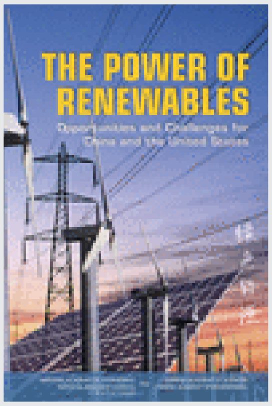


The Power of Renewables: Opportunities and Challenges for China and the United States

DETAILS

256 pages | 6 x 9 | PAPERBACK
ISBN 978-0-309-16000-1 | DOI 10.17226/12987

AUTHORS

Committee on U.S.-China Cooperation on Electricity from Renewable Resources; National Research Council; Chinese Academy of Sciences; Chinese Academy of Engineering

THE POWER OF RENEWABLES

Opportunities and Challenges for China and the United States

Committee on U.S.-China Cooperation on Electricity from Renewable Resources

Policy and Global Affairs Division

NATIONAL ACADEMY OF ENGINEERING
NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

AND

CHINESE ACADEMY OF SCIENCES
CHINESE ACADEMY OF ENGINEERING

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, D.C. 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This study was supported by funding from Google.org (Grant No. 25-2008), the U.S. Department of State (Grant No. S-LMAQM-09-GR-306), the U.S. Department of Energy (Contract No. DE-DT000093, TO# 26), the National Science Foundation (Grant No. CBET-0917786), the National Academies, the National Academy of Engineering, the Chinese Academy of Sciences, and the Chinese Academy of Engineering. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

International Standard Book Number-13: 978-0-309-16000-1
International Standard Book Number-10: 0-309-16000-6

Copies of this report are available from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, D.C. 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet, *http://www.nap.edu*.

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Charles M. Vest is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

COMMITTEE ON U.S.-CHINA COOPERATION ON ELECTRICITY FROM RENEWABLE RESOURCES

U.S. Committee

LAWRENCE PAPAY (NAE),[1] *chair*, PQR LLC
XUEMEI BAI, Commonwealth Scientific and Industrial Research Organization
RICHARD BAIN, National Renewable Energy Laboratory
ROGER BEZDEK, Management Information Services Inc.
HELENA CHUM, National Renewable Energy Laboratory
J. MICHAEL DAVIS, Pacific Northwest National Laboratory
JOANNA LEWIS, Georgetown University
JANA MILFORD, University of Colorado at Boulder
JEFFREY PETERSON, New York State Energy Research and Development Authority
CARL WEINBERG, Weinberg Associates

Chinese Committee

ZHAO ZHONGXIAN (CAS),[2] *chair*, Institute of Physics, Chinese Academy of Sciences
CHEN YONG, Guangzhou Branch, Chinese Academy of Sciences
DAI SONGYUAN, Institute of Plasma Physics, Chinese Academy of Sciences
FEI WEIYANG (CAS), Tsinghua University
GANG WU, Chairman and CEO, Xinjiang Goldwind Science & Technology Co. Ltd.
HE DEXIN, Chinese Wind Energy Association
HUANG QILI (CAE),[3] Northeast China Grid Company Ltd.
LUO ZHONGYANG, Zhejiang University
MA LONGLONG, Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences
SU JILAN (CAS), Second Institute of Oceanography, State Oceanic Administration
WANG XIFAN, Xiían Jiaotong University
WANG ZHIFENG, Institute of Electrical Engineering, Chinese Academy of Sciences
WU CHUANGZHI, Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences
XIAO LIYE, Institute of Electrical Engineering, Chinese Academy of Sciences
XU HONGHUA, Institute of Electrical Engineering, Chinese Academy of Sciences
XU JIANZHONG (CAS), Institute of Engineering Thermophysics, Chinese Academy of Sciences

[1] National Academy of Engineering
[2] Chinese Academy of Sciences
[3] Chinese Academy of Engineering

YAN LUGUANG (CAS), Institute of Electrical Engineering, Chinese Academy of Sciences
YANG YULIANG (CAS), Fudan University
ZHAO DAIQING, Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences
ZHAO YING, Nankai University
ZHENG HOUZHI (CAS), Institute of Semiconductors, Chinese Academy of Sciences
ZHOU FENGQI, Energy Research Institute, National Development and Reform Commission (retired)
ZHU RONG, Center for Wind and Solar Energy Resource Assessment, China Meteorological Administration

U.S. Staff

DEREK VOLLMER, Study Director, Policy and Global Affairs Division, The National Academies
LANCE DAVIS, Executive Officer, National Academy of Engineering
PROCTOR REID, Director, Program Office, National Academy of Engineering
PENELOPE GIBBS, Senior Program Associate, National Academy of Engineering
DAVID LUKOFSKY, Christine Mirzayan Science and Technology Policy Graduate Fellow and National Academy of Engineering Fellow

Chinese Staff

CAO JINGHUA, Deputy Director, Bureau of International Cooperation, Chinese Academy of Sciences
DU FENGLI, Director Assistant, Institute of Electrical Engineering, Chinese Academy of Sciences
KANG JINCHENG, Deputy Director-General, Bureau of International Cooperation, Chinese Academy of Engineering
LIAO CUIPING, Research Director, Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences
LIU FENGSONG, Deputy Director-General, Bureau of Academic Study, Chinese Academy of Sciences
LU YAO, Research Assistant, Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences
SHEN YIMIN, Office Manager, Bureau of Academic Study, Chinese Academy of Sciences
WANG ZHENHAI, Deputy Director-General, Bureau of Policy Studies, Chinese Academy of Engineering
XU HAIYAN, Deputy Director, Bureau of International Cooperation, Chinese Academy of Engineering

Preface

The U.S. National Academies have had an ongoing program of cooperation with the Chinese Academies (Chinese Academy of Sciences and Chinese Academy of Engineering) since the late 1990s, focusing on issues of mutual interest in the fields of energy and environmental management. Their first joint publication, *Cooperation in the Energy Futures of China and the United States* (2000), was the first examination of broad energy questions both nations faced as they entered the new millennium.

