue that Libya is a good-news story with respect to nuclear security and nonproliferation. Libya was violating its nonproliferation treaty obligations under Muammar Gaddafi, pursuing a nuclear weapons program with assistance from the global black market nuclear network led by Pakistan's AQ Khan, which was attempting to provide a turnkey service. They basically were going to provide the conversion plant, and the enrichment plant. They provided a nuclear bomb design. They were providing UF6, apparently coming from North Korea, et cetera.

However, they were having difficulties, in part because Libya's own domestic capabilities were so extremely limited. The US and British intelligence succeeded in penetrating the Lybian network, and in finding out what was going on. Essentiality they went to the Libyans secretly and said, "Look, we know what you're doing, and we know enough about it that we're going to be able to stop it." And after some back-and-forth they managed to talk Libya into making an announcement that they were giving up the entire program, and letting us basically airlift all of the equipment out of Libya.

So, that's the nonproliferation story. The nuclear security story is less well known. There was a research reactor in Libya fueled with high-enriched uranium that had been provided by the Soviet Union. There were more than ten kilograms of HEU. The United States managed to convince Libya to give up that HEU, and airlifted it back to Russia.

I think, given what's going on in Libya now, we should all imagine what might have been true had those things not happened, had they not gotten rid of all the elements of a nuclear weapons program, had they not gotten rid of the HEU. Imagine that you're the next dictator who wants the bomb. Gadaffi died in a ditch with a bullet in his head.

Matthew Bunn: Indeed. A bad message. And in fact, Ayatollah Khomeini specifically commented on that. He said, "Libya gave up its nuclear effort and look what happened to them." So I personally think that too little consideration was given by the United States and the NATO countries to that potential impact of the decision to go after Gadaffi, and overthrow him. Now we basically have a failed state in Libya. So, from a humanitarian perspective it didn't work out well at all either.

Alan Kuperman, at University of Austin, has a number of interesting articles basically making the case that humanitarian intervention almost never actually helps the people it's intended to help. He has used Libya as one case where it made things worse, rather than better, for the people who it was intended to help.

Scott Kemp: I add another bad-news element to the Libya story. It is that there was a review commissioned by the Congress of the United States on how we detected the Libyan program that it was eventually enabled to intervene. In that review, they reveal that it took them 16 years to see the program. And, almost none of the useful intelligence came from internal Libyan activities. Rather, it just came from trying to piece together the black market network.

Now, Libya was not successful over 16 years because it was paranoid. It kept moving equipment around to different areas and different tents in the desert, and setting things up and taking them down. But, imagine a country that's slightly more competent. If it were to take us 16 years to detect that program, we would have a real problem.

5.4.6. Expanding nuclear likely implies expanded enrichment. Will it be easier to access weapon-grade materials than reprocessing? How do you balance this while expanding nuclear?

Participant 27: Reference has been made to some of the conclusions from the MIT Fuel Cycle Study, and indeed abundant uranium availability was one important conclusion. But the other one which I haven't heard much comment about is that if you are going to supply a large amount of energy, larger than the fraction we are having today from nuclear sources, you're going to have to also expand enrichment services. We're talking about a factor of, let's say, seven, or an order of magnitude. Won't it be somewhat easier to access weapon-grade materials than reprocessing it? How do you see the trade between these two as we expand nuclear?

Matthew Bunn: Again, my view is that it matters a lot where that's being done. So you could imagine that the companies that have managed to achieve a more or less dominant enrichment position – the Russians, the Europeans, maybe the Americans will get back into the game – will essentially expand their existing capacities, and that you won't see a whole lot of spread because they're so far ahead of everybody else that it doesn't make economic sense for anybody else, or at least for very many other people to go into the game.

In that case, you could imagine five, ten times as much enrichment with only a modest increment of additional proliferation risk. You could also imagine that if there is that much more nuclear power in the world, there are going to be more countries that are going to want to go into enrichment, and that more effort on enrichment, total, will mean more R&D on enrichment, more probability that even more problematic technologies will be invented, deployed, et cetera, and that the risks from enrichment will increase. However, in the near term, I don't see anybody who isn't operating an enrichment plant already, other than the South Koreans, who has any significant interest. And I don't expect that to change really substantially in the next couple of decades. I've been wrong before, but that's my guess.

Frank Carré: I'm not an expert in these political aspects, but from the technical point of view, I totally support what Matthew Bunn has said. So, the main thing is where those sensitive technologies are being located. The vision of fuel service centers that are safeguarded in nuclear material countries could give confidence that this would offer appropriate proliferation resistance with maybe the slight difficulty that the nonproliferation treaty so far does not preclude, does not hinder any country that wants to have access to civilian nuclear to develop necessary technologies for that, including enrichment and reprocessing. And therefore, maybe one of the challenges is to discourage these newcomer countries from investing in this technology.

Of course there are advantages in doing so, because of just not having to invest into a litigated facility and maybe the burden that goes with some safeguarded facilities concerning this sensitive technology. But then I think this is probably a challenge and I'm sure it is a matter that is being worked on. It is important to make sure that the growth in enrichment services are appropriately located in countries in which one can be confident. Indeed, some work has to be done along these lines in order to discourage some countries that could be authorized by the nonproliferation treaty to invest into enrichment facilities not to do so, and rather to rely on existing services.

Scott Kemp: Well, I don't think we've solved the problem of proliferation today, but I think we have made clear that we do need some kind of framework for thinking about this, perhaps give it more thought than we have so far.

SESSION 6: Renewable Energy Systems Long-Term Requirements, And Options. What Are the Long-Term Geographical Implications of Renewables in Terms of Economics and Institutions?

6.1 Session Question

The variations in wind and solar energy inputs with location imply large differences in energy production costs. Does a renewable system imply large differences in energy costs across a country with resulting large differences in costs and standards of living? Are there credible energy transportation strategies to levelized costs? Can such megasystems be made secure?

6.2 Introductions

John Pierce: This session discusses renewable energy futures and what happens when you start putting a lot of renewable capacity into the system. Aaron Bloom is from the National Renewable Energy Laboratory (NREL), he's especially going to be relating some lessons from a previous and ongoing studies there about the impacts of trying to integrate fairly high percentages of intermittent renewable sources into the grid. John Reilly is from MIT Sloan School, and is the Co-Director of the Joint Program on the Science and Policy of Global Change. He's an economist. John is going to speak based upon a study that he performed, using the EPA model, for big mission prediction and policy analysis. Aaron's has a U.S.-centric view. And John's is more global. Aaron's concerns what does intermittency do to the energy system, and John's asks, if you put a carbon price on energy, how does the system respond?

6.3 Presentations on long term strategies

6.3.1 Renewable Energy Futures: Aaron Bloom (NREL)

Renewables, meaning wind and solar, make up a very small but growing percentage of the installed electrical capacity in the United States. We have a lot of renewable potential in the US. The cost of renewable energy technology has dropped significantly over recent years. The other advantage is that they have very low lifecycle greenhouse gas emissions and water requirements. However, there are a lot of questions for renewables. An evolving question concerns the sub-hourly variability and uncertainty of the resources. In our research on the Renewable Electricity Futures we analyzed how the electrical systems could operate with very high penetrations of renewables.

What we showed is that the electricity supply and demand can be balanced in every hour of the year, in each region, with 80 percent of electricity coming from renewable resources. We cooperated with industry to make sure that what we are simulated is realistic.

We looked at a variety of different scenarios. We performed a series of studies that were spread across the U.S. grid interconnections in order to understand the importance of a variety of long-term and short-term reliability metrics. In the Western Wind scenarios in Solar Phase 2 studies, we found that the costs of cycling are actually negligible compared to the overall emissions savings obtained of high penetrations of wind and solar. What was shown in Western Wind and the Solar Phase 3 study is that the system can provide reliability and transient stability of services with high wind and solar penetrations.

In our work on the Eastern interconnection, what we found is that we were able to balance the system by means of active power control, even with high renewable technology penetration. The system can also follow the frequency changes and provide high responsiveness.

Extensive analysis with large amounts of industry stakeholder input has shown that it is feasible to integrate 20 percent penetrations of wind and solar into both the Eastern and Western grid interconnections. We’ve analyzed it according to a variety of reliability metrics, and we've seen that there are probably going to be some changes needed in order to reach these high penetration levels. For flexibility you're going to want them, because they make economic sense. You could try to change their ability to ramp up and down in power. We also simulated performance all of our thermal plants using industry-vetted assumptions about the plant heat rates, the power ramp rates, and the ability of these resources.

Detailed and rigorous explorations beyond 35 percent penetration have recently started. We’re starting to dig deeper into these Renewable Energy Future (REF) scenarios. Again, REF looked at hourly performance of big systems, using several appropriate assumptions for examining performance in entire country. We’re investigating demand response in more detail, because demand response offers both flexibility and can help to integrate renewables. The most appealing thing is that it offers elastic supply for the sector when everyone wants it.

We’re also starting to bring this research to the rest of the world. We have now set up active projects in Canada, Mexico, India, China, South Africa, and new projects are starting up in the Philippines and elsewhere in Africa.

6.3.2 The Feasibility, Costs, and Environmental Implications of Large-scale Biomass Energy: John Reilly (MIT)

In our analyses we explored use of different kind of crops and pathways of converting crops into energy where we allow imports and exports of the feedstocks and we imposed a carbon price. We often talk about the fact that 40 percent of the U.S. corn crop land is going into biofuels. But about 30 percent of that effectively goes back into feed. So it isn't really as big a use as you might think. We’re pricing all of those things in terms of market functioning.

We analyzed several scenarios, and have in place renewable fuel standards of the EU and U.S. included in all scenarios. We also use fuel blending constraints that don't go away very fast. In the base case, we assume that they do gradually go away.

Then, importantly, there is a case where we extended that carbon pricing to land carbon. This carbon price doesn't generate much change in cases of wind and solar. It does reduce coal use substantially. But this carbon price doesn't go very far toward fully decarbonizing the economy. We still have a fair amount of gas and coal.

With carbon pricing, we usually see a big demand response that typically appears as improved energy efficiency or reduced fuel use, with a shift in the supplies as well. For global transportation fuels, bio-ethanol is the dominant new fuel, but it's mostly limited to the gasoline fleet, and not the diesel fleet. So, that limits the amount of the petroleum market that it can generate. Biofuels are not replacing all fuels.

I think the idea that building biomass plants based on farmers being nearby is not realistic. The reason is, if the source becomes unreliable, you will want to draw on the broader biomass market to keep the plant running. So, I think that these crops will become bulk commodities.

In conclusion, the effect of bio-energy production upon food prices is likely to be relatively small. The penetration of low carbon biofuels relies on achieving large cost reductions for these technologies. Otherwise, first generation biofuels remain in the fuel mix, and bio-electricity and bio-heat will be the major forms of energy, regardless of location of the bio-energy production.

High pricing of carbon and land can eliminate deforestation. This can create reforestation and can actually benefit biofuels, because land owners producing low carbon stocks can increase them and receive payments for doing so.

As for trade barriers, what if countries aren't participating in protecting land? Well, if you erect trade barriers, we found that doing this doesn't have a big effect upon carbon emissions necessarily. But, it does create an economic penalty. You saw that Africa and Latin America should be big exporters of biofuels, but instead, they're not participating. You know, banning their imports of biofuels would give them an incentive if we were saying that if they would protect their forests, then, we'd be happy to import their biofuels.

