Wind *and* Solar Energy

A CORE ELEMENT OF A GLOBAL ENERGY TECHNOLOGY STRATEGY TO ADDRESS CLIMATE CHANGE

A TECHNOLOGY REPORT FROM THE SECOND PHASE OF THE GLOBAL ENERGY TECHNOLOGY STRATEGY PROGRAM

GTSP
Global Energy Technology Strategy Program

Wind *and* Solar Energy

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PHASE 2 FINDINGS FROM AN INTERNATIONAL PUBLIC-PRIVATE SPONSORED RESEARCH PROGRAM

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TO THE READER

This report reflects research conducted as part of the Global Energy Technology Strategy Program (GTSP) at the Joint Global Change Research Institute and in collaboration with partner research institutions around the world. The first phase of the GTSP began at a time when the importance of a technology strategy in addressing climate change was unappreciated. GTSP Phase 1 made the case that a technology strategy was an important part of a larger strategy to address climate change and needed to be included along with the other major components: climate science research, adaptation to climate change, and emissions mitigation.

The second phase of the GTSP recognized that to craft a global energy technology strategy it was important to develop a deeper understanding of potentially important technologies and technology systems, and to embed that knowledge in the context of the larger global energy and economic systems. In Phase 2 we identified six energy technologies and technology systems with the potential to play a major role in a climate-constrained world: CO_2 capture and storage, biotechnology, hydrogen systems, nuclear energy, other renewable energy, and end-use technologies that might be deployed in buildings, industry and transportation. Knowledge gained in each area has been integrated into a larger global energy-economy-climate frame. That combination of depth of study and integrated assessment produced a unique strategic perspective and a bounty of fresh insights. In this document, we have distilled and summarized some of the most salient.

The past nine years have flown by and, looking back from the present, it is amazing to see how far we have come. The GTSP has accomplished much, but much work remains. As we enter Phase 3, we will build on the knowledge gained thus far. We will continue to deepen our understanding of technology and we will continue to integrate that understanding into a larger energy and economic context. And, we will add a new dimension to our work to provide a deeper understanding of the *regional* and *institutional* contexts in which technology is developed and deployed.

Our research has been supported by numerous firms, nongovernmental organizations, and government agencies. Their support has enabled us to continue to explore the implications of designing and implementing a technology strategy. Moreover, we have received the help of many peer reviewers, who throughout the process of developing this document provided their expertise and advice. And for that support we are grateful. Of course, the views and opinions of the authors expressed herein do not necessarily state or reflect those of the sponsoring, participating institutions, or reviewers and any errors that remain are our own.

Jae Edmonds
May 2007

Wind and Solar Power

Wind and solar are iconic renewable resources, characterized by large potential, no direct emissions of pollutant or greenhouse gases, and the capability to produce sustainable energy indefinitely. Consequently, wind and solar technologies have enormous potential to meet a significant portion of the world's future energy demands with little impact on the atmosphere. However, large-scale deployment of wind and solar raises unique research and systems analysis issues.

The first issue involves limits on availability. In contrast to other sources of electric power, wind and solar are intermittent resources in that their availability, while predictable, cannot be completely controlled. In addition, wind and solar power generators must be located where the physical resources exist, often requiring an investment in transmission capacity to deliver power to populated load areas.

Moreover, current wind and solar technologies require large up-front capital investment, although they offer low recurring costs. The present and future potential of these technologies will be determined in large part by the extent to which technological developments can lower their capital cost. Finally, wind and solar generators are typically much smaller than fossil and nuclear plants, requiring multiple units over a wide area to build up to a large scale. This dispersion results in challenges for land use and environmental aesthetics. The extent of eventual deployment of these technologies will depend on land-use decisions and social acceptability. Key GTSP insights include:

- With or without a climate policy, the contribution of wind and solar power technologies will continue to increase. Their role would become even more important under greenhouse gas emissions constraints.

- Reducing the capital cost of solar technologies to make them competitive with other sources of electricity is a critical R&D challenge.

- Intermittency of solar and wind energy resources must be considered as part of the cost of wind and solar power. The cost is small for low penetration levels, but will increase as wind and solar gain higher market share. Improved grid management and storage technologies may play a role, particularly at high penetration levels.