This initial study was followed by *Personal Cars in China* (2003), which examined China's nascent automotive industry and the implications of increasing personal vehicle use. Subsequently, the respective Academies jointly published *Urbanization, Energy, and Air Pollution in China: The Challenges Ahead* (2004) and *Energy Futures and Urban Air Pollution: Challenges for China and the United States* (2007), offering two detailed examinations of the interrelation between energy use and air quality on an urban scale. By the time this last study had concluded, the committees had witnessed a dramatic shift in terms of global interest in energy issues, climate change, and the U.S.-Chinese bilateral relationship.

It is against this backdrop that the present study was developed. Leaders from both countries' respective Academies agreed that renewable energy provided a topic of mutual interest, with implications domestically and globally, and with important scientific and technical questions to address. Upon consultations with government agencies in each country, the respective Academies proposed a study that would focus on utility-scale electricity generation from three major resources: wind, solar, and biomass.

The expert committees appointed by the Academies were tasked with comparatively assessing resource potential, exploring near-term market opportunities for mature technologies, and providing recommendations on priorities for enhanced U.S.-Chinese cooperation in this field. Recognizing that a tremendous amount of work was already underway, at a domestic level in each country but also bilaterally in the form of public and private collaborations, the committees sought to identify areas where cooperation might bring the most benefits in terms of technology development, cost reduction, or deployment.

Four bilateral meetings were organized over the course of 12 months so that the committees could jointly gather information, examine issues on a regional basis, and formulate their joint findings and recommendations. Meetings were held in Guangzhou and Beijing (December 2008), Hawaii (March 2009), Xining, Qinghai province (July 2009), and Colorado and California (October 2009). During each of the meetings, committee members benefited from the help of state/provincial and local government agencies, local industries and electric utilities, and local universities and research laboratories. This report has been prepared on the basis of those visits, the information provided during the public meetings, publicly available data and academic literature, and the professional expertise of the U.S. and Chinese committee members. The report attempts to provide side-by-side comparisons where possible, but in sections where more information or data were available on the United States than on China, the committees decided to present this additional information rather than omit it. This is particularly true for information on resource assessments in China, and so the additional information on experience in the United States should be instructive as China improves its own capacity in this field.

This study did not examine in detail the trade, intellectual property, and economic competitiveness issues that are an important dynamic of the U.S.-Chinese bilateral relationship. The committees acknowledge in several places in the report that these issues have a bearing on U.S.-Chinese cooperation in renewable energy, but the committees do not provide any specific recommendations on trade or intellectual property matters, which are outside the scope of the report. The study also does not explicitly examine the effect of climate change legislation, in the form of an economy-wide cap or tax on greenhouse gas emissions, on bilateral cooperation in renewable energy, although it does describe how these mechanisms could affect the market for renewable power. Such legislation, or a global agreement to reduce emissions, would eventually influence the structure and timing of some cooperation, but as the report notes, cooperation has been ongoing for many years and is motivated by a range of factors.

We hope that the resultant report is of value to decisionmakers in both countries, as well as to a broader international audience. We face many challenges in scaling up electricity generation from renewables, and we acknowledge that renewables represent one portion of a larger, diverse portfolio of energy options.

But it is our hope that international cooperation in this field, between the United States, China, and the global community, can help accelerate progress toward a cleaner energy future.

We were honored to serve as chairs of these distinguished committees, and we compliment the U.S. and Chinese committee members for their efforts throughout this study process.

Lawrence T. Papay
U.S. committee chair

Zhao Zhongxian
Chinese committee chair

Acknowledgments

We wish to thank the U.S. Department of Energy Office of Policy and International Affairs, the U.S. Department of State, the Asia Pacific Partnership on Clean Development and Climate, the George and Cynthia Mitchell Foundation for Sustainability Science, Google.org, the U.S. National Academy of Engineering, the U.S. National Science Foundation's Engineering Directorate, the Chinese Academy of Sciences, and the Chinese Academy of Engineering for their financial support of this project.

The committees also wish to thank the many individuals and organizations who so graciously hosted us and organized site visits for us as part of our bilateral meetings. On the Chinese side, we would like to thank the Development and Reform Commission of Guangdong Province, the Chinese Academy of Sciences' Guangzhou Institute for Energy Conversion, Guangzhou Xingfeng Landfill Gas Recovery and Electricity Generation Plant, Nanbo Group Co. Ltd., Guangdong Fivestar Solar Energy Co. Ltd., Camda New Energy Science & Technology Co. Ltd., Guanting Wind Power Plant, Badaling Solar Thermal Power Station, Tianwei Yingli New Energy Resources Co. Ltd., Baoding Huayi Wind Turbine Blade Research and Development Co. Ltd., Qinghai Province Department of Science and Technology, Asia Silicon (Qinghai) Co. Ltd., Qinghai Huagui Energy Co. Ltd., Qinghai Suntech Nima Solar Power Co. Ltd., Qinghai New Energy Group Co. Ltd., Qinghai Institute of Salt Lakes (CAS), and Zhuangkuo Solar Valley.

On the U.S. side, we would like to thank the Governor's Office of the State of Hawaii, the Hawaii Department of Business, Economic Development and Tourism, Hawaiian Electric Company Inc., U.S. Pacific Command (PACOM), the University of Hawaii, Hilo, Hawaiian Electric Light Company Inc., Puna Geothermal Ventures, Natural Energy Laboratory of Hawaii Authority, SunPower

Corp., Parker Ranch, Mauna Lani Resort, National Renewable Energy Laboratory (NREL), the University of Colorado, Boulder, and Southern California Edison.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Academies' Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the process. We wish to thank the following individuals for their review of this report:

Robert Bower, Device Concept Inc.
Kelly Fletcher, GE Global Research
Yu-Chi Ho, Tsinghua University
Jin Hongguang, Chinese Academy of Sciences
Shi Pengfei, Chinese Renewable Energy Society
Ouyang Pingkai, Chinese Academy of Engineering
Mark Pinto, Applied Materials, Inc.
Pedro Pizarro, Southern California Edison
Gerald Stokes, Brookhaven National Laboratory
Richard Swanson, SunPower Corporation
William Wallace, National Renewable Energy Laboratory
Zhou Xiaoxin, Chinese Academy of Sciences
Wang Zhongying, National Development and Reform Commission

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Maxine Savitz (retired), Honeywell, Inc. Appointed by the National Academies, she was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Summary

The United States and China are the world's top two energy consumers and, as of 2010, the two largest economies. Consequently, they have a decisive role to play in the world's clean energy future. Reviews of the bilateral relationship have identified renewable energy as one of the key areas in which the United States ought to "significantly enhance" its cooperation with China (Council on Foreign Relations, 2007), pointing out that the United States and China are likely to become far more active partners in developing low-carbon economies to help reduce the risks of climate change (Asia Society and Pew Center on Global Climate Change, 2009). Both countries are also motivated by related goals, namely diversified energy portfolios, job creation, energy security, and pollution reduction, making renewable energy development an important strategy with wide-ranging implications. Given the size of their energy markets, any substantial progress the two countries make in advancing use of renewable energy will provide global benefits, in terms of enhanced technological understanding, reduced costs through expanded deployment, and reduced greenhouse gas (GHG) emissions relative to conventional generation from fossil fuels.

The United States and China face similar technical and economic constraints in terms of scaling up renewables' share of power generation: with the exception of hydropower and some wind and geothermal, most renewable power generation is not presently cost-competitive with baseload rates based on coal-fired power; and geographically, concentrations of electricity demand and high-quality renewable energy resources are far apart. However, renewable power offers several advantages over conventional generation, including low emissions of air pollutants, low fuel costs, and in many cases relatively quick deployment. Moreover, technologies such as solar photovoltaic (PV) panels are well-suited to specific

segments of the power generation market, such as peak demand, when electricity rates are highest. Implementation, that is, deploying more renewable energy technologies, follows a distinct path in each country. Despite those differences in existing infrastructure and policy/regulatory frameworks, there are substantial areas where cooperation could be mutually beneficial.

Within this context, the U.S. National Academies, in collaboration with the Chinese Academy of Sciences (CAS) and Chinese Academy of Engineering (CAE), assembled expert committees to review renewable energy development and deployment in the two countries, to highlight prospects for collaboration throughout the research-to-deployment chain and to suggest strategies that would promote more rapid and economical attainment of renewable energy goals. The United States and China have been engaged in cooperation on renewable energy officially since 1979—this history of cooperation has laid the groundwork for the sustained, high-level cooperation called for in this report.

Instead of organizing their analysis by resource or generation technology (i.e., wind, solar, biomass), the committees elected to analyze the technical, policy, and market factors that will influence overall growth in the renewable power sector. At the same time, the committees observed lessons from one country that appear to have implications for the other—these are reflected in some of the committee's recommendations. An important but sometimes overlooked aspect of the U.S.-Chinese bilateral relationship is that, through closer collaboration, each country greatly enhances its opportunities for organizational learning. This is particularly true for technological learning, because accelerated manufacturing and deployment of renewable power systems in one country can quickly have a global impact. Considering that renewable power generation is competing with well-established industries, harnessing knowledge on best practices in everything from resource characterization to research commercialization should help the sector become more competitive.

CURRENT STATUS OF RENEWABLE POWER DEVELOPMENT

Excluding conventional hydropower, renewables' share of generation in both countries is quite small (less than 3 percent from non-hydro sources) in comparison to fossil-fuel power plants. Conventional hydropower is the predominant source of renewable power, and China still has abundant potential large-scale resources that might be developed. Massive solar and wind resources exist in remote regions of each country, but both the United States and China lack the large-scale transmission infrastructure to access these resources, and there is debate as to how much of these resources can and will be exploited cost efficiently. Biomass offers a substantial resource for direct power production and co-firing in coal power generation. Other resources, such as geothermal, are being exploited to provide some generation as well as other energy services (heating and cooling).

Table S-1 illustrates the relative contributions of various renewable power sources to total electrical generation in each country for 2009. In 2009 China

TABLE S-1 Installed Capacity and Net Generation from Renewable Resources, 2009

Generation Technology	China		United States	
	Installed Capacity (GW)	Generation (TWh)	Installed Capacity (GW)	Generation (TWh)
Conventional hydropower	196.79	574.7	77.93	272.13
Wind	16.13[a]	26.9	33.54	70.76
Solar PV	0.3	0.45[b]	1.25	0.81[b]
Solar thermal	—	—	0.43	
Biopower	4.0	20.0	11.35	54.34
Geothermal	—	—	2.35	15.21
Subtotal	*217.12*	*622.05*	*126.85*	*413.25*
Entire electrical system	874.0	3663.9	1131.58	3953.11

Sources: CEC, 2010; EIA, 2010a-d; NEA, 2010; REN 21, 2010; Sherwood, 2010.

[a] Cumulative, reflecting installations that were completed and brought on-line by the end of 2009.
[b] Data is for grid-connected systems.

and the United States accounted for more than 25 percent of the 305 gigawatt (GW) worldwide installed capacity of non-hydro renewable power (REN 21, 2010). To put this in perspective, though, worldwide *generation* of all non-hydro renewable power in 2008 (EIA, 2010c) could have powered the United States for only seven weeks.

The past five years (2005–2009) have been a period of rapid growth in terms of installed capacity, particularly for wind turbines, and China and the United States are now global leaders in wind installations (Figure S-1). This can be misleading, however, because realistic indicators of progress must be measured in terms of Watt hours (Wh) generated, not merely GW of installed capacity, because capacity factors of variable-output renewable power technologies are lower than for fossil and nuclear energy or baseload renewable power sources such as biomass and geothermal energy.