So, I think one has to look at biomass not as a single technology, but as many different technologies which, under different circumstances will compete mutually. I think that the idea of trying to associate a particular carbon co-efficient with a particular fuel or particular source, is like assuming existence of an engineering fact, when in reality, it's a result of the policy environment that we have set up and in which biofuels are operating.

6.4 Discussions of long term strategies

6.4.1 Actual system configuration and cost

Participant 28: Even though it has been proven that we can run our energy economy based upon high penetration of wind and solar, the system configuration and cost remains big questions.

System reliability and capital investment source are questionable. Moreover, whether the public will be satisfied by the actual configuration of the system remains unknown since there is a possibility that the future system will need to have much larger capacity than that of today to serve the load. Transmission will also be a problem.

Aaron Bloom: In our model we included considerations of cost and transmission in detail. Moreover, we have another research project that will concentrate on the actual system configuration and capacity. That may help to answer these questions.

Participant 28: Whether the public is willing to pay for the actual system is a question that should be considered seriously.

Participant 12: What about the economics of the base load providers, of the renewable base load providers?

Aaron Bloom: The traditional base load units that are 60 years old, will probably go out of the market. That's what happens when new inframarginal resources enter the market with lower marginal cost structures. We saw that when nuclear came online in the '60s and '70s and displaced a lot of generation. And we're seeing that substantially right now, with very low natural gas prices that are significantly affecting nuclear plants today, even at modest penetration levels.

So, if you want to talk about what's happening to units today, you can talk about the price of natural gas and how it's ruining the day for coal and nuclear plants. That is the greatest influence on electricity prices right now, because the renewables set the price.

6.4.2 Cropland consumption

Participant 28: The Food Agriculture Organization (FAO) projects that we shall need more crops to feed people all over the world in 2030 and 2050. However, in John's lecture, the cropland decreased slightly. Is the cropland enough for producing the crop that we need?

John Reilly: Our result is really coincident with what FAO projected in its latest study. The reason is the population growth is slower, and, thus, the crop that we need will not increase very much.

6.4.3 High renewable penetration accomplishment

Participant 29: I'm a little skeptical on the REF Study with being able to balance the grid with 80 percent penetration by renewables. How are you accomplishing 80 percent penetration? What's the actual installed capacity?

Aaron Bloom: The methodology is well established and quite heavily industrially-influenced and vetted. As for reserve requirements, interestingly, we have not found a documented need for increased contingency reserve requirements with high penetrations of renewables.

Participant 29: So, do some of those methods to balance that penetration include a significant amount of demand response and transmission increases?

Aaron Bloom: We studied a variety of different penetration levels, but the result is that we don't need to increase demand response and transmission capabilities.

Participant 29: My other question concerns grid reliability metrics that you're applying to assess reliability. What are they?

Aaron Bloom: There's a variety of grid reliability metrics based on the timeframe of interest. In the long-term, the traditional, very bad, reliability metric is the planning reserve margin.

The next types of reliability metrics that we consider are the balancing one, which is why we do five-minute load level analysis, and an hourly analysis in order to see whether we can balance the system at a five-minute level. Then, at very high frequencies, we examine things like CPS1, CPS2, ACE and BAAL. These are all NERC reliability standards. I guess that there're almost 137 standards, with multiple components, used by NERC.

John Reilly: When the renewable capacity goes up to 70 or 80 percent, the demand is really flat. A lot more capacity is required because wind and solar are operating at small generation of the total energy levels consumed. Moreover, intermittent renewables do not equal 80 percent. We also have other kinds of renewable energy like biomass, hydro and geothermal available to balance the system.

Aaron Bloom: Typically, in the United States, our only Concentrating Solar Power (CSP) resource is in the Western interconnection except for New Mexico, which has some CSP quality resources. But it does include both CSP and PV. Also, CSP includes thermal energy storage, an amount of storage that's consistent with industry thoughts on likely futures.

Participant 30: We will get the more renewable electricity for sure. But our transmission and distribution infrastructure needs to be consistent with that?

Aaron Bloom: I think that distributed generation renewables present a really interesting question. They can provide an alternative to transmission improvements and updates. We also have additional research projects examining the effect of high penetrations of electric vehicles.

Participant 4: So, we have this other hypothesis that in the case of large renewable capacity, that we can dispatch some of that as thermal energy obtained from power production over to the other industries, in particular manufacturing, and maybe even making fuels, such that we can lower the carbon footprint of all industries collectively. What do you think is the importance of that?

Aaron Bloom: It would be interesting to see how industrial operations, or high level commercial operations might change with large amounts of renewable generation. I think what you're asking is, can you get enough heat if you have an all-renewable electricity system? Also, converting wind energy to electricity, then to heat, is inefficient.

Participant 4: Yes, but the other part of the problem concerns large capacity generators, nuclear plants, coal plants. If you dispatch the thermal energy from those units into a secondary product market, and it might be hydrogen that you make, if you can produce the heat where needed.

Aaron Bloom: Right now, our models concern only the electricity system. We're now working on a project, on renewable nuclear hybrid systems to try to start bridging that gap. It concerns what would happen if you could take heat off from a nuclear system to provide industrial services?

I think that one of the interesting questions concerns at what point is it more expensive to create a system for dumping heat into industrial processes versus just curtailing use of renewables? Renewables are incredibly flexible. You can turn off individual turbines. You can turn off parts of panels. And inverters can be useful. We don't know when we should be building all these other systems, or which parts in order to balance the system?

Participant 29: The second scenario does not begin to reduce carbon in the industrial sector.

Aaron Bloom: The largest consumer of electricity in the United States is the industrial sector. So, if you decarbonize a lot of the electricity sector through renewables, you decrease industrial 40 percent of the load in the United States.

Participant 1: My electrical engineering question is an idea I had from our system operator in the UK, National Grid. That's to do with the situation where distributed generation to the system operator looks just like less demand. However, the operator doesn't see it. It's not metered.

These system balance experts, with the UK system which is pretty small and homogenous watch the TV schedules. They know when a football match is on. They know when the kids get back from school, and all that kind of thing. After 60 years of experience they know what the load looks like.

But what happens when a cloud goes in front of the sun, and London suddenly appears, on the grid. London, with all its solar panels in the future, wasn't there, because it was making its own distributed generation. And then when the cloud goes in front of the sun; vroom, suddenly the demand is on the system. What do we do about that?

Aaron Bloom: Island nations are going to have a more difficult time integrating large amounts of renewables. I think that the number one thing that I would suggest to the UK is to, one, build more transmission lines to Ireland; two, to build some more lines to the mainland. I think that that's what you're really going to need to do, because a very small system will have bigger challenges.

Participant 1: The U.S. has big cities like New York City and clouds as well. In the UK, we're connected to France, this applies to the U.S. as well as the UK.

Aaron Bloom: So New York City is very much transmission-constrained. That is why they have localized thermal generation today, with a lot of combustion turbines and boilers that run on "Reliability Must Run" contracts, all the time.

Participant 1: I suggest that they will continue to need that thermal generation.

Aaron Bloom: They probably will —It all depends upon what happens with a variety of different technologies. You could install storage there. You could install thermal generation. You could use biofuels or something else, as well. You could use small module nuclear reactors as well, depending upon where you put them.

John Reilly: How about a hydrogen fuel cell?

Aaron Bloom: A hydrogen fuel cell could be another option. Sure. I think there're many options. You're right to point out that load-constrained regions that cannot get a lot of transmission capacity into them, that also have a large cloud go over head, will see some problems. Here is the great thing about transmission and AC power. The power transmits instantaneously, at the speed of light, for the entire system, based upon the impedance of the system. So, when you do see that cloud, while at some level it does hit just New York City, if it's connected to the rest of the system electrically and synchronously, it will be balanced instantaneously on the system. It will be felt everywhere that is interconnected.

Participant 28: I don't think that your response was actually quite accurate, because the concerns of distributed solar and reliability really manifest themselves principally at the distribution level. Your transmission system does not necessarily save you at the distribution level. We're already having examples in the United States in the Duke Service territory and Southern California Edison, where you have high penetration of rooftop solar on particular distribution feeders, the cloud effect happens, and you have voltage stability problems.

Aaron Bloom: You're absolutely right at the distribution level, the distribution level questions are real.

Participant 28: Then, the untold story about Germany is that, in the past 36 months, the number of (N-1) configuration violations of the grids within the four German TSOs, has gone from one or two per month to hundreds per month. The agency that collects the data and regulates the network went from openly publishing these data, as we do in the United States, to suddenly making it a state secret.

So, the reliability questions are really not restricted to the transmission system. We used to say that the transmission was the poor cousin of generation. You know, the generation planner sort of defined the world. And the transmission planners were the poor electrical engineers just sitting in the corner, waiting for whatever the generation guys required.

So, then distribution is the poor cousin to the poor cousin. Globally, our distribution systems are woefully underbuilt and outdated, and probably not well-adapted to this new world that people envision.

Participant 31: My question concerns increasing amounts of renewables, where management of such great loads become more and more time-responsive. How are the investment tax credit (ITC) to manage this—but will have to change? I believe that research in this field is almost as important as with the more electrical, technical one.

Aaron Bloom: Yes, at the distributed scale, we do have a variety of voltage concern questions affecting how you manage that system. Typically, almost every distributed system at least aligns. The components of those lines are highly regulated in the United States. There are no market incentives for providing voltage responsive characteristics at the distribution scale. So, while you could use static components, you could use capacitors, you could use a variety of resources that are located on the lines, you could also use the inverter-based technologies themselves to provide the voltage resources. But there currently exist no incentives to do that. That's because distribution is a natural monopoly.

6.4.4 Question on biomass study

Participant 4: First, concerning the biomass study, were you looking at carbon capture and sequestration for the coal plants in that expansion of biomass? Second, do food crop increases, per year of production, assume use of genetically modified crops?

John Reilly: Carbon capture and storage is an option for gas and coal generation, but it's not really going to work at those carbon prices. We need much higher carbon prices for that. We have yield trends that reflect historical yield trends, that are consistent with FAO types of projections, perhaps at one percent or 3/4 of a percent.

We haven't made an assumption about the causes of what exactly is behind those yield increases, whether it's genetic modification or conventional plant breeding,.

Participant 12: Analysts tend to focus on the need for cropland. As you know, there's twice as much pastureland, or at least land classified as pasture, as there is cropland. We recently asked, "What fraction of global nutrition comes from pastureland?" You can examine that in terms of protein, or calories. The answer is 2.7 percent of global protein, dietary protein, and less than that, about half of that of calories.

Most studies of where the bio-energy would come from see more of it coming from current pastureland than cropland. So you're right to account for cropland. But people readily forget pastureland. There's much larger potential for sustainable intensification of food output from pasture than from cropland.

The big question concerning bio-energy playing its most effective role in carbon mitigation, is that cellulosic ethanol comes on first among the second energy generation biofuels. But, later we would actually be making things that biofuels can more uniquely provide for, aviation fuel, diesel substitutes and things of that kind. At one level in the consequences, it almost doesn't matter what fuel is being made, as far as carbon displacement is concerned. Are you pessimistic that in 30 years we could be seeing that kind of substitution?

John Reilly: I think that this level of carbon price that we considered is not enough to do what is needed. This carbon price is not going to keep warming below 2 °C. It's not going to stabilize the temperature. So, if we examined a carbon price that would generate the needed change. We focused on 150 exojule per year, primary biomass energy production rate, asking should we have biomass energy output of that size, what would it look like? We have looked at the problem of pushing biodiesel into jet fuel. We performed some studies with the Federal Aviation Administration. They really want to get the biodiesel into use by the airlines. What we found is that, of what you produce only a fraction is actually biodiesel. So, in order to produce enough jet fuel, you have to flood the market with the other byproducts that no one wants. Then, you must underprice it in order to get it into the market. Then, as you do this more and more, the total production cost is borne by the jet fuel. We don't really have to go to zero carbon. The earth, the ocean is actually taking up a fair amount of carbon. We can stabilize carbon and not go to zero carbon for 10,000 years, once we account for the ocean uptake. There are some uses of carbon that are fairly precious and flying an airplane is one of those.

