Published in J. Pittock et al., eds., *Climate, Energy and Water: Managing a Complex Trinity*, Cambridge University Press, 2014.

Implications of Climate Change for Energy Systems in a Multisectoral Context

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For decades, energy production and use have been considered the primary culprits as observers try to assign blame for climate change. Beyond question, patterns of energy resource development and technology use, combined with growing global appetites for energy services for socioeconomic development, are important *drivers* of climate change. But energy systems are also vulnerable to *impacts* of climate change on energy activities themselves and also on other infrastructures on which energy systems depend. Energy systems are therefore *victims* of climate change, as well as culprits.

The process of understanding how climate change impacts can be a challenge for risk management by energy policy-makers, decision-makers, and stakeholders is just beginning to emerge, because for so many years impacts were not a focus of research – or even of serious discussion. A number of recent assessments, however, are beginning to sketch out a picture of vulnerabilities, risks, and possible impacts; and many energy providers are seeing enough evidence of climate-related impacts on their operations that they are taking climate change impacts seriously.

This chapter will first summarize what is currently known about sensitivities of energy systems to climate change, including linkages with other systems and infrastructures. It will then summarize the exposures to climate change that are of the greatest concern for energy systems, along with several issues raised by a less than perfect fit between the outputs of major climate change models and the needs of energy risk management. Next, it will summarize recent findings about the most serious implications of climate change for energy systems in both the near and the longer terms. Finally, it will consider possible strategies for reducing vulnerabilities and impacts of climate change on energy systems.

Several themes thread through the various parts of the chapter: the current focus of decision-makers on extreme weather events; the fact that direct effects of climate change interact with other driving forces for energy sector impacts; and capacities for major energy-sector institutions to reduce vulnerabilities and manage risks once they are recognized.

1. SENSITIVITIES OF ENERGY SYSTEMS TO CLIMATE CHANGE

Direct effects of climate change are temperature increases, including changes in extremes as well as averages; changes in precipitation, including changes in variability and extremes and changes in their forms (e.g., rain vs. snow); changes in extreme weather events, possibly including changes in frequency, intensity, and location; and a rising sea level. Sensitivities of energy systems to these effects vary by location, differences in the climate change threat, differences in systems exposed to the effects, differences in geographic scale, and differences in socioeconomic development context (ranging from institutional capacities to available financial resources).

1.1 Energy Supply and Use Vulnerabilities

Vulnerability is defined by a combination of exposure to a threat, sensitivity to that threat, and coping capacity in responding to the threat (Clark et al., 2000). Vulnerabilities of energy supply and use to climate change have received very little research attention until recently. For example, the massive 1800-page Global Energy Assessment published in 2012 (GEA, 2012) includes only a few pages on climate change and energy systems (pp. 200-207). But a number of assessments in recent years have summarized what is known about vulnerabilities of energy systems to climate change (CCSP, 2008; USGCRP, 2009; UK, 2012; World Bank, 2011; ORNL, 2012), based mainly on studies in the United States and other industrialized countries. In general, these studies indicate the following implications of exposure to climate change effects, moderated by sensitivities to such effects:

(1) The major near-term risk for energy systems is from episodic disruptions due to extreme weather events, especially in particularly vulnerable regions. For both energy supply and energy use, extreme weather events such as hurricanes, tornados, floods, droughts, heat waves, and wildfires are the most dramatic threats to sustainable energy services for social and economic development. Although such events are difficult to predict for any specific location and time period, based on available climate models, there is some evidence that frequencies, intensities, and locations of extreme weather events over the past several decades are different from century-long averages, indicating effects of climate change (NCA, 2013). For example, in many regions across the world a greater proportion of total precipitation is falling in a smaller number of more intense rainfall events, contributing to both seasonal flooding and seasonal drought.

(2) Both electricity demand and electricity supply will be affected by increases in temperatures. These increases, in both averages and extremes, will affect energy systems, as heating requirements shrink and cooling requirements grow. Data for the US (most likely also applying to other mid-latitude countries) indicate that <u>overall</u> effects on total energy consumption at the

national level may not be substantial, as savings from heating offset increases for cooling. But these two energy services differ in their fuel mixes, as heating is provided by liquid and gas fuels as well as electricity but cooling is provided almost exclusively by electricity. As a result, climate change will increase demands for electricity, especially in regions where the number of cooling days increases considerably compared with historical experience (CCSP, 2008; USGCRP, 2009; ORNL, 2012a). At the same time, capacities for thermal electricity generation will drop as air and water temperatures increase (ORNL, 2012a), which would make it more difficult to meet the growing demand, at least in some regions in some seasons.