China has made impressive strides to improve its manufacturing capability in wind turbines and solar PV systems, although the latter are almost exclusively being sold as exports. The United States has recently been the world's top market for wind turbines, and a leading supplier of second-generation, thin-film PV materials. Much of the near-term growth in renewable power in both countries will be in wind installations, as well as some larger scale solar generation. Both countries can also harness renewable resources at smaller scales using modular technologies that are readily and rapidly distributed among population centers and, thus, generally more accessible by existing transmission and distribution systems. For example, the majority of PV capacity installed in the United States has been in installations less than 500 kW, and nearly half of that capacity has been installations ranging from 5-15 kW (NREL, 2010b).

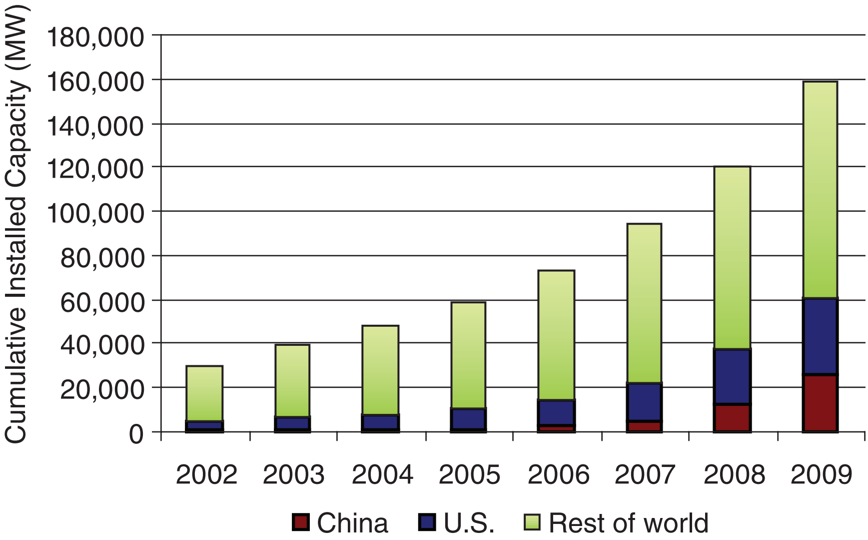


FIGURE S-1 Cumulative deployment of wind turbines in China, the United States, and globally, 2002–2009. Sources: AWEA, 2009, 2010; GWEC, 2010.

The challenge in scaling up renewable systems in general is a function of (1) their costs compared to conventional generation, (2) their ability to be integrated into the grid, which may require new controls to optimize variable output from multiple distributed sources, and (3) the availability of cost-effective multiple-hour storage. There is potential for technological improvement in each of these areas, but continued progress will also depend on policy or financial incentives.

Growth in the U.S. and Chinese renewable energy sectors is taking place in the context of a transformation of their overall energy structures. In the United States, this is being driven by the desire to reduce GHG emissions, reduce dependence on foreign sources of energy, and replace aging infrastructure. China shares the first two concerns, but its main priority continues to be meeting a rapidly increasing demand for electricity, particularly in the industrial sector. As its service sector grows (as a share of the overall economy) and its population becomes more urban, these factors will in turn shape the country's overall energy demand. It has taken 125 years to build today's U.S. energy infrastructure. China's infrastructure has developed much more rapidly, although it has been based on marginal improvements to the paradigm utilized in the United States and other industrialized countries. As both countries look ahead, there are certain opportunities to shift this trajectory in a way that will enable renewable power sources to come on line more quickly and increase their contribution to the overall energy portfolio.

FINDINGS

The following sections detail the committees' main findings and are organized according to chapter topics from the full report. The committees' most critical findings are highlighted by bold text.

Renewable Resource Assessments

In both China and the United States, solar and wind resources offer substantially more total energy and power potential than other renewable resources. These other (non-hydroelectric) renewable resources can contribute significantly to the electrical energy mix in certain regions.

While the United States has assessed the technical potential for its renewable resources, with increasing confidence and high resolution, and is now focusing efforts on estimating economic potential (supply curves with cost of delivered resource), some of the Chinese resources have been only assessed at the inventory level, in many cases with low resolution. **A reassessment of China's wind resources using higher resolution wind resource data and higher turbine hub heights could help to identify new wind development sites. A similar assessment in the United States led to a reevaluation of wind resource potential in many states. The link between high-resolution knowledge of the resource base and technology progress was demonstrated for wind power, and similar efforts are needed in China.** Areas where the United States could lend expertise include measurements of direct normal incidence radiation (for concentrating solar power [CSP] potential) and enhanced geothermal systems (EGS) mapping.

Scenario modeling (combining geographic information systems with estimated economic resource assessments, renewable technology development with time, current and possible evolution of transmission infrastructure, and balancing costs) is becoming increasingly important for planning and rational development of both traditional and renewable energy resources. It requires the use of coupled models that enable exploration of a large number of scenarios and the consequences of their deployment. **China and the United States can collaborate in this area to identify ways to reduce implementation costs through integrated resource planning.**

Biomass resource assessment collaborations among the U.S. Department of Energy (DOE) and Chinese government, academia, and industry are ongoing for biofuels feedstock supply curve developments, but these conversion technologies are still under development. Some biopower technologies such as co-firing are the most cost effective and could be developed for appropriate regions of the country using residues if an efficient collection infrastructure is established. Mapping multiple layers of resources and infrastructure may facilitate co-development of biopower and biofuels and capitalize on the economic potential of biorefineries.

Technology Development

In the near term (to 2020), wind, PV, CSP, conventional geothermal, and some biopower technologies are technically ready for expanded and accelerated deployment. CSP has been proven at utility scale (much of the experience has been in the United States), and specific concerns such as water use should not overshadow the potential benefits of CSP, including lower costs (than PV) and opportunities for thermal energy storage, which could help CSP operate as baseload generation. **CSP could be a suitable technology for China's large-scale solar energy bases, particularly if it is coupled with low water-use and storage technologies.**

Although wind turbine design is mature for onshore deployment, there remain opportunities to design wind turbines for offshore applications that are resilient to storms and typhoons. Other technologies, particularly hydrokinetic (ocean, wave and tidal) technologies, require further development but exhibit promise as locally available baseload generation options. Finally, a unified intelligent electronic control and communication system overlaid on the entire electricity delivery infrastructure would enhance the viability and continued expansion of renewable electricity—and all other electricity as well.