In reality we can create a substitute for almost any hydrocarbon if we need to. A question is that of whether it's technologically possible to run the economy without fossil energy? I think, given our technological innovation in turning biomass into drop-in fuels, that the answer is, yes. The more important question is, how fast and at what cost? I think that the cost of using biofuel is much less than using carbon capture and storage at coal power plants, for example.

Participant 6: John Reilly, did your scenario building include any of the optimal fuel uses? For example, using the alcohol fuels in their optimal way in existing agents, or perhaps the most efficient way to use ethanol in a gasoline engine is at about a 30 percent blend, but putting it in either mixed, or putting it in when the torque requires it. Or perhaps it is with methanol and perhaps ethanol also in a diesel engine, when you inject it upon demand.

John Reilly: No. So rather, we assumed that there's some way of optimizing it further. We assume that it's going into a conventional engine as a variable blend, and receiving some energy penalty, competing on an energy rather than a volume basis.

Participant 6: Yes, I also want to respond to, and agree with your comment. However, the price for an electrical car is much more expensive than that of using biofuels. The more that I look at it, the more that I'm not convinced that we're going to be able to get the price of those fuels down.

So, it's really incumbent upon us who work with the biofuels to get their costs down. Concerning your scenarios, it looked as if you assumed that the lignocellulosic ethanol price actually never becomes more than a factor of maybe a couple of dollars per gallon. In other analyses it was always quite a bit more expensive than grain ethanol. And yet, with that, it's still the dominant energy contributor. Is that because of the carbon price? Yes, it pushes the cost of the other stuff up a little bit more.

6.4.5 Biofuel land use

Participant 6: In terms of the biofuels we have a concern about land use. Obviously, the footprint for the collection of the solar and wind is small. But maybe the collective footprints, considering that for distribution of it is (a) not small, or (b) also contentious. I mean just getting the right of way is difficult. What do you see regarding land use or land availability for expanding use of the biofuel use?

Aaron Bloom: I believe that REF includes some analysis of land use for the renewable generating resources. I'm not so sure if they include that needed for transmission. I think that we will face a challenge concerning transmission, regardless of the resources that we build.

Also, if you're talking about small countries, they are going to need transmission as well. The good thing about transmission is that, once you build it, there's not a lot of additional impact on the land. The same is true with distribution. Also, HVDC lines require much less land than do AC lines.

6.4.6 High penetration electricity price

Participant 24: The graphs indicate a lot of curtailment of PV over wind. Translated, that means that the price of electricity on the wholesale market is zero. That means the person who owns these resources gets zero. I'm not quite sure how you build PV for zero. This raises the question, is NREL considering any market analysis, where you account for the variable price of electricity in a deregulated market, and the fact that, as soon as you have such curtailment, your price of electricity is zero, and there provides zero revenue?

Aaron Bloom: In several of the intervals, we have curtailment, but we also have thermal generation online. So, the electricity price is not equal to zero in those intervals. You can have curtailment for reasons that are non-economic. You can have the curtailment due to transmission constraints, for example, or due to thermal constraints, or for providing reserves. That does not necessarily always mean that the price is equal to zero, though your point about very low marginal prices still obtaining holds for many intervals, including those for other variable cost resources. Historically, the number one source of negative prices was nuclear plants in the evening, which is why we built pump hydro facilities in our scenarios. An exciting area of work is market design, concerning how do you design these electricity markets to recover sufficient rates, in order to keep people in business. So, market design is linked here.

Participant 24: In the United States, we have different Independent System Operators (ISOs), using different rules. By contrast with the Texas ISO, it’s a free market. Attentively in California, they’ve rigged the game in more ways than you can count.

Aaron Bloom: Well, they all have very different approaches to assuring capacity. I mean the historical approach to maintaining capacity was to provide rate of return regulation. But in the 1990s, came the idea of locational marginal prices, that really changed the framework of a deregulated paradigm.

So, the important question, today concerns how very high penetrations of nuclear or renewables or other very low cost resources, how do you assure revenue sufficiency?

John Reilly: In a recent PhD thesis about Mexico we saw that you do get negative prices; but you also get very high positive prices at other times. Where the system runs into problems, as we saw in Europe, is where you regulate the high prices, and then, the plants that are built have to survive based upon a few days or weeks of incredibly high prices. So you have to let that market work. Otherwise, we're going to have problems.

Participant 1: My question concerns energy economics. I view matters in a British context; and wish to contrast it to the U.S. context.

We rebuilt our electricity market in the UK over the last two and a half years, substantially. This included capacity payments. So we left the energy-only market, and we now pay people to have a gas turbine that doesn't run, but could run. So, in a world of moderately low decarbonization, you have a mix of renewables and gas, and the gas runs part of the time. The owners are paid every day for being able to run. But in the world of 80 percent renewables the system has a lot of excess power capacity. Charles Forsberg alluded to the idea that no money changes hands on those no-generation days. My point is that in the UK system, yes, it does.

Aaron Bloom: So, it depends upon which region you're talking about. Capacity markets are not uniformly adopted in the U.S. There are three capacity markets. In ERCOT they use an energy-only market, which is why they increased their price cap recently. The reasons that we have these market structures predates renewables by a lot. The reason that we have them now is because of excessive amounts of market power and monopolistic tendencies in the industry.

So, as you diversify the production resources, spread them out and have smaller plants generally, some of these concerns, at least in the generation side, start to go away. This settles doubts about whether you're right. I mean this is the big question. So, you can operate the system successfully. The question now is, how do you get to the system that you want to have in a way that is revenue-sufficient to stay in business?

6.4.7 Appropriate Carbon Price

Participant 32: It seems to me that it is not clear that this carbon price is going to be sufficient to permit warming to stay below two degrees. The previous analysis incorporates many assumptions about technology and how it will change and how much R&D we do, et cetera. Optimistically, with McKinsey's graphs, they envision a huge amount of carbon reduction for pretty small carbon prices. I'm unsure that this is realistic.

For many of these things, we ought to be thinking about whether the implied carbon price makes sense? After all, there is a limit to how much we ought to be willing to pay. So today, for rooftop solar in the United States the implied cost of avoided carbon is something of the order of $300 dollars a ton. There are people who are working on the concept of taking carbon right out of the atmosphere, who think they're going to be able to do it at $150 or $200 dollars a ton. If they turn out to be right, then we shouldn't pay for anything near $300 dollars a ton. My guess is, for carbon capture and storage, even from a coal plant, where there's a lot of carbon available, in a fairly concentrated form, that the cost may still turn out to cost $300 dollars a ton or more.

What's the cheapest way to get rid of carbon? It has looked as though, at a relatively modest carbon price, you have a lot of bio-energy coming in, and not very much wind, solar and nuclear coming in.

John Reilly: I think that the market should make that determination. Then you can decide what carbon price you want to live with. One of the things that we see is that our studies reflect the way that incentives are now. Future incentives could be different. In this forecasting, we have tended to be conservative regarding advances in technology, though internal combustion ethanol was very optimistic. The problem of being very optimistic about technology is we fool people into thinking this is really easy to do, and then we don't do as much as had been assumed.

If you take an economically optimized system, and you assume that technology will become very cheap in 50 or 100 years, then you might say, "Oh good, I don't have to do anything now. I'm just going to wait until the solution become cheap."

Participant 32: I come to exactly the opposite conclusion, because it seems to me what makes responding to carbon becoming cheap is for a lot of people to invest in response to incentives to emit less carbon.

John Reilly: The carbon price will do that.

Participant 32: A problem with many of the economic models of climate change is that the changes in technology are exogenous to the model. So, if putting on a carbon price has no effect on people's investment in R&D, it makes sense to postpone imposing on the carbon price. If, in fact, putting on a carbon price now causes more, early investment in low carbon with people throughout the economy figuring out ways to emit less carbon, it might greatly reduce our long-term costs if we were to get that investment started today.

John Reilly: We've performed studies like that. If you assume that the carbon price is going to come in the future, and you think that there's a benefit in learning connected with starting early to reduce carbon, you have to believe that those technological gains are going to be captured by a private firm.

On the other hand, if you think there's an unwillingness of society to pay a lot for carbon reduction in the future, and you put an escape price in, then having that connection makes it sure that no one will do anything now, because they know that you're going to trigger this escape price. So these facilities can work in both ways.

6.4.8 Interstate Differences

Participant 11: I note that in California, energy demand is much way less than for the rest of the United States, and it has been dropping, relatively, for a long time. I call it the Art Rosenfeld effect. Because of policies in California, our electricity growth was very different for the last 20-25 years, and continues to be different from that of the rest of the country. And yet, we have the same patterns of consumption of everything else as do everybody else.

The example provided, from the Lawrence-Berkeley Laboratory, and Art Rosenfeld's work there was prescient, and has remained the hallmark of what people ought to be doing everywhere in the world. The largest potential for carbon decrease in the United States in the next decade or two, is for the rest of the country to do what we've already done in California, which is to take seriously getting the services that energy provides, while using less energy.

Even in transportation, we're doing better than the rest of the country. Not as much, as in the electricity and industrial sectors though. For the industrial sector the change is not just in electricity, it involves the other fuels in industry too. There's a huge potential for efficiency improvement, worldwide, that hasn't yet been tapped. And in the next 20 years, surely, the easiest improvements are with efficiency for decarbonizing our planet.

Now, the crucial thing about this is that it doesn't cost money, it saves money. Almost everything we've done in California saves money. That's a reason why our economy in California is doing so well (although we also have Silicon Valley). But the rest of the story is that our economy is prospering in the industrial sector because we are more efficient than the rest of the country, and more efficient than almost everywhere else in the rest of the world too.

I want to argue that this improvement isn't just the result of a social change. There are also researchable technical questions here. We have understood this, now that we've gone as far as we've gone, because there's a tremendous additional potential for using energy more efficiently, where the needed research hasn't yet been realized.

We have the benefit in California of having a political environment that's conducive to efficiency improvement that is almost absent in most of the rest of the United States. Maybe Massachusetts, is the other place like California. But there aren't very many other such places. Maybe the key to this problem is that the lesson hasn't penetrated to the people who seem to be uninterested in this, because they don't understand that it actually saves money.

John Reilly: One of the things that you have to examine is not only overt energy use, but embodied energy use. California, through its imports of products, is a major importer of embodied energy use. Whereas, other states are exporting it. So, if you just look at the energy use in the state, it looks like California is much, much better than other states. But, when you look at their consumption patterns, and what its consumption implies for world energy use, it's not that much different. You have in California the advantage of having a slightly less severe climate. Warming your house is easier. We'd all move there, but apparently there's not enough water.

Participant 5: I want to build on that, because, one of the challenges that we face is that of being careful that we don't think too much about our state boundaries. As we know, there's a tremendous wind resource in Wyoming. It could be the cheapest source of zero carbon, having the highest capacity factor wind in the world. But yet there are huge market and political barriers, such that California wants to make their own electricity.