(3) Seasonal and/or chronic water supply constraints pose threats to reliable energy supplies in many regions. A number of recent assessments have shown that climate change effects on seasonal and/or long-term average precipitation are very likely to become challenges for energy production in many areas, both in the US and globally (e.g., UCS, 2011; EPRI, 2011; Dell and Pasteris, 2010). Among the sensitivities are that many arid areas are projected to become more arid, areas dependent on snowmelt for spring surface water supplies are projected to see reduced flows, and many other areas are likely to be subject to seasonal droughts that are more frequent, longer, and/or more intense, in some cases coupled with seasonal heat waves that would tend to increase water demands (ORNL, 2012a). Energy system sensitivities can include chronic or seasonal reductions in hydropower potential, effects of reduced water flows on the ambient water temperature (which is related to allowable temperatures of power plant water emissions), and reduced effectiveness of thermal power plant cooling technologies (ORNL, 2012a).

(4) Geographic patterns of renewable energy supply will be affected by changes in climate. As temperature and precipitation patterns shift, environmental conditions for renewable energy supply will also shift. Wind speed and direction will be affected, impacting windpower. Changes in cloud cover can affect solar insolation, impacting solar energy generation. Changed conditions for agricultural production will affect potentials for biofuels cultivation, and changes in water availability may impact biofuel production. In nearly every case, as environmental conditions shift, some areas will see reductions in renewable energy supply potential while others see improvements; but shifting patterns of resource development will interact with other driving forces shaping land use decisions in localities and regions, which adds strategic challenges in increasing the renewable energy share of total energy supply (ORNL, 2012a).

In nearly every case, climate change vulnerabilities of energy systems are embedded in relationships between climate change effects and other driving forces that are shaping resilience and sustainability (IPCC, 2007), including linkages with other geographic areas, infrastructures, and systems.

1.2 Linkages of Energy System Vulnerabilities with Water and Other Systems

Energy systems are linked with and often dependent upon other systems and infrastructures that may be vulnerable to climate change effects. Figure 1 illustrates some of the connections, of which water and land are often especially important.

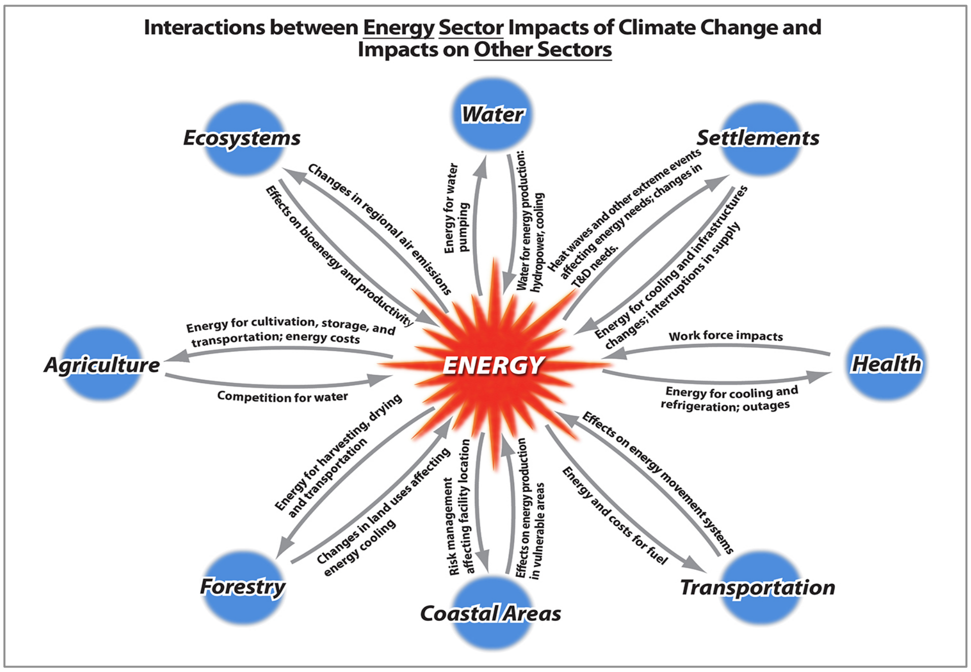

Figure 1

A suite of simulation and analysis tools has been developed in the United States to unravel linkages between different kinds of infrastructures and to explore their interdependencies. Intended initially to simulate effects of terrorist acts on US infrastructures, they have mainly been applied as decision support tools during responses to extreme weather events, such as major hurricanes (ORNL, 2012b). Over a period of nearly a decade, learning from each application, the models have become remarkably accurate in depicting connections with elements of different infrastructures during major disruptive events, including cases where impacts cascade through the system of systems to cause major disasters. Figure 2 shows a simplified summary of interactions between energy infrastructures and some other infrastructures, based on this experience.