- Wind is already cost-competitive with other technologies in several locations and applications. Thermal central station solar electric plants are currently the most cost-effective solar electric technology, although only practical in fairly cloud-free regions.

- If deployed at a large scale, wind and solar facilities would be both much more numerous and spread over a larger area than the equivalent fossil-fired facilities. This provides both benefits, such as lower cost variability and income to landowners, and new challenges, such as the need for additional transmission infrastructure.

WIND POWER

Wind power is a well-known and commercially successful technology for electric power. It is rapidly growing in the United States and in other parts of the world. Although wind is still a small fraction of U.S. total electric capacity, its deployment has more than doubled in the past several years (see Figure 1). Generation costs are competitive or nearly competitive with fossil-fueled power plants in many places. This expansion has been accelerated not only by policies such as tax incentives and renewable portfolio standards but also by an evolving market for green power in which firms or individuals are willing to pay to secure generation from renewable sources like wind to meet their electricity demands. Under a climate policy that increased the costs of fossil fuels, wind power would expand substantially.

The technology for generating electricity from wind is fairly straightforward. Most commonly, double or triple blade turbines are mounted high overhead on cylindrical towers; the turbines capture the blowing winds and generate electricity. For large utility-scale applications, multiple wind turbines are generally placed together, either along a line or spaced in an array configuration (Figure 2). Wind turbines are a fairly mature technology with commercial deployment and management worldwide.

SOLAR POWER

Solar energy can be utilized in many forms. The least expensive technology for generating electricity with solar power is central station thermal or concentrating solar power (CSP), where solar energy heats a working fluid to high temperatures to power a turbine (Figure 3). This technology requires direct sunlight and thus must be sited in fairly cloud-free locations to operate.

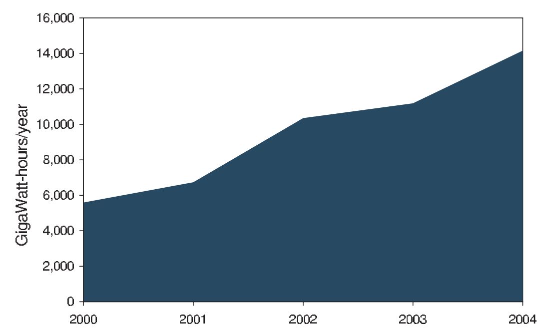

Figure 1. US wind electricity generation. Wind generation has been growing rapidly in the United States since 2000.

Figure 2. An array of wind turbines. Typical new wind turbine size is on the order of 1.5-2.5 megawatts (MW). Turbines are sited in wind farms to build economies of scale for transmitting electricity to load centers.

The most versatile technology for utilizing solar energy is photovoltaic (PV) conversion (Figure 4). PV technology can be deployed in any location, with output roughly proportional to the amount of sunlight. PV systems can be mounted at a fixed angle or in configurations that track the sun in one or two axes. There are two broad approaches to photovoltaics: crystalline and thin film. Crystalline PV cells offer higher efficiency but are more expensive. Thin film PV systems are less expensive but have lower conversion efficiencies.

Outside of electricity generation, the least expensive method of using solar energy is as a source of direct heat. Residential solar hot water systems are economically attractive in many locations and are widely deployed in a few countries (Israel, Greece, and Cyprus).

WIND AND SOLAR IN THE ELECTRIC SYSTEM

Although both wind and solar are intermittent resources, they operate much differently from each other within the electric system. Since wind may be available at all hours, wind largely operates to supply baseload generation (defined as generation that operates at all hours). Thus, wind competes most directly with electric generation plants such as coal or nuclear plants. This also means that the potential contribution from wind is very large, as the largest fraction of total electric supply falls into this category.

In contrast, solar power is only available during hours of sunlight—i.e., the daytime. Fortunately, solar power's availability does generally coincide with the peak electricity demands that also occur in the daytime. Consequently, solar power competes in the market for intermediate and peak power, which typically receives a much higher market price than baseload power. To operate beyond daylight hours, solar hot water and CSP systems can be constructed with thermal storage that can extend the time over which they can effectively operate. However, this is not true for solar PV systems; they convert the light directly to electricity rather than using heat from the sunlight, which can be stored. Therefore, external storage would be needed to allow PV systems to provide services outside of daylight hours.