Now, the question that I have for Aaron Bloom and John Reilly is, if I think about getting to a zero carbon end-state, it seems that we're missing a tool from our toolkit. We need a dispatchable form of electricity, that has zero carbon fuel. We can talk about biogas feeding the gas turbines. But there seems to me that there is a dominant option that is missing that we must consider if we're going to have a cost-effective, zero carbon future, and not have tremendous excess capacity built.

This is because we don't have an option to take advantage of those sources of electricity to produce a fuel that could be used at different times of day.

It seems to me that we're missing a piece, and that has been the thesis of the workshop. After listening to the discussions of these two days I certainly come away with a feeling that we're missing decent technologies that society needs in order to achieve the future two-degree goal.

SESSION 7: Closeout: Agenda for Creating the low Carbon Energy Future

7.1 Creating the Low Carbon Energy Future: *Robert Armstrong* (MIT)

7.1.1 Pathways to Low/zero Carbon

7.1.1.1 Price on Carbon

Robert Armstrong: I have three slides to reflect on what I've heard, and what some of the issues are, as we look to creating a low carbon energy future. A key to getting there is a price on carbon. But we'll return to reality in just a second. I think that setting a price on carbon is important for leveling the competition of renewables relative to hydrocarbons. An under-appreciated factor is that we have a lot of the technological expertise that's idle, and not engaged in developing solutions, because there is no money to be made at the moment in doing so. There is not a market for such efforts.

For the global energy industry, there is no viable low carbon business model, given the current price structures. We need a way to get that vast talent pool engaged. A way to do that is to raise a price on carbon to turn some of these other technologies into viable businesses. Ross from Google alluded to that yesterday in his talk, the need to have a market that's viable.

7.1.1.2 Efficiency

Robert Armstrong: The second item on my list, in the absence of a carbon price's efficiency, is that there is sometimes a rebound effect with efficiency. You use more of a technology as it becomes more efficient, and you may end up using more of the related resource instead of less. For that reason, I think that the first opportunity lies with efficiency improvements in the commercial sector, where there's a much better understanding of the direct impact coming from having manufacturing operations that are more energy-efficient. So, concerning efficiency, I would look first to the commercial sector, both manufacturing, but also commercial buildings, for great opportunities. Certainly, property managers are always interested in reducing costs.

7.1.1.3 Lower carbon footprint of fossil fuels

Robert Armstrong: The third factor is reducing the carbon footprint of fossil fuels. Producing fossil fuels is what we know how to do at a really large scale. So we must use the fossil fuels that we have and lower the carbon footprint. Moving from high carbon content to coal to oil and gas is clearly a great opportunity. We have used it to great advantage in the U.S., and because of leakage effects, Germany has used it to great disadvantage over on the other side of the Atlantic. So, this can cut both ways.

I also emphasize CCS, because it's hard to imagine that we're going to get to a low carbon future without some major role for hydrocarbons. Using those having low carbon effect is going to require making CCS work. It's much more likely, of course, that we're going to be able to remove CO2 economically at the source rather than once it's in the atmosphere. That becomes a very, very difficult problem because of the very low concentrations involved.

Participant 21: Getting carbon at the source is the low hanging fruit. Everybody recognizes that. But the big problem is that if you're not coming up with fossil fuel substitutes you're going to have distributed consumption with all kinds of people using it in different places. That model doesn't really work. So, one of the remaining questions concerns what can really be done for getting CO_2 out of the atmosphere, where, as you know, the low concentration of the atmosphere is a bad place to start.

Robert Armstrong: Yesterday in her talk, Jane Long made a very good comment, namely that the energy system that you may envision for the very long term isn't necessarily the energy system that you envision getting you there. We certainly use a lot of fossil fuels at point sources, in the electric sector in particular, so from coal and natural gas, it's easy to imagine doing much better job at CCS.

Participant 23: I think CCS is great and it would be even greater if we could get its cost below about $250 dollars a ton of CO_2. Then, maybe, one could imagine using it. There exists a very effective technology to remove CO_2 from the air, that of all the green plants that live out there, where they make a living doing that, and they also sequester carbon. They just don't put it down in a hole, instead they put it close in the ground.

Robert Armstrong: I also think that there is a place here for new technology. We can go back to the incumbent energy industry, where there is a lot of expertise that could be brought to bear on these problems. There is a fairly new technology, from a company named Net Power. This is not an endorsement for the technology, but it's possible that the technology that they have developed, called a power cycle with an alum cycle on the back end, brings out a stream of CO_2 at super critical conditions, so that it's ready for sequestration. It's on the high pressure side, not the low pressure side, so you don't need a compressor for the sequestration part. So, it's conceivably a very interesting solution in the electric sector.

Participant 6: At the risk of getting on a soapbox, I would just remind us that there is another technology in use already, called agriculture. As John pointed out, it's using green plants. I know that it's not fancy or high tech, but it's ready to implement and maybe it wouldn't take a lot of cost to expand. I think we have to be serious about this. Biological carbon capture and storage is a real possibility that has to be part of what is investigated here.

Robert Armstrong: I am completely agnostic of this. I think that we ought to do whatever is cheapest and can get us to our goal. It has also been noted that there is the possibility of having a negative CO2 footprint if you do CCS on a biomass fired power plant. So, there is a lot out there, but we need to develop yet.

7.1.1.4 RD&D to Lower the Price of Renewables

Robert Armstrong: The R & D that I put on this list is a reminder that there is a lot of work to be done, even in the absence of a price on carbon. In order to lower the policy burden to be faced eventually when a price is placed on carbon. I recall that Ronald Prinn had considered a price of $4200 dollars a ton. In current situation that is not feasible.

A great story is that of the old SO_2 cap and trade system that was put in place back in the early 90's. There were projections of enormous prices on SO_2 and they never appeared. The prices ended up being much, much less than anybody thought that they would. This is partly because technology appeared that made it a lot cheaper. That could happen here also.

Participant 7: If we're going to restrict the temperature increase only to two degrees we have to do everything feasible right now, immediately, before technology improves. That's the challenge if we really want limit increases to be below two degrees. That's the target that has been set. I think that that is possible, but there is no time to improve technology if we're getting to no more than two-degrees' increase. We have to do this with what we have.

Participant 32: I just don't agree with that. It seems to me that we're never going to limit increases to only two degrees with the technologies that we have now. I don't think that we're going to limit increases to two degrees, period. It seems to me that we need to be spending money deploying capabilities that we have to create markets for low carbon technologies, but we also need to be spending substantially more money globally on inventing new technologies that will be cheaper, easier, more effective, and that can allow us to reach this goal with lower carbon prices.

Participant 7: By the time that that becomes our policy we shall have need to have done everything that we need in order to be on a path to only two degrees temperature increase. We only have until 2030 to do this. You can't invent a new technology by then and have it deployed, period. We have only until 2023 to limit our emissions, innovation is not going to help us attain a two-degrees limit. Innovation may make it cheaper to stay there later on, though.

Participant 6: I agree, I don't think that we have the time to innovate, and to scale up. That's doubly the reason for taking advantage of existing technologies, plants and agriculture, for a lot of this. We know how to grow stuff, and there are other uses for biomass for energy. We can always burn it. It can provide electricity now. Then, other innovations will come along. Green plants can provide a big help here, getting them needs to be part of this discussion.

Participant 32: Globally we're spending about 200 billion dollars a year on low carbon energy deployments, and we are on a carbon emission track that is well above the worst case scenario that the IPCC put out in 1992. So apparently deploying what we've got at a scale of 200 billion dollars a year is not even getting us to the worst case scenario, let alone to a scenario that we would like to be on.

7.1.1.5 Co-benefits: Health and Reduced Transportation Needs

Participant 32: I would like to see a fifth bullet here which would consist of paying attention to co-benefits. I think in a lot of places that the drive for wind or nuclear, or what have you, has as much to do with avoiding fine particulates, assuring energy security and diversity of supply, as avoiding dealing with the gigantic transportation problem of coal. In China something like 30 or 40% of all rail traffic at this point is for moving coal. I think that moving to some of these other technologies looks kind of daunting if all that you're dealing with is carbon, but if you're dealing with carbon and simultaneously saving huge numbers of people who would die from the fine particulates, or making Beijing livable again, then it looks a lot more attractive.

7.1.2 Challenges of Low/zero Carbon Energy at Scale

7.1.2.1 Fossil Fuels: Cost, CCS

Robert Armstrong: So, we have a set of challenges. They have been touched on in much of the conversation already. With fossil fuels, an issue is cost. We see cost being helpful in the U.S. with natural gas prices being low, and that is driving coal out of the system. There is the cost of the CO2 emissions, which is a problem with fossil energy. Here I remind us again that CCS has got to be an important part of future on energy system.

One question concerns to what extent can we use retrofits? Given that we have a lot of fossil energy infrastructure in place, we need to consider what of that could be retired without serious loss to the system and what could be retrofitted? We held a symposium here in 2009 where we examined the possibilities of retrofitting existing coal fired power plants as a way to meet the Waxman Markey targets. The rough cost estimates that we produced were in the low 20% range, not a big number.

The technology exists for CCS. We know how to do it, but we have never really done anything at big scale, meaning using a full sized power plant over its lifetime. We don't have the costs knowledge yet for capture, but that could be a fertile area for research.

Participant 5: You've said a couple of times, that from your perspective, you just can't see the future without CCS. I think that if there were a carbon tax to motivate the incumbents that would be best suited to sort out CCS and EGS, and they could be the ones who would determine the better pathways.

Robert Armstrong: I agree. We have got to get CCS involved. In solar there is concentrated solar power. It's basically a process plant. It's full of heat exchangers. Many of the companies that build CSP plants aren't really that good at using heat exchangers. So there is some basic engineering that we need the right expertise on.

Participant 23: I just want to make the point that the fossil fuel industry is not a monolith, and that the people who make electric power don't know the first thing about what goes on under the Earth. The people that produce oil and gas know what goes on under the Earth, but they don't know the first thing about producing power. So, there is an interesting dynamic.

7.1.2.2 Biofuels: Cost, Land, Water, and Fertilizer

Robert Armstrong: For every type of biofuel, the top issue is cost. Energy at the end of the day is a commodity, and cost is what drives the story ultimately.

7.1.2.3 Solar/wind: Cost, Transmission, and Intermittency

Robert Armstrong: For solar and wind, it has been noted that today's incumbent solar technology is crystalline silicon. We'll be using it for the next couple of decades, it is likely too expensive for a long term reliance, however. There is a strong need for technology development to produce solar that is cheap to manufacture and has a cheap installation format. You've got to consider a system here, not just cost of making the cells, but the cost of putting it on roofs or in utility scale installations.

Environmental concerns are important for all of these technologies. We have a lot more experience with some than others, i.e., nuclear and fossil energy, where we know what some of the difficulties are. We frankly don't know with a lot of the renewable technologies what their important products may be. With materials like Cadmium telluride (CdTe) the first solar model is that they lease the panel to you and they take it back at the end for recycling of toxic materials. With perovskites, if that would come to be a major material for emerging thin film solar, today it is in a soluble form. So, that would not be good if it should get into the soil. I think that any of these technologies have some environmental questions.

Participant 5: A challenge that you might want to consider, particularly with solar, is that of being restrained by the availability of rare materials.

Robert Budnitz: We envisioned the future technology being focused on emerging thin films. The leading candidate is perovskites, consisting of Earth-abundant materials. As Francis O'Sullivan mentioned, you're not going to scale up something like CdTe technology. You need 1400 years of current production rates to get to the needed output level. So, Earth-abundant materials must be part of the picture. But, then we shall still have problems of transmission and intermittency.