As both countries continue and accelerate the build out of renewable power generation facilities, it would be highly beneficial if a mechanism can be established to rapidly exchange information. Although learning and cost reductions have already been achieved from deployment in the United States, the rapid growth of renewable energy projects in China is likely to expand learning opportunities. China is now moving ahead of the United States in terms of offshore wind development and has plans to begin deploying next generation 5 megawatt (MW) wind turbines. Readily available information on these developments could enhance technology evolution and make renewable technologies more accessible globally, especially in developing nations.

In addition, joint efforts could include the analysis of distributed PV options at a regional level (e.g., metropolitan areas) for both countries. **A stronger focus on deploying distributed PV could encourage rapid reduction of balance of system cost and make the overall system more cost effective.** China is a world leader in integrating solar thermal technologies for direct use in buildings, and there are lessons from this experience that could transfer to building-integrated PV. Regional analyses would help optimize PV to best meet electricity demand, particularly peak demand, and take advantage of existing electrical distribution infrastructure.

To a large extent, major deployment of renewable power generation is constrained by location and intermittency issues. These issues have technical solutions that impose additional costs which, if applied to individual renewables projects, greatly affects their cost-competitiveness vis-à-vis conventional generation. Both the United States and China are making sizeable public investments (greater than $7 billion each for 2010) in next-generation grid technologies, with China spending nearly 10 times that amount ($70 billion from its economic recovery package) on new high-voltage transmission infrastructure. **China and the United States will need to transform power delivery systems to accommodate and integrate large amounts of variable-output renewable electric power. Specific issues that deserve attention are grid stability, load management, system flexibility including MW-scale multiple-hour storage, and compatibility with an electrified transportation infrastructure.**

Environmental Impacts

Environmental and public health benefits, including reduced GHG emissions, are a primary motivation for moving to renewable power sources. Life cycle assessment is a valuable method for broadly comparing environmental impacts of alternative electricity generating technologies, and identifying where improvements are most likely to pay off. Life cycle GHG emissions benefits of most renewable technologies are high. Land use is a significant issue with some renewable energy technologies, especially as deployment grows further. Increasing system efficiencies and operating lifetimes will reduce environmental impacts for all renewable power technologies. In addition, it is critical that both countries apply and enforce regulations to ensure that waste products of renewable energy equipment manufacturing, particularly those from silicon PV panels, are minimized and handled properly.

Research is needed to better understand impacts of renewable power installation development on plants and wildlife and to develop effective methods to mitigate these impacts. **Land-use impacts can be reduced by focusing on previously developed sites, co-occupation with other land uses, military and government sites, and emphasizing distributed generation technologies to minimize need for transmission.** Renewable power development will need to be restricted in some areas with sensitive ecosystems, or high cultural or scenic values; public involvement is valuable for helping to identify these areas. Water consumption is a major issue for all thermo-electric generating technologies, including solar thermal and biomass combustion. **The United States and China would benefit from efforts to further improve the cost effectiveness and efficiency of low water-use cooling systems to help expand their utilization.**

Policy, Deployment, and Market Infrastructure

The national governments in China and the United States, and various U.S. state governments, have established goals, mandates, and subsidies for production of electricity from renewable energy, although the levels and methods of subsidies, targets, and implementation mechanisms differ. At a national level, Chinese renewable policy is characterized primarily by “outcome-based goals” set at the national level (e.g., 15 percent of total electrical generation from non-fossil [nuclear and renewable] energy by 2020), and provincial or local incentives to support manufacturing facilities. U.S. renewable policy is characterized by a greater focus on advancing specific technologies, such as wind, at the national level with market outcomes being encouraged at the state level (primarily through a renewal portfolio standard [RPS]).

The most prominent national policy approach for renewable energy in both China and the United States has been price support, both direct and indirect. U.S. subsidies have been primarily in the form of tax breaks for producers and consumers, and have been effective in driving specific market and technology development. Chinese subsidies, primarily government-set pricing and, on the local level, low electricity rates, have been effective in driving manufacturing development. In part because of China's manufacturing taxation policy and price control, China has captured a higher market share of renewable energy-associated manufacturing, particularly in the solar PV market and increasingly more in the wind energy sector as well. In less than a decade, China has emerged as a world-leader in manufacturing of renewable power technologies and has linked this sector's development to its overall national strategy for economic growth.

Both countries set subsidy values specific to particular resources (wind, solar, etc.). **Subsidy values, generally driven more by specific policy goals and objectives, remain difficult to justify by real costs of production from competing supply resources. Development of renewables has suffered because the costs of externalities, particularly the impact of GHG emissions, are not reflected in current energy prices.** In the United States, renewable energy investment has suffered during periods of suspended subsidy, demonstrating the importance of price support in an emerging renewable energy market, both for technology development as well as manufacturing capacity investments. For the United States, consistent national-level support, in the form of longer-term production tax credits or a national RPS, would send a clearer signal and reduce risk for potential investors in manufacturing.

Both countries would greatly benefit from a better understanding of specific government entities' capabilities and responsibilities in implementing renewable energy plans and from better coordination across agencies. In the United States, multiple regulatory agencies are often responsible for overlapping areas, creating uncertainty and delay for renewable project applicants. In China, renewable energy goals have lacked clear enforcement mechanisms (e.g., assuring that wind power installations are actually operating), and many support policies would benefit from broader stakeholder engagement upfront and throughout development of the resource.

As both countries attempt to make a transition to a clean energy economy, deployment issues will come to the fore. Material constraints (from inputs like rare earth metals to construction equipment like lattice-boom cranes) may hamper some development in the short run. Workforce requirements (skilled manufacturers, installation technicians, and equipment operators) must also be addressed if these technologies are to be widely deployed. **Operating experience will become**

a valuable tool—utility and grid operators in both countries have much to gain from sharing their experiences in integrating and managing larger shares of renewable power generation.