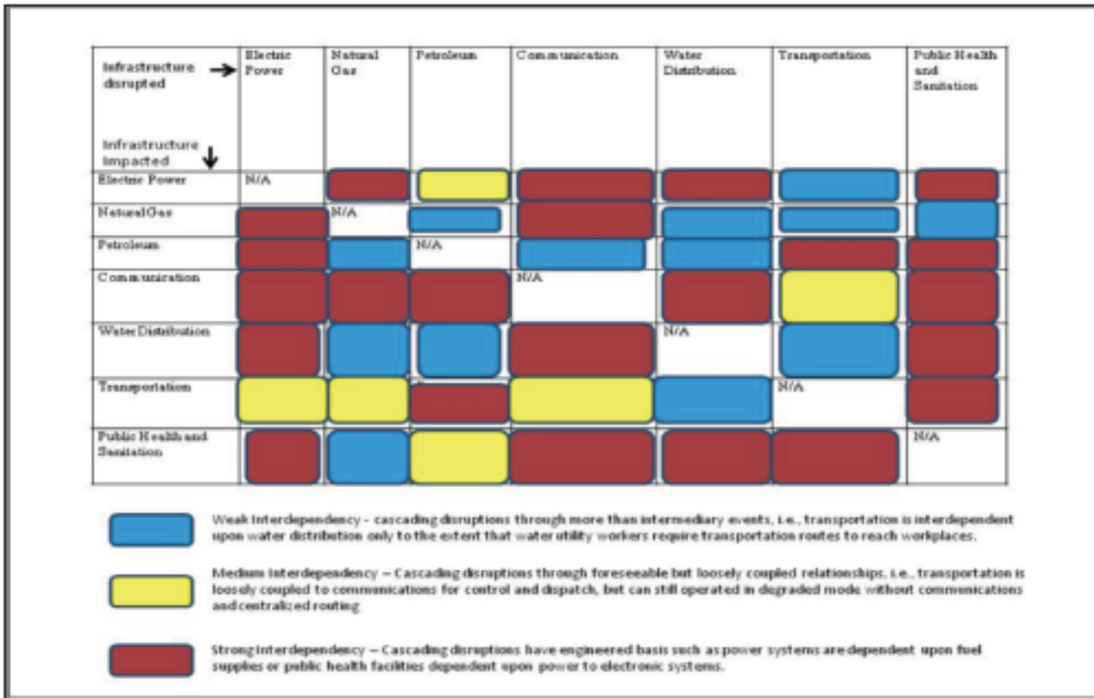

Figure 2. Interdependencies among sectors in the event of major disruptive weather events (ORNL, 2012b).

Examples of such interactions from the US experience include effects of electricity system interruptions due to extreme events on transportation systems (e.g., traffic control in cities and in air transportation), on water pumping and wastewater management where systems are powered by electricity, and on human health as space cooling for vulnerable populations is interrupted (ORNL 2012b). At the same time, interruptions of other infrastructures can affect energy systems, both within the energy sector (e.g., interruptions of natural gas supply because pipeline compressors are powered by electricity) and in interdependencies with other sectors (e.g., the reliance of Smart Grid approaches on reliable electricity services for communication, movements of fuel sources by river freight, and relationships between urban energy demands and storm impacts on vulnerable coastal area: ORNL, 2012b).

II. Exposures To Climate Change Impacts

Exposures to climate change in the future are projected by climate change "scenarios," representing different possible futures under a set of assumptions. The two major families of climate change scenarios used in recent years are:

(a) Scenarios developed by IPCC's Special Report on Emission Scenarios (SRES: IPCC, 2000), utilized by the IPCC Fourth Assessment Report and often referred to as CMIP-3 (referring to the Climate Model Inter-comparison Project – CMIP – which is the global repository for climate scenario projections); and

(b) Scenarios developed more recently by the science community to provide a more current perspective on possible futures, called Representative Concentration Pathways (RCPs), now being referred to as CMIP-5 (Coupled Model Intercomparison Project). RCPs sketch out four illustrative futures defined in terms of radiative forcing, elaborated by Integrated Assessment Models (IAM) that associate illustrative forcings with greenhouse gas (GHG) emission scenarios that would lead to such alternative futures (Moss et al., 2010).

As the RCPs indicate, in principle climate science scenarios include representations of three sets of relationships: (a) drivers of greenhouse gas emissions and accumulations, (b) changes in climate as a result of greenhouse gas emissions, and (c) effects of those changes, some of which which feed back toward the drivers (Figure 3) – although the links between effects and drivers have been less comprehensively analyzed than the drivers and climate changes per se.

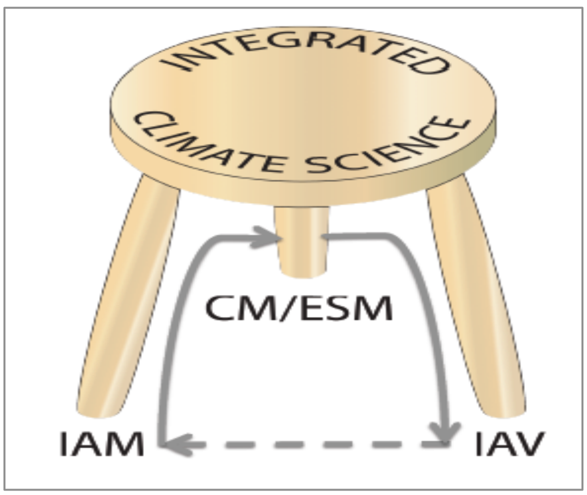

Figure 3. Elements of climate change science: CM/ESM refers to climate and earth system models; IAV refers to impact, adaptation, and vulnerability analysis; IAM refers to integrated assessment models.