▲ **Figure 3.** Concentrating solar power from a central station such as this is currently the least expensive solar electricity generation technology.

Although windy and sunny conditions can potentially be predicted, they cannot be controlled. Therefore, to provide reliable energy services either backup capacity needs to be provided or the provision of services delayed until power becomes available. If a relatively small portion of power is supplied by wind and solar (for example, around 10–15 percent, although each situation will be different), the reserve capacity already present in the electric generation network is likely to be sufficient to compensate for these variations. Beyond these penetrations of wind and solar, additional capacity or reserves would be required.

As larger amounts of power are supplied from intermittent sources, the remedies available to ensure reliable energy service delivery depend on the time scale. Over relatively short time scales, minutes to perhaps tens of minutes, some services (such as cooling) could be postponed or accelerated using advanced load management. For longer variations, some sort of backup generation or storage would be necessary. Countering this to some extent is the geographic dispersion of sources that will tend to come with greater penetration.

The variation in wind is thought to be fairly randomly distributed across a large enough regional scale (e.g., it is unlikely that the wind would stop blowing in several places at once). However, solar irradiance can decrease coherently over large regions. This coherence means that an electric system could see much of its solar capacity reduce its generation all at the same time, potentially causing supply problems. While the intermittency of these resources should not be considered insurmountable, understanding the impact of these effects at the high levels of wind and solar penetration that could be realized under a climate policy is still at a rudimentary level.

THE ROLE OF STORAGE

Because electricity generation must be timed to coincide with electricity demand, the intermittency of wind and solar provides an additional challenge beyond reliability. The availability of these resources will not always coincide with the timing of the demand for them. The development of effective and economic storage technologies would attenuate this problem and allow further use of wind and solar power.

Figure 4. An array of solar photovoltaic (PV) panels. PV is the most versatile solar technology. It can be deployed in any location, with output roughly proportional to the amount of sunlight.

For example, consider a system with a high penetration of wind capacity. In such a system, there may be times when more wind energy is available at night than what is needed without turning down electricity generation from baseload plants. In the absence of storage, it may be less costly or even physically necessary to throw away some wind electricity than to turn down the baseload plants. But with the development of advanced storage technologies such as compressed air energy systems (CAES) or large-scale batteries, this wind power could be stored for use during the day. Using storage in this manner would increase the amount of electricity generation met by wind without additional reliability considerations.

Electricity generated from wind and solar resources can also be used to produce hydrogen. While hydrogen can be considered a form of storage in the electric sector, it tends to be a relatively expensive form of storage because of the combined effect of capital costs and conversion losses. Hydrogen is more likely to be supplied from wind and solar if there is a direct end-use demand for hydrogen fuel.

RESOURCES

Wind turbines extract energy from the kinetic energy of moving air. The amount of energy extracted is proportional to the wind velocity cubed. Energy generation, therefore, falls rapidly with a decrease in wind speed. This implies that high-speed wind resources are much more valuable than low-speed wind resources—although this value can be reduced if the resulting electricity must be connected over long distances to available transmission lines or load centers.

Large physical wind resources are present in many regions of the world. An International Energy Agency study of global wind resources estimated some 40,000 terawatt hours/year may be available globally, several times total world electric demand. How much of this resource would be used depends on generation cost, site selection issues, transmission to load centers, and integration with the electric grid at high penetration levels. Wind turbines have a relatively small footprint, allowing other uses of the land (Box 1). The height of wind turbines, which make them visible for some distance, partially offsets this advantage.

Box 1. LAND AREA AND RENEWABLES

Harnessing relatively diffuse wind and solar resources on a large scale would result in the widespread deployment of wind turbines or solar photovoltaic arrays. The land-use consequences of these technologies differ considerably. Consider the use of residential rooftops for the generation of solar power in the United States. 100 million households with an average of 850 square feet each of usable rooftop area might produce around 700 TW-hr of electricity annually.[a] This would represent 18% of current electricity generation.