Feedback to downstream market participants, including manufacturers, equipment installers and utility operators can be critical for reducing overall costs of renewable power generation. **Both countries could benefit from programs to capture performance data from renewable energy technologies operating in the field and the distribution of the data throughout the supply chain.** China's renewable power market could experience a more rapid evolution by establishing more formal and informal mechanisms to capture this organizational learning.

Consistent and supportive policies would help the developing industry in both countries, but over the long-term renewable power developers will need to focus on becoming cost-competitive with fossil fuels. Financing will be attracted by a competitive levelized cost of energy (LCOE) or total cost of ownership. Project developers could begin placing value on the risk reduction attributes of renewable energy sources, notably the uncertainties of fossil-fuel prices and the threat of emissions regulation, when evaluating investments in new power generation.

Toward a Sustainable Energy Economy

The scale and diversity of the energy system should not be underestimated, in terms of existing infrastructure and how pervasive it is throughout both countries' economies. Meeting electricity demand sustainably is an important driver for renewable power development, but it is not the only one. Manufacturing, deploying, and operating renewable power generators also represent potential new pillars of economic growth, something that China is embracing more rapidly than the United States.

As both countries endeavor to integrate renewable energy technologies into society, there is an opportunity for enhanced U.S.-Chinese cooperation in areas that will have medium- to long-term impacts. Much of this may not be on renewable power generation technologies themselves, but on the key "enablers" that could form part of a sustainable energy economy. Examples include developing urban areas that maximize use of renewable energy and electrifying transportation infrastructure to enable optimal vehicle charging behavior, generation resource optimization, and reduced energy-related emissions from motorized transport.

In the United States, clean energy research is carried out at a variety of government and academic institutions, but the National Renewable Energy Laboratory (NREL) performs the integration of various renewable energy RD&D efforts into a coherent national overview. In China, the National Energy Administration, the Ministry of Science and Technology, and other ministries, have established a number of national research centers and laboratories working in the renewable energy sector. Given the geographic distribution of renewable resources, having a distributed network of affiliate research institutions has some value. However,

China could better leverage its existing research infrastructure and avoid duplicating efforts by establishing an institution with primary responsibility for coordinating research activities in renewable energy.

Although the United States and China have recently increased investments in energy R&D, **both countries are severely underinvesting in clean energy RD&D, which will make it difficult to achieve goals for 2050 and beyond.** Consistent, long-term public investments in clean energy RD&D will send a clearer signal to private industry and should leverage more industry investment in both applied research and commercialization.

Platforms for Future Cooperation

As identified throughout this report, there are several reasons for both countries to harness their renewable resources. From an international perspective, climate change presents an additional driver. Both China and the United States have three main options to reduce GHG emissions in the energy sector: (1) reducing emissions from coal-based power, (2) promoting energy efficiency and conservation, and (3) developing renewables and other low carbon sources of energy. For decades, both countries have cooperated in these three areas, through governmental and nongovernmental channels. Given the scale of the climate challenge, there is now an additional impetus to continue and even enhance this sort of collaboration.

The United States and China have a history of bilateral cooperation on renewable energy technologies and policy dating back to 1979, including the 1995 Protocol for Cooperation in the Fields of Energy Efficiency and Renewable Energy Technology Development and Utilization between the U.S. Department of Energy and several Chinese ministries. **Official bilateral cooperation on renewable energy has suffered, however, both from a lack of consistent funding as well as insufficient high-level political support and commitment.** Concerns about industrial and economic competition are often a barrier to scientific and technology cooperation between the United States and China.

The U.S.-China Presidential Summit in Beijing in November 2009 resulted in a significant set of new agreements on joint energy and climate cooperation between the two countries, which if implemented effectively could serve as a platform for enhanced cooperation on renewable energy. **The proposed Renewable Energy Partnership includes several project activities that could integrate many of the recommendations detailed in this report, including technology road mapping, deployment solutions, subnational partnerships, grid modernization, R&D in advanced technologies, and public-private engagement.** Such engagement would be most effective if a sustained public-private forum were established with a multi-year commitment for ongoing communication. In addition, the forum could help facilitate new partnerships by coordinating participants from both sides and act as a clearinghouse for project information and funding or investment opportunities.

Important areas for cooperation that are not included in existing partnerships and should be the topic of future cooperation include joint technology development and demonstration efforts for advanced renewable energy technologies. Subnational cooperation should be further developed, based on resource profiles, allowing states/provinces in both countries to work together in advancing their renewable energy goals (examples include Colorado-Qinghai and Hawaii-Hainan). In addition, the development of a personnel exchange program, through government-sponsored fellowships that would involve short visits of U.S. and Chinese researchers and grid and power plant operators to each other's countries, would foster more organizational learning in the fields of renewable power development and grid integration and would help to promote understanding and trust in the years to come.

RECOMMENDATIONS

Specific recommendations have been limited to those that the committees judge to be most likely to accelerate the pace of deployment, increase cost-competitiveness, or shape the future market for renewable energy. They are also, in the committees' estimation, pragmatic and achievable. The committees recognize that implementing these recommendations will often involve more than one entity. While recommendations 1-7 are geared toward enhanced bilateral cooperation, recommendations 8-10 are country-specific. In addition to the 10 recommendations presented here, 5 additional recommendations are presented at the end of the full report chapters.

Recommendation 1

- To ensure that existing China-U.S. partnerships are utilized most effectively, a stable stream of funding must be committed to their support. Activities should build upon existing cooperative activities between U.S. and Chinese experts and foster additional subnational cooperation on implementation issues.

Recommendation 2

- The United States and China should establish a comprehensive base for official bilateral energy cooperation, including (1) basic research in fields that can contribute to future breakthroughs in renewable energy technologies; (2) joint strategic studies advising policy makers; (3) joint research and development in advanced renewable energy technologies; (4) joint demonstrations of pre-commercial technologies, and (5) sharing of best practices in regional implementation, policy making, planning, operations, and management.