7.1.2.4 Nuclear: Cost, Safety, Waste Disposal, Proliferation

Participant 10: I don't think that safety is the correct description of the problem for nuclear. Maybe it's one of public perception, or public acceptance. I say this because nuclear is the safest way to make power.

Participant 17: Alternatively, we should note that safety is a concern with fossil fuels as well as environmental impact and water. I know of no instances in this country in the last 20 years where we have wiped out a major water supply from any towns from a spill of nuclear waste, and fossil plants have done that on more than one occasion.

7.1.2.5 Geothermal: Cost

Robert Armstrong: I had a meeting with some Geothermal experts from Iceland not long ago, and they pointed out that they have environmental groups there that fight back against building new geothermal plants. I was surprised because I thought, "What could be simpler and cleaner than that?" It turns out that it's viewed as an eyesore to see this thing with a big tower out in the middle of a pristine field in Iceland.

Participant 5: I think the other possible challenge with geothermal is the capacity problem. For hydrothermal in the U.S. maybe we have 30 or 40 gigawatts capacity, but that's not enough to change anything. If we really wanted to use geothermal as a major resource we must succeed with enhanced geothermal systems. That is a major challenge.

Robert Armstrong: Cost is also a problem. This is a place where we can learn from the fossil energy industry, having much experience in subsurface production technologies, drilling technologies. A big challenge with the engineering of geothermal is the cost of drilling deep.

7.1.2.6 Wave/Tidal: Cost

Robert Armstrong: Wave Energy is too expensive.

7.1.2.7 Hydroelectric Generation: Little Room for Expansion

Robert Armstrong: Hydro is the greatest of the renewable technologies, but it's more or less exhausted at least in the United States. I think that we should take advantage of all the hydro that we can, but there isn't much room for expansion of this sector in the U.S.

7.1.3 How to Make it Happen

7.1.3.1 Focus on the Goal not the Tactics

Robert Armstrong: How do you make all this happen? One point I want to make is that we need to focus on the goal, and not so much on tactics. I find that even in audiences like this we often each tend to have our own pet technology. I'm guilty of it at times. I'm a big CSP advocate, I drive people nuts with that. But I think we have to just be able to step back and say the goal is to use the money that we have to get the most carbon out of the system. It can't be, "But I've got to do it this way" and it can't be, "I need solar on my roof so that I can be energy-independent." There are certainly a lot of advocacy groups hovering around Washington and other governing bodies pushing specific technologies. At the end of the day it can't be about a tactic, it's got to be about the goal.

7.1.3.2 Focus on the Energy System

Robert Armstrong: Focus on the energy system, that has come up quite a few times during our conversation, and that is really important. This group maybe more than others that I've met with seems very sensitive to that, that it's not just about technology but it's about affecting the rest of the energy system.

7.1.3.3 Need for a Business Model

Robert Armstrong: I want to touch on the importance of putting a price on carbon. I thought that Ross made a really valuable point about that in his presentation, where he talked about returns on investment, about the time horizon for recovery and about how much money you can attract. That's critical, and we have not yet addressed it. We're getting the penetration of the renewables that we use today with subsidies. However, reliance upon subsidies cannot persist up to the scales of such penetration as we need. So, the sooner that we get off of subsidies, and onto a market system the better off we'll be.

7.1.3.4 Public/Private Partnerships

Robert Armstrong: Related to that is the idea of public/private partnerships, again that Ross highlighted in his talk. I thought it was a great point, the need to have the discipline of investment of the private sector coupled with the funding that only can come in all likelihood from governments. You will need massive amounts of money, but sometimes the government is not the best group to decide how to spend it. Sometimes is probably not even the right word. But, I think that figuring out what those public/private partnerships should look like is going to be one of the greatest challenges that we should face in getting to the low carbon goal.

7.1.3.5 Revitalize the Innovation Chain

Robert Armstrong: Lastly, I emphasize revitalizing the innovation chain. In my view, it has become degraded over the last 30 years, or so. Back when, a long time ago, I left college I could go to an industry for a job. I spent a little time at Exxon Mobile in production research, where they had a vast R and D system. If you were to come in there you could do pretty basic research, and you had years or decades you that could spend to take that on to the stage applied research and then onto commercial deployment. There was Bell Labs back in those days, where you could have these hotbeds of discovery for new science, and the time and leisure to take it into various application areas. That's gone, as well.

And we have gotten to the place where the one piece of the innovation chain that still works well is that where if you have a bit of science that you understand, and you have a new idea for where it might be applied, then you can advance the early idea with government funding, with DOE or DOD or NSF money. Then, you can move to creating a startup company three, four, five years from there. That system works pretty well. But, beyond that I think that we have a system that has got some problems in all parts of the cycle. Basic research funding is down. The right partnerships for the applied research and commercialization are also missing for a lot of different technologies. We'll need these as well.

7.1.4 Contingency Planning and Geoengineering

Participant 1: I'm a great believe in contingencies, of being ready with ideas and plans that we hope that we shall never need. Contingencies cost far less than power stations or geoengineering kit, but on the day when you might need one you really wish to have it. There was the Janus Committee from the Cold War days that worked on such things in the U.S. In the same rein I think that the United States of America should have a group of people who are figuring out a national plan for what to do when the world agrees and the American public insists that something must be done about climate change.

Robert Armstrong: So, the plan B, similar to what Ron mentioned in his talk, is that we should be thinking seriously about adaptation, because we're not likely to hit the two degrees target. But, geoengineering scares me to death. We have demonstrated, well that the climate system is highly nonlinear. We have demonstrated that we don't fully understand it. The idea of starting to turn knobs on that system's controls is, a pretty scary thought.

Participant 1: Two quick comments. One is that we hope that sustainable approaches, will be sufficient, but if it is like World War Two when it hits us, one will need more extreme responses. These can be utterly unsustainable, and nevertheless the right things to do for a while. So, I'm thinking of a group of people who can imagine unsustainable activities. The other thing to say concerns fears. I agree that geoengineering is frightening, that's why I hope that we never need it.

7.2. Closeout: Agenda for Creating the Low Carbon Energy Future: *Robert Budnitz* (LBNL)

7.2.1 Outline: Reviewing Workshop Objectives – Beginning to define viable pathways forward through examining fundamental questions on how to achieve a low-carbon world

Robert Budnitz: So, I put together a set of slides that couldn't be more complimentary to the last one. I ask several questions, based upon the questions that came up during the discussions. The point of this is to try capture not just the questions, but also the basic issues that we are here to discuss. I start by quoting from the note that I got from Charles Forsberg and Michael Golay about the workshop's objectives. We haven't actually focused on them exclusively, but I'll just say what they are. Examine the fundamental questions on how to achieve a low carbon world, and begin to define viable pathways forward.

Well, we talked about that a good deal and it's fair enough to say we were mostly in the U.S. context. We're mostly Americans and we're sitting here in America. I have no apologies for that. Although a good deal of the discussion was more global. With those objectives as why we came here, I go over some of the things that we have covered. First, I make a list of the fundamental questions by categories. I have four categories of fundamental questions. These questions come to mind because a good deal of the discussion was focused upon answering one or another of them.

7.2.2 Fundamental Questions

7.2.2.1 Technical Energy (Technological) Options

Robert Budnitz: The first category of questions concerned what should be used as energy technological options. We had a good deal of discussion about which technologies could be useful, and also should any be excluded. Some people think nuclear power or coal ought to be off the table. That is certainly a view of some sectors, not necessarily in this room, but of our body politic. Such considerations are ever-present. The question about which technologies to use and whether some things ought to be excluded, and if so, why, or of how could we accommodate them, and if so why, constituted more than an undercurrent in this discussion. It was an important part of it.

The second topic concerns energy consumption. I made the point more than once that we don't really want energy, we want the services that energy provides. So, I asked, does every carbon-guilty energy consumption sector need to be attacked? Well, of course, they all need to be attacked, but equally? Of course not, first because some are more essential and some are more peripheral, and second of all because some are easier to improve. Besides it's not that we need to get to zero use of all undesirable technologies. We can't get to zero. there is always going to be a residual level of use.

Some of these decisions must be applied equally worldwide. Are there any exemptions to worldwide decisions? These are very hard questions. I'm talking to you after having spent some time in deepest, darkest Africa, where they don't have anything. It's hard to see how you could deny the people there a diesel generator until you find some other way to provide the services that a diesel generator provides by other practical means, which by the way, is light when it gets dark. You haven't answered this question, that's what it's about, and radio and television.

7.2.2.2 Cost Issues

Robert Budnitz: The next category has to do with costs. We didn't discuss, whether the real future costs really need to be close to current costs. Under what circumstances could substantially greater future costs be tolerated, or worse, could be required?

Then, the real question concerns how the costs are to be borne, or shared. There is also the related question of how much interference in the market is needed or could be tolerated? These questions are different from country to country. In fact in our country they're different from one state to the next. I can tell you, because I'm a Californian that we are different from a lot of the other states in these terms.

Those are very difficult questions. In the end much of what is going to happen in this decarbonization worldwide is going to be determined by how those questions are worked out in the real political world. People will determine the answers. Nobody thinks that the world could tolerate a tripling of the cost of energy, but some people don't think we can tolerate even a 10% increase. It's going to be worked out, but at a different level from the group this room.

7.2.2.3 Geographical Differences

Robert Budnitz: Finally, for global questions we must address geography. Within the United States we have vast geographical differences in the availability of some alternatives. Geothermal is the trivial one. There is none in Boston. But certainly it's true of the solar insulation, and even more so with wind. And how much geographical distribution, location differences can be tolerated worldwide with the renewables being major energy provides? With such big differences, who is going to pay to distribute the energy products? Distribution is part of the cost. I'm convinced myself that working that out is going to have a major influence on how all of this actually plays out.

Questions arise concerning what subsidies are needed, which are politically tolerable, and tolerable to whom? And then, finally are there credible energy transportation strategies that can help to equally distribute the costs? Well, we have that in the oil business. We have a worldwide oil transportation business that distributes oil everywhere. If you run a car anywhere the fuel is usually coming from someplace else. So, such distribution is credible. Do we have a credible means of distribution for a decarbonized system?

Should the renewables appear only as biofuels, we can move them around in tankers. If the energy is all from solar PV you don't need to move it around. Rather, we have grids to do this. So, many of the responses to these fundamental questions are going to be the determinants of what actually happens.

7.2.2.4 Meeting both Short and Long Term Goals

Robert Budnitz: The question that the organizers asked came down to, in part, asking what short term actions might seriously compromise our long term goals. The easiest answer is that if you spend a billion dollars on some electric installation you're not going to walk away from it in 10 years, and if you spend a hundred billion dollars on something you're not going to walk away from it in 50 years. So, we have the danger of the short term, becoming the enemy of the long term excellent solution which might be available only a few decades hence. That's a really difficult problem, because we are worried about the trajectory where we must go fast. We must act now, how does these, compromise solution progress on what we need to do later?

If we wait for the problem to be solved it will likely get much harder. We can't wait, so we've got to move, yet we've got to worry about the long term too. We've got to worry about this compromise.

This question from the organizers wasn't at the center of every discussion, but it was at the center of much of what we talked about, and in that sense this workshop focused on this sort of thing in the context of the others I said, and that was great.

7.2.2.5 Who Should act First?

Robert Budnitz: A really interesting question, especially from an American perspective is who needs to act first. Of course, this affects others, also. In the short term can the U.S. make a sufficient difference if we act first, whether or not others follow? I'm not thinking only technically. Of course if you develop a technology somebody else can pick it up. I'm mainly addressing related political and institutional factors. These involve very complicated questions, where part of the reason that they are complicated is because of the political environment in the United States.