Existing scenarios depict a wide range of possible futures, from relatively modest climate change to very severe climate change (in both magnitude and rate of change), not generally associated with estimates of the probability of one versus another. Figure 4, for example, shows the futures depicted in SRES scenarios, while Figure 5 shows the futures depicted in RCPs. Although RCPs are becoming the standard framings of climate futures, SRES scenarios continue to be widely used

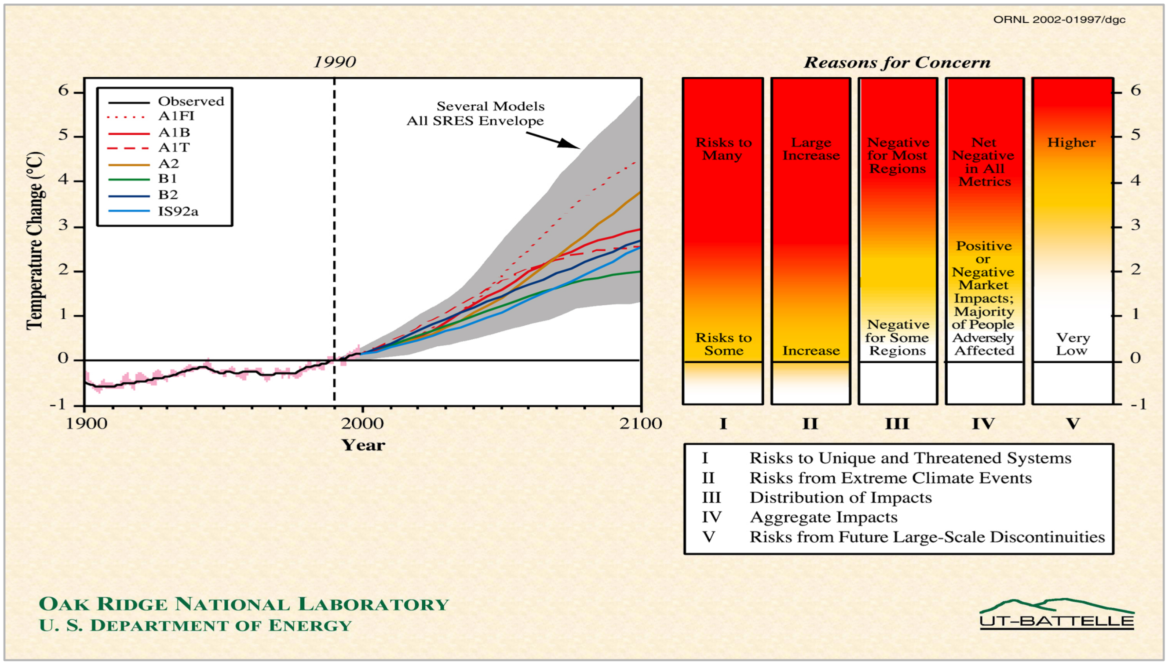

Figure 4. SRES Scenarios: IPCC, 2007'

because of familiarity, in some cases easier access, and continuing development of ensemble analyses of CMIP-5 projections. As one case in point, the US National Climate Assessment scheduled for release in late 2013 uses SRES scenarios B1 and A2 to represent relatively moderate and relatively severe climate change trajectories. Downscaled versions of the RCPs are becoming available, and current attention is focused on RCP 4.5 as a relatively moderate future (although well above SRES B1) and RCP 8.5 as a relatively severe future (well above SRES A2). Although such scenarios are useful for framing and illustrating the nature and magnitude of climate change trajectories and risks, along with what they depend upon, they are often insufficient to address major energy system concerns, especially in the next several decades. The major concerns are:

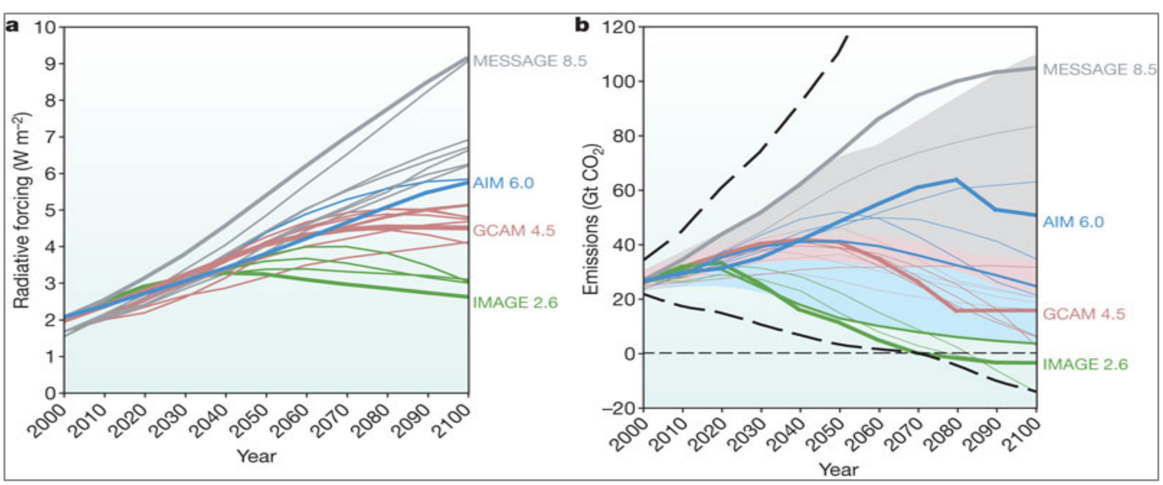

Figure 5. Representative Concentration Pathways (RCPs), both projected forcings and associated greenhouse gas emissions (Moss et al., 2010).

- Potentials for severe climate change, given current trajectories of global GHG emissions. As extreme as RCP 8.5 appears to be – the most extreme ever modeled to date – current global greenhouse gas emissions are on a trajectory above the emission assumptions that RCP 8.5 embodies (Figure 6). This strongly suggests that future climate change impacts are likely to be very large indeed, often disruptive, and in many cases requiring transformational changes in the systems that support and use energy services.

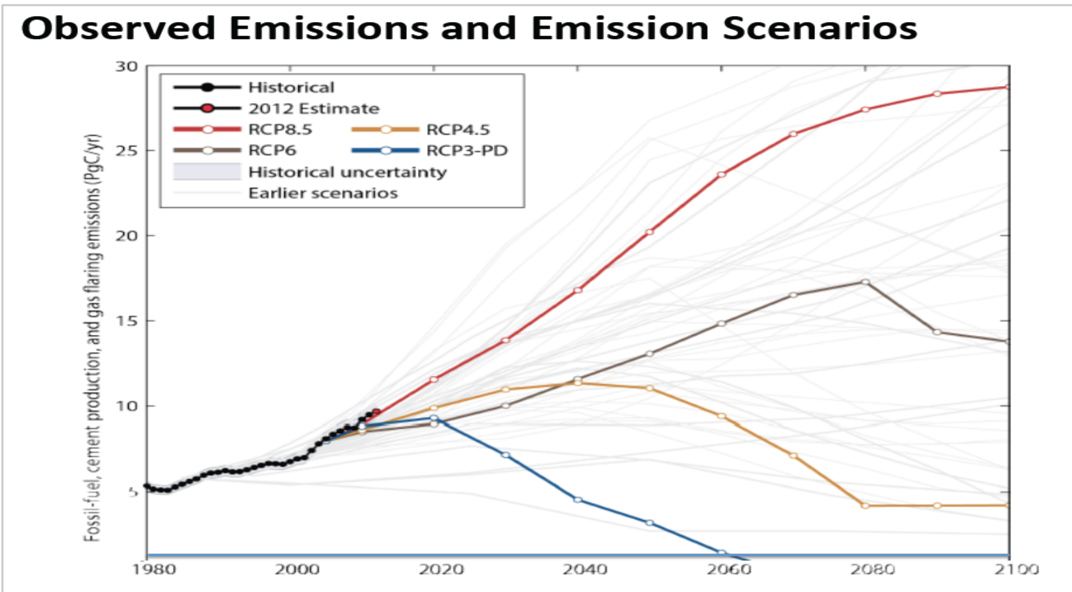

Figure 6. Current global emissions are above the worst scenario: Peters et al., 2013.

- Limited current capacity to project extremes and climate-related extreme weather events. Clearly, implications of climate change for energy systems are numerous, interconnected, and in many cases potentially serious. Climate scenarios primarily address changes in temperature and precipitation over time, usually average changes over decadal periods. On the other hand, concerns of energy system decision-makers and managers are mainly focused on climate extremes and climate-related extreme weather events (ORNL, 2012a), especially in the next several decades. In many cases, current climate models are not very useful as sources of information about projected climate-related phenomena such as severe storms and sea-level rise; and they are not very useful as sources of information about projections of extreme weather events that combine climate phenomena with other driving forces, such as flooding, heat waves, droughts, and wildfires.

- Issues related to the sustainability of energy services for lower-income areas and populations. Most framings of climate change mitigation responses by energy systems emphasize relatively rapid decarbonization of energy supply and use, e.g., significant increases in the use of renewable energy systems (see, for instance, IPCC, 2012b and Vergara, 2012). Although this issue is not always confronted directly, most alternative energy pathways would imply higher, perhaps much higher, energy costs than at present as the world transitions to a new mix of energy sources. Many observers, however, associate the sustainability of energy services for development with low energy costs (e.g., IPCC, 2012b), which adds significantly to the challenge of assuring a smooth but relatively rapid transition to alternative energy systems worldwide.

III. PERSPECTIVES ON IMPACTS FROM CLIMATE CHANGE

Impacts of climate change on energy supply and use are potentially numerous and diverse, and if climate change is relatively severe the impacts could be disruptive, at least seasonally and/or episodically. Figure 7 illustrates some of the factors that could affect energy supply systems.