Expansion of solar beyond this level would require additional land area. Photovoltaic cells have the advantage that there is no fundamental need for contiguous space so they, could in principle, be placed wherever land is not otherwise needed. In contrast, central station solar plants, which are significantly less expensive currently than photovoltaics, require contiguous land area for operation.

Wind power has a very different profile in terms of land use. In order to generate the same amount of power, wind turbines would be more ubiquitous—spaced out over seven times the area (compared to total rooftop area) and visible for miles around each turbine facility. The land surface area dedicated to wind power in terms of tower footprint and associated land, however, is much smaller—only one fifteenth of the space used by solar panels.[b]

[a] Assuming 1250 residential square feet per household, accounting for multi-story dwellings, and assuming 50% of the rooftop space is installed with solar panels that operate at 12% efficiency with an average effective radiance of 4 kWh/m^2/day.

[b] Assuming 2 MW turbines operating at 30% capacity factor and requiring an acre per turbine and compatible land uses such as agricultural activities immediately adjacent to the turbines.

Solar resources are even larger than those for wind. The primary limit for solar resources is the amount of land that society is willing to dedicate to this purpose. In terms of land surface fraction, 0.1% of the land surface of the earth could supply several times the total wind resource. While small in fractional terms, 0.1% of the land surface area is comparable to the global area of cultivated land. Thus, supplying solar energy at this magnitude would entail a significant land-use change. More modest, but still significant, amounts of solar power could be supplied using rooftops, for example (Box 1).

Although fossil fuel resources are not uniformly distributed geographically, they can be transported over long distances at relatively modest costs. Solar and wind resources, however, vary substantially across the globe. Solar resources are concentrated largely in lower mid-latitude and equatorial regions (Figure 5). Wind resources vary as well, although there is substantially more uncertainty in global wind resources.

Comparisons to current energy demands, while useful, underestimate the scale of the future challenge. For example, in GTSP scenarios used in this report, global electric generation expands more than fourfold by 2100.

COST AND PERFORMANCE

Reporting costs for wind and solar technologies is more difficult than for fossil technologies. First, the cost of energy production for these technologies depends on the quality of the resource being used. Second, there can be a tradeoff between generation cost and location. Generation costs are lowest where the highest quality resources are located. Some of these locations may be located far from load centers, incurring costs for transmission lines. Finally, the intermittent and non-dispatchable nature of these sources means that, as penetration increases, additional costs may be required to assure reliable power.