Recommendation 3

- China and the United States should collaborate on mapping integrated resource and development options at regional scales. Such multi-resource maps and evaluation can help to identify options for distributed generation, potential resource constraints (e.g., water availability for thermoelectric power), and least cost routes for needed transmission.

Recommendation 4

- China and the United States should cooperate on defining the needs and requirements to transform power delivery systems to accommodate and integrate large amounts of variable-output renewable electric power. Such cooperation should address technical challenges to maintaining reliability, informational needs for regional planners and utility operators, and the "all-in" costs of integrating a high penetration of wind and solar power into the grid.

Recommendation 5

- China and the United States should cooperate in developing large-scale (>50 MW) physical energy storage systems. Both countries have experience with pumped hydro and are currently investigating options to create additional capacity, which could directly benefit large wind and solar farms. The United States could also work with China to develop and demonstrate a compressed air energy storage system (CAES) in China, which currently has no experience with utility-scale CAES.

Recommendation 6

- Scientists and engineers in both countries should work together to solve key technical challenges in waste treatment and recycling of components. Opportunities include reducing or reusing silicon tetrachloride and other toxic byproducts of polysilicon production, and recycling PV panels and wind turbine blades.

Recommendation 7

- Cognizant organizations in China and the United States, including government agencies, international standards organizations, and professional societies, should collaborate on developing technical standards and certification mechanisms for renewable energy technologies for: (1) product performance and manufacturing quality control and (2) standard grid interconnection for both distributed, customer-sited resources and whole, central station resources. The United States has experience with developing standards through the National Institute of Standards and Technology, National Renewable Energy Laboratory, and professional societies, and there is an opportunity for closer U.S.-Chinese interaction on efforts to establish voluntary international standards through the IEEE.

Recommendation 8

- The United States should consider conducting a multiagency strategic assessment of U.S. renewable energy manufacturing capabilities, in alignment with U.S. innovation activities, to determine where additional capacities should be promoted. Financial support should be considered to expand the manufacturing base for existing and near-term deployment needs through the research and demonstration of process improvements and efficiencies and the establishment of mechanisms to share the risk of private-sector investment in building new manufacturing capacity. In addition, targeted public/private risk-sharing programs should be considered to move technologies from concept through to manufacturing.

Recommendation 9

- China should establish national facilities with capabilities to test performance and safety characteristics of complete renewable power systems and their subcomponents. Examples include testing PV systems to UL[1] standards or evaluating the Power Curve from a small wind turbine.

Recommendation 10

- China should conduct a nationwide inventory of research centers and their capabilities in various aspects of renewable energy and related fields. Based on assessed capabilities, some facilities could be designated as technical centers of excellence in their major competencies. One option is to integrate some of the existing entities and to establish a research institute, under the National Energy Administration, that is responsible for the renewable energy sector. A new institution would not need to be the center of excellence for all technologies, but for the integration of technologies and understanding of the RD&D pipeline from resource base through to commercialization. It could also be a facility for investing in capital equipment that is otherwise too costly for individual research centers.

THE ROAD AHEAD

The United States and China are entering a pivotal period where they will be both collaborators and competitors on critical global challenges and major participants in the marketplace. Effectively connecting their respective

[1] Underwriters Laboratories

capabilities and experience holds promise for accelerating progress in both countries and could make these technologies more accessible globally. The United States and China will continue to pursue national priorities of economic development and energy security, and there will be ongoing multilateral dialogues on ways to mitigate climate change. As both countries increasingly acknowledge, their leadership and cooperation on renewable energy development will be key to addressing these challenges.

1

Introduction

The United States and China, the biggest energy consumers and carbon emitters in the world, may unlock the potential of renewable power sources and dramatically transform the energy profiles of both countries. In a single day, enough sun shines in China to meet its energy needs for more than 10 years, at least theoretically.[1] Wind resources in the central United States could theoretically satisfy more than 16 times the current U.S. demand for electricity (Lu et al., 2009). The ultimate challenge, of course, is to harness these and other clean, abundant resources in a cost-efficient way, which will require not only overcoming temporal, spatial, and energy-conversion limitations, but also integrating them into an electrical infrastructure that was not designed for distributed, variable-output power generation.

The United States and China face similar technical and economic constraints in terms of scaling up renewables' share of power generation: with the exception of hydropower and some wind and geothermal, most renewable power generation is not presently cost-competitive with baseload rates based on coal-fired power; and geographically, concentrations of electricity demand and high-quality renewable energy resources are far apart. However, renewable power offers several advantages over conventional generation, including low emissions of air pollutants, low fuel costs, and in many cases relatively quick deployment.

Recent efforts in the United States to develop renewable power have been driven by a desire to substantially reduce greenhouse gas (GHG) emissions, improve energy security, and stimulate the domestic economy. China has been

[1] This estimate is based on an assumption of annual global radiation of 14.1 million terawatt hours (TWh), or 1.7 trillion tons of coal equivalent (tce), and annual electrical generation of 3,400 TWh.

pursuing similar goals, under the more general goal of sustainably meeting its growing energy demand and avoiding the environmentally unsustainable trajectory followed by many industrialized nations.

Working cooperatively to develop and deploy renewable power generation technologies makes strategic sense for both countries. First, the United States and China have a 30-year history of collaborating on renewable energy, although the level of activity has ebbed and flowed. Second, each country has unique strengths that have helped the other achieve its current level of renewable power deployment. U.S. innovations in many key renewable power technologies have influenced the industry for decades; China's manufacturing capacity has brought down the cost of some technologies thus making them more cost competitive. Third, by working together the United States and China have an opportunity to accelerate the deployment of renewable power technologies and substantially reduce GHG emissions, thereby gaining international recognition for their accomplishments.