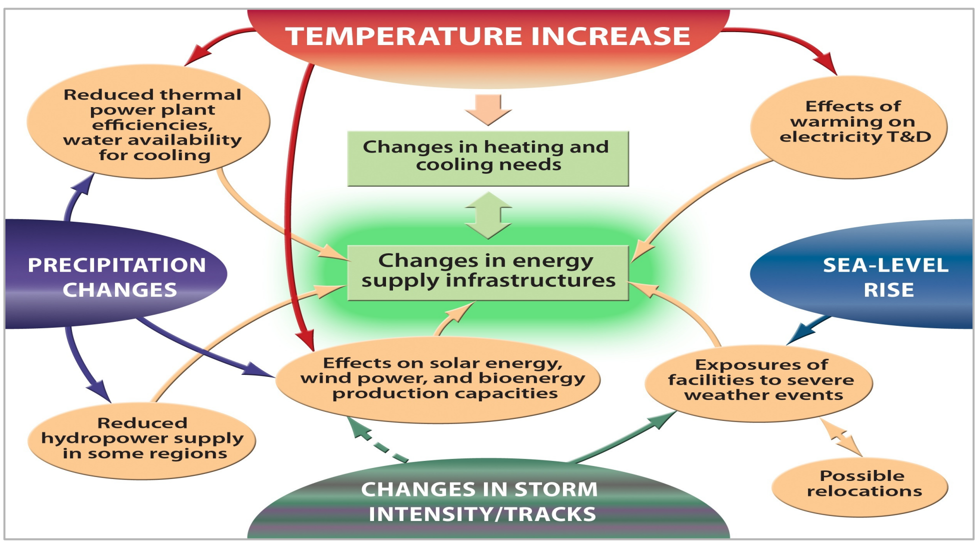

Figure 7. A summary of potential climate change effects on energy supply infrastructures.

Although the current body of research on implications of climate change for energy systems is still weak, there is a relatively robust consensus about the potential impacts that are of greatest concern:

- The dominance of extreme events over the next several decades. As indicated above (see also IPCC SREX, 2012 regarding this concern for most potentially impacted sectors), the of extreme events is the major concern, not only for energy supply but also for energy use – where disruptions in supply not only affect such energy services as lighting and cooling but also such related infrastructures as water pumping and transportation system controls.

- Effects of temperature increases in vulnerable areas, including lower-income urban areas that lack access to air-conditioning, especially heat waves during summer periods

- Effects of changes in precipitation regimes on water availability and water temperature, both chronically and seasonally, especially droughts in areas where water is already scarce and floods during periods of extreme precipitation

- Sea-level rise, especially in combination with storm exposures in vulnerable areas, relative to the map of energy facilities (e.g., facility siting) and consumer markets for regional utilities (e.g., longer-term population shifts away from vulnerable areas)

- Effects of climate change on patterns of energy demand and use more generally, including possible demographic and economic shifts

- Effects of climate change policies on energy supply and use. An issue that is seldom addressed in energy sector impact assessments, although it is a very prominent concern on the part of most energy decision-makers, is impacts of climate mitigation policies on regions and energy sector institutions (CCSP, 2008, Chapter 4; NRC, 2010: 48-50; IPCC SRREN, 2012: Chapter 8). Climate change policies aimed at reducing the rate of increase in global greenhouse gas concentrations in the atmosphere have the potential to affect market shares and the financial viability of energy systems based on fossil fuels, especially coal; to raise energy prices as a result of emission controls and technology transitions; and to present challenges for regional economies linked with fossil fuel production and/or use. They could also affect energy technology research and development (R&D) agendas and international energy technology and service markets, e.g., related to innovative renewable energy alternatives. Such effects are an important aspect of interactions between adaptation and mitigation (Wilbanks and Sathaye, 2007), where synergies may offer co-benefits for both.

IV. STRATEGIES FOR ENERGY SYSTEM ADAPTATION TO REDUCE VULNERABILITIES AND IMPACTS

Both globally and in most larger nations, the energy sector is large and complex, with impressive financial and management resources, capable of responding to major challenges (GCRP, 2009; ORNL, 2012a). And, after decades of avoiding discussions of climate change because they are connected with discussions of climate change policy responses (e.g., cap and trade policies, carbon emission restrictions, and carbon taxes), both energy suppliers and energy users are beginning to recognize that climate change impacts may pose ris to some of their activities.

Most sizeable energy supply institutions pride themselves on their risk management, and they are well-adjusted to climate variations – so well so that in some cases they have been slow to recognize that climate change presents new challenges. As climate-related changes begin to be observed, however, exposures to such effects as extreme weather events, environmental changes in polar regions, and acidification in oceans where offshore production is taking place, energy institutions are adding climate change to the host of uncertainties addressed by their risk management strategies, seeking not only to reduce vulnerabilities but also to identify market opportunities (Dell and Pasteris, 2010; ORNL, 2012a).