7.2.2.6 Will an "incremental" strategy work?

Robert Budnitz: An additional question before we go on to the details, concerns to what extent and with which technologies can an incremental strategy actually work. For some technologies and some sectors an incremental strategy can work well, and for others it really doesn't. Will it work on the technological front? Sometimes for some technologies. Will it work on the sociological or political front? Well, sometimes yes, and sometimes not. We need to think about the trajectory in the context of those two questions about incremental versus really bold leap strategies.

7.2.2.7 How Much Risk of not Working can we Tolerate?

Robert Budnitz: Then of course, all of this must be asked in the context of the last question, of how much risk of failure can we tolerate. However, you think about it we are as a planet faced with the certainty of some things, and a risk of the future being worse with risks of some of our technologies not working out. Technically, but especially in an institutionally or political sense.

My grandmother used to say that there is many a slip between the cup and the lip. And you understand that colloquially, for the coffee is in the cup, but you didn't drink it because of some problem in-between. Actually I'll say something that will amuse some of you. My grandma said that in Yiddish and it rhymes in Yiddish too. But it's the same thought. No matter how you say it, this question about how much risk of not working do we risk failure because of something that we didn't anticipate that should have worked well, but didn't for one or another reason, is: A, a reason for redundancy and diversity and overkill; and B, a cause for concern that we won't succeed; but also C, something we really can't afford too much of, because we can barely afford what we've got at a minimum. We might not be able to afford even that. And how much of that extra diversity and redundancy can we afford? How much insurance can we afford? Probably or politically, at least in this country, it is not willing to put up with the costs that are needed to cover enough of those risks.

7.2.3 Opportunities discussed

Robert Budnitz: We discussed many opportunities; and for each of those we discussed their problems, I talk about the opportunities first, and then for each of those their problems.

7.2.3.1 Biofuel and Biomass

Robert Budnitz: We discussed biofuels options in some detail. It was very helpful, because there are nuances that turn out in the end not to be nuances, they're at the center of whether biomass is going to actually be a major, or not so major, piece of decarbonizing the planet. The discussion about biomass and land use opportunities was very helpful, because it pointed out to all of us that hadn't thought about it before the link between agricultural uses, agriculture writ large, which is often grazing. The word, agriculture, to me always means plant to plant, but of course agriculture writ large is mostly the other stuff in terms of land. The interface between that, and the other biofuels problems was at the center of what is going to be a difficult political problem in many countries where using that land is going to raise the political question of how to use it, or what to do and who gets paid and who get hurt. That is going to be hard. It's going to be hard in my country and it's going to be hard, all over the world.

7.2.3.2 Advanced Nuclear Power

Robert Budnitz: Concerning advanced nuclear power, we had a very useful pair of presentations about using the heat also as a means of displacing carbon, and also about making the nuclear technology more economically viable. It's not just for co-generation but for other uses too. Then, we had this morning's discussion about expansion and the whole question of proliferation and security and of expanding into which countries. That is a big concern to me. I am really concerned about expanding to some countries that don't have the right culture. That really bothers me, but more concerning than safety with nuclear power, is the link to proliferation. Safety risks are actually modest compared to these other things, but there is an important intersection with culture that is very concerning in this.

7.2.3.3 Solar

Robert Budnitz: We discussed opportunities for solar energy in two places. The first was that we probably aren't going to want to get beyond 50 more years with the PV technology of today. It's just hard to see how we're going to deploy that technology at 50 times today's scale. But there are technical advances in the wings, thin film PV is an example, but it isn't just the thin film, it has to do with making the entire system. A lot of the cost of PV isn't that of the cells, it's in the rest of the system, the cost of making that whole system work so that solar, going straight to electricity can really fulfill a bigger promise than it does today.

The other solar version is with the concentrating thermal systems. They have two advantages, one of which is in storage of the thermal system. It's substantial. There needs to be research, and then engineering deployment before those systems are going to be ready for widespread use in the marketplace. Their role can be major.

7.2.3.4 Electricity Grid

Robert Budnitz: Last on my list here are the issues of the grid. We had a very nice discussion this morning about the grid. I thought it was more than helpful. It was really at the center of answering or trying to understand some of these really difficult questions about how much the intermittent electric technologies can contribute and how our discussion allayed some of my fears to a degree. There is a reason for hope.

7.2.3.5 Electricity "Storage"

Robert Budnitz: Something that we didn't talk about technically very much, is electricity storage. By the way, of course we can store electricity; we pump water up hill. We have a reservoir called Helms, that can store many hundred megawatt. But, in a system of 30 gigawatts that isn't much, but it helps. The FIRES system that Charles talked about is an example of storing electricity as heat and then generating it again. Of course you lose some in doing this, but not enough to be of concern.

That whole challenge offers an opportunity for research in a number of different technical areas, some of which are in chemical engineering, in material science, and at the interface between what we know how to do in principle and something that we've got to make into an engineering system. Taken together, I predict that over the next 10 or 20 years that storage will become an area of importance. There could be new developments having global reach that would help us all, and make a big difference in the deployment of some of these systems. That is my prediction.

7.2.4 Problems discussed

Robert Budnitz: Now we must discuss the problems. The word problem is a surrogate for concerns and issues, and so on.

7.2.4.1 Biofuel and Biomass

Robert Budnitz: Concerning biofuels there are both technical and cost questions, and they're interrelated of course. Taken together they may be an important barrier to the very widespread deployment of biomass. Part of this comes down to how much cost increment our collective political systems, not just the American ones, will be willing to tolerate. As for biomass we have land mass requirements, I didn't really see any issues or problems there.

7.2.4.2 Advanced Nuclear Power

Robert Budnitz: For the advanced nuclear power systems there are the well known social and political problems. I'm not arguing that they're technical, but there are major social and political problems with nuclear power deployment around the world as a major decarbonized way of making electricity, and we all know what they are. I mean you see it in major important countries that have walked away from nuclear power, like the Germans, at least temporarily. This is also true in our country, where it's very hard to guess how that is going to play out.

A good deal of this comes down to concerns that are very difficult to answer to people whose concerns are expressed in social terms. I mean the best way that I could describe it myself, and I deal with the public in California a lot because of a California committee that I'm on. There are people for whom there isn't any acceptable nuclear deployment of any kind, it doesn't matter. It's just not, because it starts with the word nuclear. And sadly, they are not two percent of the population, they're an important percentage of the population. I say sadly because it's frustrating, but that it is as real as it can be, and, everybody has one vote in our country. It's a view that's going to be hard. Resolving this is really going to be hard.

A way around this would be to find out a way to deploy a nuclear power station for which there could be no plausible accidental radiation release. We discussed yesterday the system that MIT and Berkeley and Wisconsin are developing, a liquid fluoride system for which I can't figure out how to engineer a radiation release. Can that system, this fluoride system with triso pellets, can that system actually be cheap enough to deploy? I don't know, but at least it is an example of what might be accomplished.

Also, none of us has said much at all, about the nuclear waste disposal problem. However, everywhere I go that people raise it. I don't understand why, but people always raise it.

Participant 21: I think there are three points to make about that. One is that if nuclear is to play a role in mitigating carbon, it can only come about if societies decide that they want it. Until now we have had a situation, with the major exceptions of France and Japan, where after a burst of enthusiasm, it wasn't sustained by societies deciding that it was a positive good that they really wanted or needed. In the U.S. we had a positive social environment until roughly the time of the Vietnam War, when the post - World War Two optimistic consensus fell apart.

My second point is that if something like that social climate isn't restored probably nuclear energy isn't going to be a player in carbon mitigation. If you don't have the right conditions for these projects, they won't be undertaken. The greatest obstacle is proliferation. The question of whether societies want nuclear energy isn't really going to be the key concern. To me the biggest obstacle to using nuclear energy is that if we don't come up with a way of a having high probability that proliferation isn't going to be a hazard, then you'll have serious disagreement about whether to use nuclear.

The third point, one that we haven't talked about in this meeting is that most of the nuclear technology that we have today are not well suited to helping to alleviate carbon emissions. The products that you want in addition to electricity, being high temperatures and synthetic fuels, are produced much better by other nuclear concepts that have been recognized, but not pursued very much. There are many degrees of technological freedom that can be exploited. If nuclear is to play a realistically important role this also implies development of much different kinds of nuclear systems than we have today. But that only comes about after you decide it is something that you want to have.

Robert Budnitz: Your comment, deservers an important qualification. The fact that we haven't deployed 200 reactors in this country, while around 1980 we had a hundred running and another hundred reactors under construction or planned. Then, those hundred reactors were canceled. It had nothing to do with the social opposition, nothing at all. That came entirely via adverse economics, and the fact that our electricity demand stopped growing. The utility companies also stopped building fossil plants at the same time. We have about a hundred uints now, but we would have had 200 had that economic change occurred five or six or eight years later.

Also, we should note that nuclear electricity is not quite 20% of all electricity; it's more like 17%, and it could have been 35 but for that timing. This result wasn't due to the opposition, but growth today has to do with that opposition because of the change in the intervening quarter of a century.

Participant 21: I agree with your statement that the result wasn't because of potential direct opposition. Rather there was a politically influenced unstable decision making climate affecting the way that those projects were implemented, and it led to large cost increases.

7.2.4.3 Solar

Robert Budnitz: Concerning solar, the problem with solar PV, as we discussed earlier, is that there is a technical challenge to coming up with a good system. Stated differently, it's not just about the thin films, but also about the whole system whose costs need to be low enough so that they can be deployed more widely than now. Solar is barely economical in the U.S., with subsidies and so on. That's being worked on, and I hope that the results will be more positive. This is also true of the concentrating thermal systems. I'm optimistic, because I think that the chemical engineering issues there are going to be resolved with less expensive systems. So, I'm optimistic about option.

7.2.4.4 Electricity Grid

Robert Budnitz: Finally, the challenges concerning the future of the electric grid are very important. Despite the reassuring discussion of this morning, we must worry about the grid. The reason that this is important is because if we want to decarbonize as much as we want we must electrify more. Electricity is about 40 or 50 or 60%, but might become 70 or 80%.

7.2.4.5 Timing Issues

Robert Budnitz: We also discussed a good deal about timing of needed action. Timing also depends upon how to pay, and who pays. That is resolved by the political process. It comes down to who decides; Well, who decides how to pay, who pays, and the timing. That is not done by only the big companies, and not by the citizens. It's very complicated.

The reason that I have become pessimistic is because of the gridlock in the American political system compared to the situation of 25 years ago. The US isn't alone in that regard. If you want to think about gridlock just watch Westminster for a week and you'll see that they also have it there. I'm really pessimistic about that.

7.2.4.6 R&D Goals

Robert Budnitz: Finally, there are concerns about the importance of R&D. It's necessary. It's the only place where the new capabilities can come from. It can't do everything, but it can enable improvement.

In all too many areas essential research isn't being supported worldwide at the required levels if we're going to decarbonize as fast as we need. When we think about how to influence policies part of that requires a scheme for how to create the needed R and D endeavor, not just here, but worldwide, one that is more extensive or concentrated differently from what we have now. Ultimately comes down to who decides about that will be done.