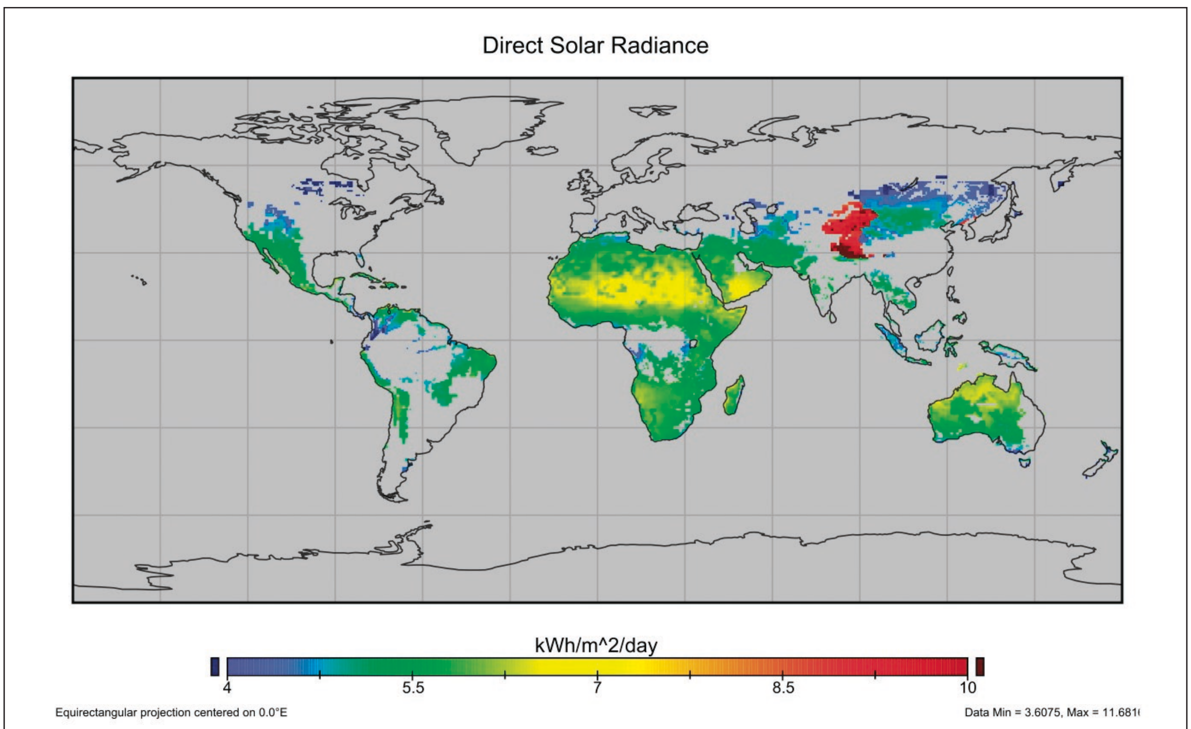

Figure 5. Direct solar irradiance on a horizontal plate for potential solar resource areas with less than 50 no-sun days per year (dense forest and croplands excluded). The colored areas show where large scale deployment of concentrating solar thermal plants could take place.

Table 1 shows costs for the dominant technologies: wind turbines, CSP, and photovoltaics for different resource categories. Currently wind is the most cost-effective, with CSP showing promise if technological advances are made in storage technologies. Photovoltaics are the most expensive, but also the most versatile of these technologies.

OTHER CONSIDERATIONS

Wind and solar power are generally perceived positively, with strong advocacy from some due to their lack of emissions and other potential benefits such as low cost volatility, rural income support, and energy independence. The use of these dispersed resources on a large scale would require widespread deployment of wind turbines or solar generation facilities. Construction of wind farms has encountered public resistance in some locations. Environmental concerns about wind turbines center on bird and bat mortality, although noise and road construction can also be issues. Visual issues are sometimes a significant concern as the presence of wind turbines alters the appearance of pristine areas. This has been of particular concern for some ridge-top and near offshore locations.

Solar power has not become widespread enough to test its societal acceptance. Aside from use of rooftops, solar energy generation generally requires dedicated land use.

Most currently utilized electric generation technologies can be sited at locations that offer the best combination of distance to load centers, ease of fuel delivery, and access to water for cooling. Solar and wind plants, in contrast, must be sited at the location of suitable resources. In most cases this will require the construction of electrical transmission lines to connect high resource regions to sometimes distant load centers. The construction of overhead transmission lines can also meet with opposition. Modest reinforcement of existing transmission lines would likely be more acceptable, but may not provide sufficient capacity to utilize some potential resource sites.

Table 1. Current Renewable Energy Technology Costs

		Solar PV	
Received Irradiance (W/m ^ 2-yr)	*1700*	*2000*	*2300*
Electricity Cost (cents/kW-hr)	29	25	21
		Concentrating Solar Trough	
Direct Irradiance (W/m ^ 2-yr)	*1700*	*2000*	*2300*
Electricity Cost (cents/kW-hr)	26	22	19
		Onshore Wind Turbines	
Wind Class	*4*	*5*	*6*
Electricity Cost (cents/kW-hr)	4.6	3.8	3.4
		Offshore Wind Turbines *(Shallow water)*	
Wind Class	*4*	*5*	*6*
Electricity Cost (cents/kW-hr)	5.3	NA	4.5

All costs are generation costs, exclusive of grid connection costs, backup costs, and tax policies.
Note that actual market costs will fluctuate due to business cycles in the supply and demand of the capital equipment.

Any new technology, particularly if highly visible, can cause concern due to unfamiliarity. It is not clear if these issues will abate over time as, for example, wind turbines become more common and people become accustomed to their visual presence in the landscape. Improved implementations, such as wind turbines with reduced noise and lower avian mortality, can also lessen impacts.