For both energy supply and use, strategies for managing risks associated with climate change will vary by resource, technology, institution, and threat – related to ongoing processes of capital stock turnover and revitalization. In industries where facilities and equipment have lifetimes of decades, over thirty to fifty years much of the capital stock will be changed; and reducing climate change vulnerabilities can be built into the choices that must be made in any event.

Table 1 (from World Bank, 2011) summarizes examples of adaptation measures that may be considered by risk management strategies in the energy sector.

More specifically, such energy sub-sectors as the oil and gas industry have recently begun considering climate change vulnerabilities and adaptive risk management. For example, catalyzed by a vulnerability assessment led by Jan Dell (Dell and Pasteris, 2010: see Figure 8), the oil and gas industry conducted a workshop at IPIECA in London in October 2012 on climate change adaptation, at which a number of major companies made presentations about their current adaptation strategy development efforts (*www.**ipieca**.org/system/files/event.../workshop_programme_v3.pdf*).

Climate change risk management by electric utilities, at least in the United States, has been more scattered but in some cases impressive. A significant example is a recent report by Entergy, a major multistate utility in the US Gulf Coast region on vulnerabilities of this low-lying coastal region to climate change combined with continuing economic and demographic growth and significant land subsidence (Entergy, 2012). The report estimated costs of combined effects, evaluated a range of adaptation options, and recommended a nine-point plan to avoid increases in vulnerability in coming decades.

Table 1. Examples of adaptation measures to reduce losses/risks in energy systems World Bank, 2011

	Energy System	TECHNOLOGICAL		BEHAVIORAL		
		"Hard" (structural)	"Soft" (technology and design)	Re(location)	Anticipation	Operation and Maintenance
SUPPLY	**Mined Resources** (incl. oil & gas, thermal power, nuclear power)	Improve robustness of installations to withstand storms (offshore), and flooding/drought (inland)	Replace water cooling systems with air cooling, dry cooling, or recirculating systems Improve design of gas turbines (inlet guide vanes, inlet air togging, inlet air filters, compressor blade washing techniques, etc.) Expand strategic petroleum reserves Consider underground transfers and transport structures	(Re)locate in areas with lower risk of flooding/drought (re)locate to safer areas, build dikes to contain flooding, reinforce walls and roofs	Emergency planning	Manage on-site drainage and runoff Changes in coal handling due to increased moisture content Adapt regulations so that a higher discharge temperature is allowed Consider water re-use and integration technologies at refineries
SUPPLY	**Hydropower**	Build de-siting gates Increase dam height Construct small dams in the upper basins	Changes in water reserves and reservoir management	(Re)locate based on changes in flow regime		Adapt plant operations to change in river flow patterns Operational complementarities with other sources (for example, natural gas
SUPPLY	**Wind**		Improve design of turbines to withstand higher wind speeds	(Re)locate based on expected changes in wind speeds (Re)locate based on anticipated sea level rise and changes in river flooding		

Table 1. Examples of adaptation measures to reduce Losses/risks in energy systems (continued)

Energy System		TECHNOLOGICAL		BEHAVIORAL		
		"Hard" (structural)	"Soft" (technology and design)	Re(location)	Anticipation	Operation and Maintenance
	Solar		Improve design of panels to withstand storms	(Re)locate)based on expected changes in cloud cover	Repair plans to ensure functioning of distributed solar systems after extreme events	
	Biomass	Build dikes Improve drainage Expand/improve irrigation systems Improve robustness of energy plants to withstand storms and flooding	Introduce new crops with higher heat and water stress tolerance Substitute fuel sources	(Re)locate based in areas with lower risk of flooding/storms	Early warning systems (temperature and rainfall) Support for emergency harvesting of biomass	Adjust crop management and rotation Adjust planting and harvesting dates Introduce soil moisture conservation practices
Demand		Invest in high-efficiency infrastructures and equipment Invest in decentralized power generation such as rooftop PV generators or household geothermal units		Efficient use of energy through good operating practice		
Transmission and Distribution		Improve robustness of pipelines and other transmission and distribution infrastructure Burying or cable re-rating of the power grid		Emergency planning	Regular inspection of vulnerable infrastructure such as wooden utility poles	