If this is pessimistic, so be it. Because on that I, frankly, am pessimistic. It's sad to have to say that, but I'm an American and I'm telling you I'm pessimistic about that. A problem is that much of what we need to do ends up being a governmental function that is followed by an industrial function. On many of these things, the flow in too many of these areas isn't appropriate compared to where it was a few decades ago. In almost every area we identified researchable questions which should be noted in the proceedings, and ought to be things that we are concentrating on, where we should try to pay attention to and try to figure out how to expedite progress on, and not just here. These important questions are amenable to research, but it requires the people to do it and it requires the financial support to make it happen.

7.3. Closeout Discussions

7.3.1 What Will it take to Force a Global Response? Would it be Worthwhile to Develop a Last Resort Plan in Order to Respond to a Triggering Event?

Participant 10: Why the pessimism? In everything that I heard discussed in these past two days, I heard everyone saying that business as usual will not accomplish what we need to do. The U.S. is terrible at solving multigenerational problems. Look at Social Security, or the nuclear waste problem. I predict that we're either going to do nothing or wait until a triggering event happens that will cause us to need to do something intense in a very short time.

Would it be useful for us to have a Marshal Plan, a moonshot, a Manhattan Project type list of actions that would occur should the triggering event happen? I'm suggesting that it might be a useful action for a group to say if you had to do this in five years, 10 years do or die, what would you do? I would be interested in what that group would say. I don't see that anything is going to happen unless there is some crystalizing event that actually drives action, and then it will likely be too late. Then, we'll have to do something unsatisfactory in the short term. Having that plan might enable us to accomplish something substantial versus not having that plan on the shelf.

Robert Armstrong: I resist the urge to think in energy like we did with the Apollo Moon Program or even the Manhattan Project, because the analogy is faulty with the Apollo project, in particular. There was a very well-defined target and it was technology-driven. Energy is not a technology problem. It involves a broad suite of technologies, and a whole suite of system problems. Also, it's a political problem. We just reviewed a broad list of things we have to deal with. I think that we delude ourselves if we try to focus on a single most important topic.

One of the discussions in Washington now concerns coalescence around the need to improve our energy infrastructure. We may disagree on which part of the infrastructure you want to see improved the most, but I think that it would be good if we could improve our infrastructure, which is certainly aging. It is a key enabler for the future.

Participant 10: What do we think would drive action on the scale that would actually address the problem? Bad weather?

Robert Budnitz: You can imagine a confluence of events that bad weather could catalyze public opinion in a way that is hard to imagine otherwise. And, they could simply be related to weather, which isn't necessity climate change. This could galvanize opinions in the needed way, even if for the wrong reasons. This sounds cynical. It's hard to see what else could mobilize people.

Robert Armstrong: So, here is where in a workshop like this it is important is to have a plan. If there comes such a time as there is a crisis that is big enough to get our leadership together to do something you need to have a plan prepared that is ready to go. It would be valuable to have thought through, for example, whether it's a revenue neutral plan, using a carbon price or whatever. We need to be thinking almost the plan so that there is something to turn to when disaster strikes.

Participant 26: The flip side of that, though, is we can't beat the economic competition from carbon. If we could get the cost of nuclear electricity down to two cents per kilowatt hour you wouldn't need a carbon tax. Nuclear would simply dominate the electric market. Implicit in this is the non-emitting technologies cannot win on an economic basis

Participant 10: None of these solutions are the most economical, or by now we would have embraced them. We're all saying that with these technologies we have to do something different. Importantly, new technologies are usually more expensive.

Robert Armstrong: The idea, though, is that they are going to be the most economical solutions for a long term. If you look at the price that you're going to have to pay ultimately to deal with the effect of climate change it will be more expensive to postpone getting off of carbon.

Robert Budnitz: The reason that you should do some advanced planning was captured by Gen, George Patton who said that planning is really important, but that the plans themselves are likely to be useless. However, the planning activity itself can put in place a cadre of people that know how to plan, and others who know how to understand them. Together they can respond to what happens.

Participant 32: It is important to remember that the carbon system operates on a scale of centuries. If we were to have a big crisis whatever would happen in the next five years after that is already determined as the legacy of the accumulated gases. There is nothing we can do to avoid that. The only thing that could change the five-year climate trajectory is geoengineering, full stop.

7.3.2 The Distribution of Geological and Geographical Beneficiaries is not that of these who will be Paying the Costs Now

Robert Armstrong: There are a few important matters to which we have paid too little attention in this workshop. One is that the timescale mismatch in our system. We have political systems that operate on two, four and six year timescales. But, we're dealing with a problem that operates on a hundred, 200, 300, 400-year timescales. A lot of what is going to happen concerning climate over the next 20 years is already determined. A lot of the emissions that we're going to have are already determined, because we have already built the gas-emitting facilities, and we're not going to be able to convince people to shut them down. So we're really discussing decisions now that will benefit our grandchildren or great-grandchildren. That's number one. Number two, we're talking about making decisions now where many of the costs will be borne in the United States and Europe and China and many of the benefits will go to even poorer countries. So, we're talking about the need to make investments now that will benefit the grandchildren of Bangladesh. That is a really hard sell, politically.

I think that this whole concept of fairness and distribution is one of how you make political decisions where we need to talk about it much more. China of course emphasizes, "Well, we have very low per capita emissions." We say, "Well, you've got the biggest emissions in the world." They say, "Well, very low per capita." And we say, "Well, but you have a lot of people." But, over the course of the century it's hard to argue that a Chinese person shouldn't have as much influence upon the atmosphere as an American person does.

So, maybe today we are not ready for per capita rational emissions allocations, but in a hundred years it seems to me that this is where things ultimately are going. If so, that means that we would have to reduce emissions even more in the United States. So, this means that the whole issue of fairness is a big one. Paris is another word that I don't think was even mentioned in these last two days. We're about to have a huge global meeting that is going to make some decisions that will improve upon where we are now, but that will be grossly insufficient. However, in any case that is the framework that we're going to have to build upon.

A third word that we have not talked about not enough is China. The reality is that China and India have big enough piles of coal that they can sink all the rest of us, even if we all were to stop emitting CO_2 tomorrow. If they are determined to burn that coal, we shall need to come up with technologies that are attractive enough to induce them to decide not to burn it. The reality is greater than only China and India, but they're the biggest. Russia matters too, for example.

So what happens in the United States, other than the United States actively developing technologies that are adapted in the needs of the rest of the world, may actually matter relatively modestly. The needs go beyond, developing technologies, though. They also include leading to convince China about needed actions. The most important thing that the United States has done recently is signing the recent cooperation agreement on climate changing emissions with China. We must have a fairness perspective, understanding the associated political difficulties, an awareness of the deep mismatch of important time scales and an understanding that it' s really about the rest of the world much more than it's about the United States and other wealthy countries. These are things that we need to be focusing up on.

Concerning R and D, we know that we must innovate, do we have enough time to innovate enough? Clearly we need to deploy some new technologies now and then we'll be deploying more new technologies at an increasing rate. Hopefully, at a greater rate than that in 2030 and at a greater rate than that, and so on. The new technologies that we're going to be deploying in 2030 I imagine are going to be different than the technologies that we're using now, and the more technologies that we deploy in 2040 are going to be different from that, and so on. Innovation will affect how rapidly we're going to be able to convince people to deploy low carbon responses during those later years when we shall need to be more effective.

We concluded very clearly that to meet our goals you can't get there only by using a carbon price, or relying only upon government investment in innovation. You need both.

7.3.3 Wind

Participant 5: I want to mention wind because it was not covered in the summary. Until the recent gas price collapse wind had been the fastest growing form of new power technology globally as well as in the U.S., and it offers many opportunities for achieving low carbon goals.

7.3.4 Steps to develop a plan

Participant 5: I have two points. First, at the lab where I work I have often heard the comparison to the Apollo or the Manhattan Project, but after spending 22 years in industry I don't think that these analogies are valid. Those projects did not have to compete economically with an incumbent. They didn't have to win based upon price. So, I think that we have to stop kidding ourselves. They're not even the same type of problem, period. The big projects were making one thing for one client, and cost was no object.

The other point I want to make is similar to that about the Manhattan Project, oftentimes I hear people complain about political gridlock. Well the reality is that for the last two days we have had 40 or 50 of the best and brightest in the world talking about a problem that is enormously challenging, and we don't have a single future scenario when we could say, "Here is at least one scenario that achieves the low carbon future we're talking about, the concern is about the urgency." I agree with the thesis of the workshop is we could easily head off on the wrong path. I think it was Covey's Seven Habits of Highly Effective People that start with the end in mind. Also, I think that it was the Cheshire Cat that said if you don't know where you're going any road will take you there.

So, I think as a group of leaders such we have here, if we can't paint at least one picture there the majority of us say, "You know, technically that could work" and then we could start to work backwards from there and figure out what is the lowest cost option. However, without even a single option I think we're taking a cheap shot to say the problem causing too little progress is political gridlock. This is a very, very difficult problem where we don't have a solution that we all agree to yet.

I think that we owe it to the politicians to try to identify a few plausible future scenarios. Then we can try to show a few future state scenarios that summarize the risks and the costs that could put we on a rapid trajectory towards a cluster of desirable future states.

Robert Budnitz: That's a wonderful suggestion where we have a precedent, from Jane Long, yesterday. She chaired a study mandated by the California political system six years ago to ask the question how can we get to 50% non-emitting systems by 2050. The study said that there are several feasible scenarios. They don't choose among them, but they outline each and what its costs and troubles are for California. Now, California is more difficult in some ways and easier than others than the entire country, but it's an example of a thoughtful analysis of, "Here is how we could get there and here is what it would cost and here is what the barriers are." Also, everything in the report was predicated on use of no new technology.

Participant 5: Also, the McKenzie report points out very clearly that once you have a cost and a target, then improving efficiency is the first thing that you try to do across the board.

Robert Budnitz: This was done in California even though we had done a lot already. Because the report was predicated on use of no new technology everything had to done using technology that existed in 2006. But I would recommend to anybody that doesn't know that study to read it. It shows an example of what you could do and what needs to be done. On the other hand, writing the report wasn't easy, I'm guessing that it requested a hundred person-years of work. So, this isn't easy.

Robert Armstrong: I would like to make a plug for the Joint Program on Climate Change. The models that John Reilly and his team work on examine exactly the question that you're posing. These are the scenarios that you ask for. They search for economic optima, given different technology mixes, fuel mixes. You can perform sensitivity studies to the price of different technologies in them.

Robert Budnitz: If you ask whether we can meet our goals only using today's technologies you remove a lot of the controversy from the discussion. Doing this helped in California at the political level because you could say, "Well, if we can do what we want using today's technology then let's go try, because we know that today's technology is going to be obsolete." So you could start with that at least as a means of getting started.

Participant 5: During these two days I have come to the conclusion that there are important weaknesses in the tools that we use that are not compatible with guiding us to a zero carbon future. However, they are still helpful because the better that we define that future state the clearer the deficiencies of our existing toolkit will be to us. Then we can proceed with innovation to develop the needed technologies.

Robert Armstrong: If you look at the projections of where big energy growth will likely occur globally it's not in the developed world. It's in the parts of the world that can't afford the kind of expensive technologies that we use here. If we propose to rely upon today's technologies, that are not accessible to the people in the countries where energy growth is probably going to occur most, are we being realistid? So, how do we develop technologies that are affordable?

Participant 7: A challenge with these energy use scenarios is we start thinking about them now, and then we start imagining that we're going to start using using new approaches in 2020. However, the world has already agreed on what it's going to do through 2020, and CAP21 is going to agree on what will be done through 2025 and 2030. Also, we had a meeting of some of the State Department staff and others, and they said that everything that people are going to agree in CAP21 has already been decided. That is the path that we modeled, and that has us being seven years away from crossing the carbon inventory that will cause two degrees of warming by 2030. So, what will be done the next 15 years has already been decided essentially.