THE FUTURE DEPLOYMENT OF WIND AND SOLAR

Research on the large-scale deployment of wind and solar technologies at levels that may occur under a climate policy is in its early stages. GTSP's current analysis indicates that wind energy can contribute substantially to meeting electricity demands (see Figure 6). Based on a reserve margin formulation of backup costs we find, in line with other studies, that the cost of backup capacity is relatively modest, although there may be additional issues at higher penetration levels. The principal limit to wind contribution is not its intermittency but rather its costs relative to other electric power technologies. The resource cost of wind will tend to increase with higher levels of deployment. As higher quality and closer wind resources are used, the remaining resource becomes less competitive with alternative electric generation options.

Perhaps the biggest challenge for large-scale solar power is reducing the high capital cost. Managing the temporal pattern of solar power in the system is another critical issue, as is the regional heterogeneity of availability and quality of solar resources. Some solar technologies, such as residential hot water heating, are relatively low cost and could potentially make significant contributions in many regions.

Concentrating solar power technologies, in contrast, are only practical in fairly cloud-free regions, although the energy is partially dispatchable and backup is relatively inexpensive. Further, solar technologies can require the operation of separate backup power or storage in times when the sun is not shining (nights and cloudy days).

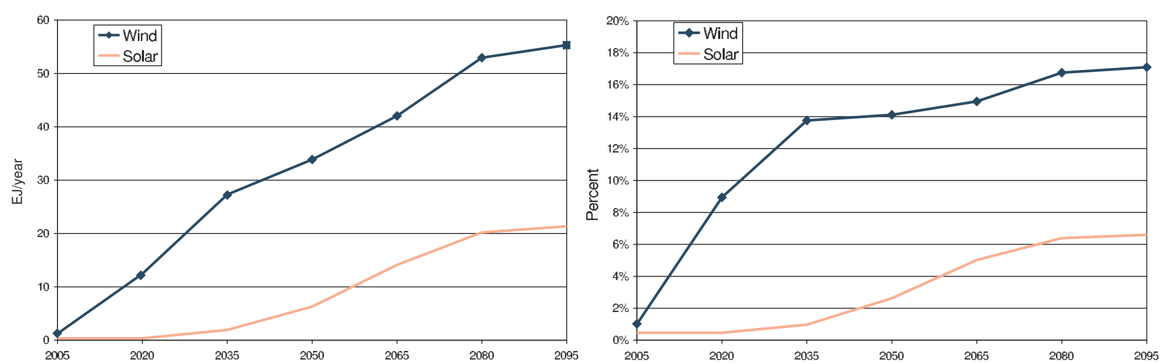

Figure 6. Potential future global deployment of wind and solar power under a 550 ppm CO_2 stabilization policy. In this scenario, wind power deployment expands dramatically, generating nearly 14% of total global electricity by 2035. Wind generation continues to grow in the second half of the century, but its share grows more slowly as total electricity generation increases at an escalating rate. Solar generation increases by 2050 as its costs become more competitive.

THE VALUE OF CONTINUED RESEARCH AND DEVELOPMENT

The deployment of wind and solar power systems around the world makes these renewable energy systems some of the fastest growing aspects of the global energy system. However, the extent to which wind and solar power can significantly expand their current market share in a greenhouse-gas-constrained world is in part dependent upon continued research and development. Selected R&D, demonstration, commercial deployment challenges and opportunities for wind and solar power energy systems include:

- Reduce the capital costs of solar photovoltaic and concentrating thermal technologies to be more competitive with conventional sources.

- Improve grid management systems to incorporate the intermittency of wind and solar energy.

- Reduce costs of storage so that wind and solar resources can be fully utilized when their periods of availability do not coincide with periods when their electricity is needed or most valued.

- Continue to develop and refine turbines that are optimized to work in offshore environments and low wind speeds.

- Reduce the cost of transmission from remote sites with large wind and solar potential to electric load centers.

APPENDIX Notes and References

Most of the CO_2 emissions in this study are stated in units of million or billions of tons of carbon (MtC or GtC, respectively). This differs from the conventions of the CCS technical community, which expresses values in millions or billions of tons of CO_2 ($MtCO_2$ or $GtCO_2$, respectively). Cost data can be converted to dollars per ton of ($/tCO_2$) by dividing by 3.667, and mass data can be converted to CO_2-based units of the climate change technical community by multiplying the mass expressed in carbon-based units by 3.667.