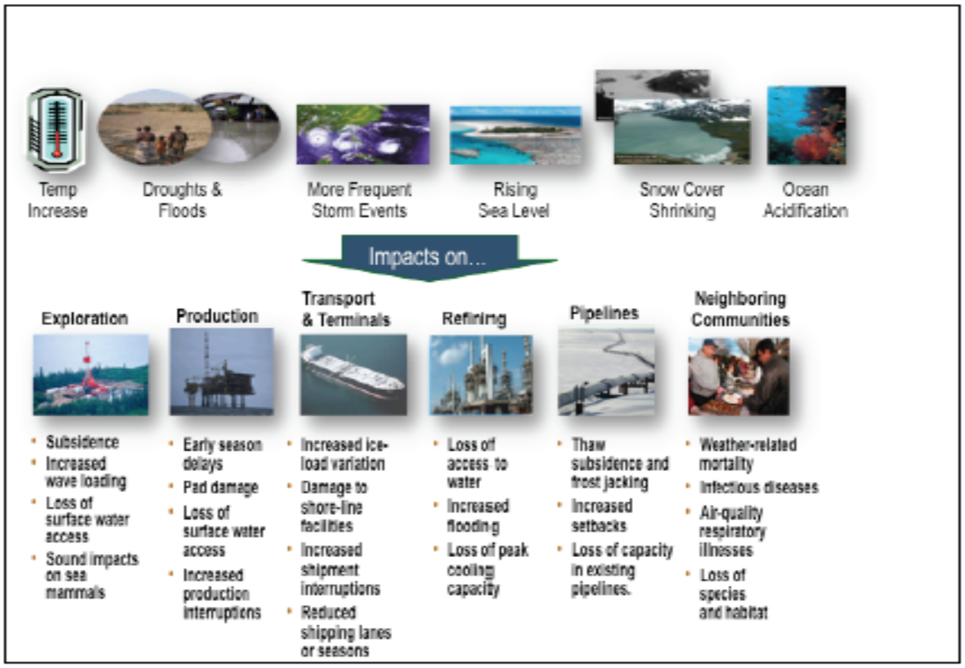

Figure 8. Oil and gas industry vulnerabilities to climate change impacts (Dell and Pasteris, 2010).

Another line of study considers ways that investments in adaptation science and technology for energy supply and use might improve adaptation capacities. Examples range from more efficient and affordable space cooling technologies to more affordable desalination, improved materials for offshore facilities exposed to ocean acidification, and improved understandings of groundwater dynamics and recharge (ORNL, 2012c; Wilbanks, 2010). Almost certainly, a strong science base to provide viable options for adaptation will increase prospects for effective vulnerability and risk management (Figure 9).

V. **SUMMARY**

The most prominent implications of climate change for energy supply and use systems are focused, at least in the near future, on vulnerabilities to extreme weather events, which can cause serious short-term disruptions in energy supplies and services. Longer-term implications tend to focus on water supply issues for energy production and temperature effects on electricity demand. But, as water issues illustrate, the energy sector is closely coupled with other critical infrastructures as well, including water, transportation, communication, and waste management; and implications of climate change for those infrastructures are of concern.

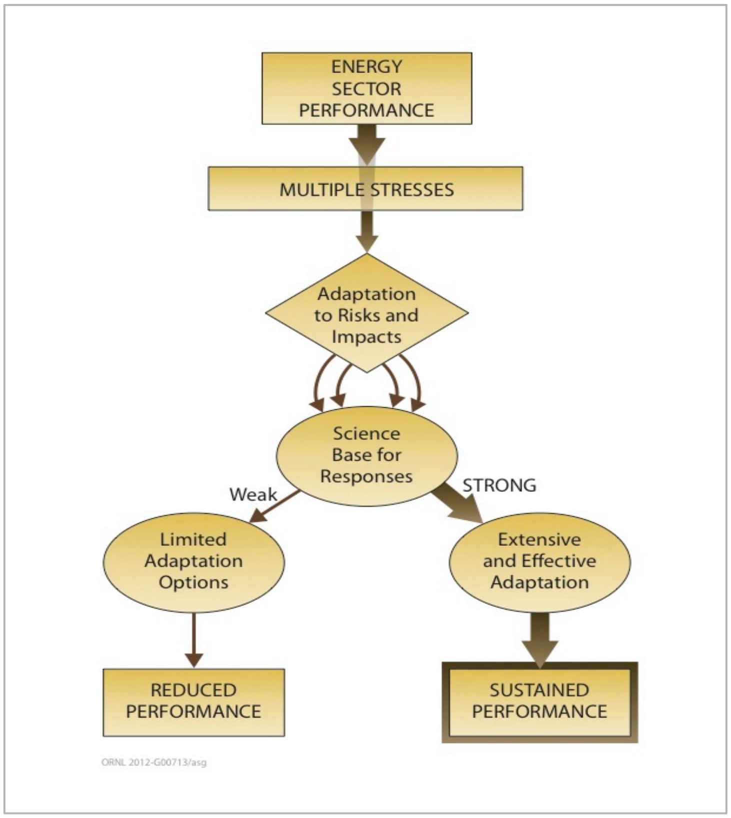

Figure 9. How a strong science base can enable and support effective adaptation

Major energy supply institutions in the industrialized world have impressive financial and managerial resources for climate change risk management, but institutions in many developing countries are not so well-equipped to cope (for instance, the capacity to access large-scale financial resources may be limited by questions about institutional performance and profitability). As a result, the greatest vulnerabilities to climate change impacts may be in the developing world, where (a) meeting rising electricity demands could be adversely affected in some regions by seasonal water scarcity, and (b) meeting needs for energy services to support economic and social development could be complicated by energy price increases to lower-income energy users.

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