Participant 33: During these two days, we have talked an awful lot about all the problems and difficulties, and what we can't do. I think that we should talk also about what this group could do, what they could do to make a difference. What I see is a lot of "stove piping" in terms of different disciplinary expertise with group from different areas coming forward with their individual versions of the the future, as opposed to creation of a collective scientific energy community multidisciplinary study that comes together with different options, probably with different regionally-dependent options for the nation to choose should the policy makers decide that they want to accomplish something.

We're a scientific group, we could suggest what R and D would we would prioritize for those different options? Could we as a community come together and do that? If it has already been done I'm not aware of it?

Participant 16: Aiming at decarbonization in a country like the US where fossil fuels are so already cheap is quite a challenge. You have the difficulty of having cheap gas, where at the moment the price of it is very low. This is quite a challenge. Anything that could be effective in this situation would have the value of being exemplary for the rest of the world. Coming to the issue of how rapidly to achieve effective results, we must recognize that we shall be doing things mainly for our grandchildren. Regarding the short term, the U.S. is currently using about seven tons of oil equivalent per capita annually, whereas Europe is about at the level of four as a result of some effort in energy saving. This indicates that the U.S. in a better position than is Europe to identify evolutions that could reduce fossil fuels in your style of life without really changing it too much so that it would be acceptable.

Regarding the long term, I think for displacing fossil fuels one ought to examine where fossil fuels are being used in an essentially way. For electricity we have several substitutes for producing clean electricity. Fossil fuels are really used for producing heat, either for the housing or industry or for transportation. So, one ought to think of clean ways of producing heat or fuel for transportation.

For producing heat as well as hydrocarbons, synthetic hydrocarbon fuels could be used either for those purposes, or as energy carriers, or for energy storage. Then, clean ways of producing heat or synthetic hydrocarbons in some economic ways are an interesting path to pursue. We could also consider what nuclear energy could do along these lines. We have had a few examples of what nuclear can do. Certainly those options are not yet reality, but I think that they could be source of inspirations. I think that the same could be done for synthetic hydrocarbon fuels.

And when Michael Golay noted that in two ways current nuclear technologies are not optimized for making hydrocarbon fuels. There are a variety of ways of making hydrocarbon fuels. So, I would be interested in knowing which process and which nuclear forms would be best adapted to the types of processes that would be best suited to the United States.

Then, if there are opportunities for demonstrations of these different types of nuclear technologies I think, that one could consider cross them with some complementary demonstrations of technologies for making non-electrical energy products along these lines.

7.3.5 Could we avoid all these scenarios if a successful carbon tax were implemented and R&D funds into energy were greatly increased?

Participant 34: What if U.S. policy makers were to impose carbon tax that increased at the discount rate, and if they were to quadruple the amount of R and D put into energy? Would we still have to be examining all these scenarios?

Robert Budnitz: Yes. Yes, of course. The reason is that scenario analysis is the best way, to inform our judgments concerning which options are best.

Participant 34: But couldn’t the private sector sort of take that on? To me it’s a scary scenario, for the policy makers to figure out what we do?

Robert Budnitz: Maybe, I think that anybody that does that kind of work can enrich us all. We need many different perspectives concerning such work, because any single perspective is inevitably going to be biased. I'm guilty of that myself. That's why we have benefited so much by this diversity, such as we see here.

Robert Armstrong: Actually we are looking for the private sector, to produce solutions that are economically driven. I think that using scenarios is great, but we need many. The big energy companies all have their own scenarios for planning purposes.

Participant 32: But if part of that policy impetus is quadrupling funding for government energy R and D somebody is going to have to decide how to allocate it. These scenarios can help a lot in deciding what to do.

Robert Armstrong: Hopefully in the future industry would go well upstream in the research space rather than just downstream.

7.3.6 Closing Comments

Charles Forsberg: In closing I note three items. First. I would like to thank our sponsors, which includes the MIT Initiative, NREL, the Department of Energy and INL. Second, I would like to particularly thank the various speakers who not only spent a lot of time putting together presentations but also sent us articles and other pieces of information that will be a resource that will be available in the Proceedings. And third, of course, I would like to thank all of you for attending this workshop, because a lot of this, a lot of the input for the Proceedings is the discussions that we've had, which has taken about half of the time.

Before we close I'll turn that over to Michael Golay and see if you have anything else to add.

Michael Golay: No. I only wish to note what you can expect. Over the coming year we're going to work on producing a Proceedings from the Workshop, where the intention is really to try to encapsulate the ideas expressed as a resource for others. We'll make this available via the web and other channels. It will contain the papers that have been contributed as well. With that we really want to say thank you all for taking the time to come and contribute your ideas, your time and effort. We know that you had other things that you could have done. We're glad that you shared the desire to be helpful with the problems in this Workshop. So thanks to all, and travel home safely.

Appendix A: Workshop Agenda

Tuesday May 26 Tang Center: E51-345	
8:30- 8:45am	**Welcome and Introductions** Robert Armstrong (MIT Energy Initiative)
8:45- 10:15am	**Session 1: Low Carbon Energy Economy Schedule and Overview** Framing the challenge: What are the time scales of needed response in creating the low carbon energy future? What options are especially worth investigation? What are the challenges? Ronald Prinn (MIT): *The Climate Challenge: Toward a Low-Carbon Energy Economy* Jane Long: *The California Low-Carbon Study: What Was Learned* Mike Golay (MIT): *Discussion Lead*
10:15- 10:30am	**Break**
10:30- 12:30pm	**Session 2: Renewable Energy Systems Near-Term Integration Strategies and Requirements / How to develop strategies that will lead to long-term cost-effective renewables?** What are attractive market design options? Should there be a requirement for visible costs of subsidies (Germany) and greenhouse release estimates to provide political feedback? What attractive options can meet policy and technological needs in order to successfully integrate renewable energy systems into the broader electrical energy economy? Ross Koningstein (Google): *The Google Adventure with Renewables: Why Incremental Advances are Inadequate to Solving Climate Change* Francis O'Sullivan (MIT): *MIT Future of Solar Study* William Green (MIT): *Discussion Lead*
12:30- 1:15pm	**Lunch**

1:15- 3:00pm	**Session 3: Nuclear Systems Performance Requirements** What are the likely needed scale and products for new nuclear technologies to provide an adequate climate change response (variable electricity, heat, hydrogen, water?) What are the technological options, and requirements for supporting technologies, to allow nuclear technologies to increase its effectiveness? Charles Forsberg (MIT): *Base-load Nuclear Power to Meet the Need for Variable Energy Output: The Value of Heat* Henri Safa (CEA, France): *Nuclear Cogeneration* Robert Budnitz (LLNL): *Discussion Lead*
3:00- 3:15pm	**Break**
3:15- 5:15pm	**Session 4: Strategy for Synthetic Liquid Fuels / What Are the Options for Liquid Hydrocarbon Fuels with Zero Net Carbon?** What are the energy markets for which synthetic hydrocarbon liquid fuels are likely to be essential? Are there more than three options for zero-carbon hydrocarbon fuels (biofuels, fossil liquid fuels with atmospheric CO2 recovery and sequestration, CO2 from atmosphere or other sources with conversion to liquid fuels)? Are there any credible non-carbon/zero-carbon transport fuels (NH3, etc.)? Can biofuels meet the needs? Bruce Dale (Michigan State): *Biomass Fuels Imply Rethinking Agriculture* Lee Lynd (Dartmouth): *Biofuels and Climate Change Mitigation: Need, Land, and Development* Michael Pacheco (NREL): *Discussion Lead*
5:15- 5:30pm	**Walk to Media Lab**
5:30- 6:00pm	**Reception** MIT Media Lab (E14): 6th Floor
6:00pm	**Dinner** William Nuttall (The Open University, UK): *Energy—A View from Across the Pond*

Wednesday May 27
Tang Center: E51-345

8:30- 8:45am	**Recap** Charles Forsberg (MIT)

8:45-10:15am	**Session 5: Nuclear Fuel Cycle and Proliferation Prevention Requirements / What technologies and institutions for sustainability?** What are the effective performance requirements for global proliferation control? What are attractive potential international fuel cycle arrangements, including those for nuclear waste disposal and fuel provision? Frank Carré (CEA: France): *Challenges and Issues Associated with the Nuclear Fuel Cycle for Sustainable Growth of Nuclear Power* Matthew Bunn (Harvard): *Avoiding Nuclear Proliferation in a More Nuclear Future* Scott Kemp (MIT): *Discussion Lead*
10:15-10:30am	**Break**
10:30-12:30pm	**Session 6: Renewable Energy Systems Long-Term Requirements, and Options. What are the long-term geographical implications of renewables in terms of economics and institutions?** The variations in wind and solar input with location imply large differences in production costs. Does a renewable system imply massive differences in energy costs across the country with resulting large differences in costs and standards of living? Is there any credible energy transportation strategy to levelize costs? Can such mega systems be made secure? Aaron Bloom (NREL): *Renewable Energy Futures* John Pierce (BP plc): *Discussion Lead*
12:30-1:15pm	**Lunch**
1:15-3:00pm	**Session 7: Closeout: Agenda for Creating the Low Carbon Energy Future** Robert Armstrong (MIT Energy Initiative): *Observations and Future Questions* Robert Budnitz (LBNL): *Observations and Future Questions*

Appendix B: Participants List

Robert Armstrong, MIT Energy Initiative
Francois Auzerais, Schlumberger
Aaron Bloom, National Renewable Energy Laboratory
Richard Boardman, Idaho National Laboratory
Shannon Bragg-Sitton, Idaho National Laboratory
Stephen Brick, Clean Air Task Force
Robert J. Budnitz, Lawrence Berkeley National Laboratory
Matthew Bunn, Harvard Kennedy School
Jacopo Buongiorno, MIT
Yinan Cai, MIT
Frank Carré, CEA
Andrew Cockerill, BP
Bruce E. Dale, Michigan State University
Francisco de la Chesnaye, Electric Power Research Institute
De Sisternes Fernando, MIT Energy Initiative/ ANL
Noah Fischer, MIT
Sarah Fletcher, MIT
Charles Forsberg, MIT
François Gendre, French Embassy
Michael Golay, MIT
William Green, MIT
Steve Hamburg, EDF
James Hansen, Columbia University
Ting He, Idaho National Laboratory
Howard J. Herzog, MIT
Edward Hoffman, Argonne National Laboratory
Eric Ingersoll, Energy Options Network
Rob Hovsapian, Idaho National Laboratory
Mujid Kazimi, MIT
Scott Kemp, MIT
Ross Koningstein, Google Inc.
Richard Lanza, MIT
Henry Lee, Harvard
Jane Long, CCST
Lee Lynd, Dartmouth College
Peter B. Lyons, DOE
Michael V. McMahon, AREVA
Nicole Mermilliod, CEA-DRT
William J. Nuttall, The Open University, UK
Michele Ostraat, Aramco
Francis O'Sullivan, MIT Energy Initiative
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Ronald G. Prinn, MIT
Everett L. Redmond II, Nuclear Energy Institute
John Reilly, MIT
Henri Safa, I2EN
Jayant Sathaye, LBNL and UC Berkeley
Erich Schneider, The University of Texas at Austin
Dan Schrag, Harvard University
Carl Sink, DOE
Robert Stoner, MIT Energy Initiative
Sara Tyler, Shell International Exploration and Production Co.
John C. Wagner, Oak Ridge National Laborator