This report makes frequent use of a very large measure of mass known as a "gigaton." A gigaton of CO_2 ($GtCO_2$) is a standard measure for scientists and policy makers familiar with carbon management, yet for most other audiences the magnitude of this unit is sometimes hard to comprehend. A gigaton is approximately equal to 77 Empire State Buildings if they were made completely of lead, 10,718 aircraft carriers the size of the USS Enterprise, or all of the iron ore annually mined in the world. For more examples of how massive a gigaton is please consult C.L. Davidson and J.J. Dooley, "A Gigaton Is…" PNWD-3299, Joint Global Change Research Institute, Battelle Pacific Northwest Division (July 2003).

Unless otherwise indicated, all scenarios and analyses result from the GTSP research, using several well-established modeling tools.

Figure 1. Data were taken from U.S. Department of Energy/Energy Information Administration, *Annual Energy Review 2005*, DOE/EIA 0384-2005, Washington, DC (2006).

The International Energy Agency report referred to on page 9 is International Energy Agency, *The Potential of Wind Energy to Reduce CO_2 Emissions*, International Energy Agency Greenhouse Gas R&D Programme Report No. PH3/24, Paris (2000).

Box 1. Wind and PV costs are from National Renewable Energy Laboratory, *Projected Benefits of Federal Energy Efficiency and Renewable Energy Programs: FY 2006 Budget Request*, NREL/TP-620-37931, Golden, CO (2005). CSP costs are GTSP calculations.

Figure 5. The solar irradiance chart comes from the National Aeronautics and Space Administration, "Surface meteorology and Solar Energy" http://eosweb.larc.nasa.gov/sse/

References of interest for further exploration of this topic include the following:

L.E. Clarke, M.A. Wise, M. Placet, R.C. Izaurralde, J.P. Lurz, S.H. Kim, S.J. Smith, and A.M. Thomson, *Climate Change Mitigation: An Analysis of Advanced Technology Scenarios*, PNNL-16078, Pacific Northwest National Laboratory, Richland, WA (2006).

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THE **GLOBAL ENERGY TECHNOLOGY STRATEGY PROGRAM**

The Global Energy Technology Strategy Program (GTSP) began in 1998 with the goal of better understanding the role that energy technologies might play in addressing the problem of global climate change. The GTSP is unique, a global, public and private sector sponsored research program, whose sponsors and research collaborators are drawn from around the world.

The completion of the first phase of the GTSP in 2001 was marked by the release of a seminal report during a special session of the Sixth Conference of the Parties to the United Nations Framework Convention on Climate Change. This report, *A Global Energy Technology Strategy Project Addressing Climate Change: Initial Findings from an International Public-Private Collaboration,* demonstrated the importance of technology development and deployment as key cornerstones of a broader set of activities designed to address climate change. A central conclusion was that a robust technology strategy required the development of a *technology portfolio*. It found no evidence for a single technology whose development promised to "solve" the climate problem. That is, *a priori*, there is no technological "silver bullet." Rather, the GTSP concluded that various technologies and technology systems show promise for making a substantially expanded contribution to the global energy system in a climate-constrained world. These included biotechnology, hydrogen energy and other advanced transportation technology systems, nuclear power, renewable energy technologies, end-use energy technologies, and carbon dioxide capture and storage. The first phase of the GTSP produced groundbreaking research, including many results that have made their way into the frequently cited literature. This phase of the GTSP successfully added to the dialogue about responses to climate change a new, previously missing, element—technology. But building productive, long-term, real-world technology strategies to address climate change requires a deeper understanding of technologies and their potential. Thus, the GTSP launched its second phase in 2002. GTSP Phase 2 pushed the frontiers of our knowledge to gain a much deeper understanding of how these key carbon management and advanced energy technologies will deploy in practice, and the means for launching and sustaining a meaningful global energy technology strategy.

GTSP Phase 3 will delve into the regional diversity and institutional dimensions of developing and deploying technologies to address climate change.

GTSP PHASE 2 SPONSORS In alphabetical order

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