In the past decade, the U.S. and Chinese Academies of Sciences and Engineering have jointly conducted and published several bilateral studies on energy and the environment (CAE/NAE/NRC, 2003; NAE/NRC/CAE/CAS, 2007; NRC/CAS/CAE, 2000; NRC/NAE/CAS/CAE, 2004). These reports have benefitted national policy makers, academic researchers, environmental managers, industries, and local decision makers and have influenced public policy, such as China's recent decision to pursue a regional air-quality management strategy and to regulate emissions of ozone and fine particulate matter ($PM_{2.5}$).

In 2008, the four academies agreed to cooperate on the present study on producing and deploying electricity from renewable resources. Since December of that year, expert committees from both countries have held meetings and conducted site visits to gain a better understanding of the complex, on-the-ground challenges facing them and as a basis for setting priorities for further cooperation between the United States and China, and by extension, the broader, global clean-energy community.

Specifically, the committees were charged with providing a report that would (1) assist both countries in developing strategies to meet renewable energy goals, (2) highlight prospects for technology collaboration, and (3) identify areas for future cooperation. In pursuit of these goals, the study includes discussions of the following topics:

- a comparative assessment of resource potential for grid-scale electricity generation in China and the United States
- near-term market opportunities for mature technologies
- priorities for further collaboration, with an emphasis on cost reduction, increased efficiency and grid connectivity, and energy storage

In addressing grid-scale electricity generation, the study focuses much attention on three major resources—wind, solar, and biomass—for near-term commercial deployment**.** It also considers resources with a longer time horizon for commercial deployment, such as enhanced geothermal and hydrokinetic power. The study does not, however, consider hydropower or non-electrical applications (chiefly, heating) in any detail, although these are important components of the renewable energy portfolios of both countries.

This study builds on the 2009 report *Electricity from Renewable Resources: Status, Prospects, and Impediments* (NAS/NAE/NRC, 2010a), in which risks and trade-offs were assessed for various energy technologies in the United States; much of the information in that report is also applicable and adaptable to China. In the present report, issues related to trade, intellectual property, and economic competitiveness are identified but not analyzed in depth.

Overall, the committees agree that the obstacles to cooperation are not insurmountable and that both countries would benefit from the results. Even though some competitiveness concerns may have to be addressed, the benefits would far outweigh the costs in time and effort.

The committees also note that renewable energy, and U.S.-Chinese relations, are both dynamic fields, making it difficult to keep current with data and developments. This is particularly true with regard to cost data and installed capacity for wind and solar PV. In general, the committees elected to not present historical cost data, but instead to discuss the factors that influence the cost of power generation from renewable resources. Information presented in this report is based on what was available as of mid-2010 and relies heavily on data from official government sources.

RESOURCES, TECHNOLOGIES, AND ENVIRONMENTAL IMPACTS

In Chapter 2, the committees focus on abundant renewable resources, particularly wind and solar power. China, for example, estimates that its available renewable resources could provide 12–14 million GWh annually (Yan, 2009). However, both countries face significant challenges to deploying their richest resources. In the United States, for example, the most abundant wind resources are on the Great Plains, which is far from major demand centers, or offshore, where aesthetic and other concerns have slowed development. In China, the best wind and solar resources are in high desert regions, also far from demand centers, or in places where there is no electrical grid at all.

Biomass (including waste), geothermal, marine, and hydrokinetic resources are also available to both countries. Hydropower has been the predominant source of renewable power for decades, but most of its potential has already been exploited in the United States. China is likely to continue to develop both small and large hydropower stations to meet its energy demands and offset coal consumption, but over time, the share of hydropower in China's renewable power is expected to shrink.

Renewable resources in both countries are usually evaluated in isolation, and sometimes less abundant, but more feasible resources are overlooked. Today, the United States is producing higher resolution resource maps (from 5 kilometers [km] × 5 km to 500 meters [m] × 500 m), layering resources and grid infrastructure on regional maps, and developing cost curves to identify economically recoverable resources. Advances that can encourage regional deployment of renewables and discussions of how China might benefit from improved resource assessments are described in Chapter 2.

The focus of Chapter 3 is on the technological readiness of renewable power generation technologies, with an emphasis on near-term, commercially available technologies that are already in use in both countries. This chapter is largely an update of the NAS/NAE/NRC (2010a) report, with an additional discussion of China's progress in researching and developing various technologies. With the exceptions of concentrating solar power (CSP) and geothermal power, for which the United States has significantly more experience than China, the technologies being developed and deployed are similar. For example, both countries are world leaders in the deployment of wind turbines, the fastest growing renewable. Supporting technologies, such as enhanced grid capabilities and energy storage systems, are also described in Chapter 3.

Another focus of activity in both countries is the cost competitiveness of renewable power generation technologies. Because certain externalities, such as emissions of carbon dioxide, are not currently factored into electricity rates, renewables have been at a serious disadvantage in terms of cost (NRC, 2010a). There are opportunities to improve conversion efficiencies and capacity factors for many renewable power generation technologies at the point of manufacturing, and doing so would improve their cost profile. Improving the balance of system components, resource forecasts, and increasing grid connectivity can also bring down the total costs of renewable power generation. These cost reductions are likely to be realized as experience with the deployment of renewables increases. This so-called "organizational learning" provides an opportunity for the United States and China to share information to improve overall system performance.

The discussion in Chapter 4 is based on the desire of both countries to reduce environmental impacts, particularly air pollution, from energy consumption, which has long been an important motivation for using renewable energy instead of fossil fuels (e.g., NAE/NRC/CAE/CAS, 2007). As both countries increase their efforts to improve air quality and reduce GHG emissions, the deployment of renewable power technologies is likely to become increasingly important. Life cycle analyses are a valuable way to assess the relative impacts (positive and negative) of different generation technologies. Moreover, as individual renewable power plants and requisite manufacturing bases increase in scale, their environmental impacts will also have to be taken into account. Some photovoltaic (PV) manufacturing processes, for example, are energy intensive and produce hazardous waste streams that must be addressed.

POLICY AND ECONOMIC CONSIDERATIONS

Many barriers to accelerating the deployment of renewable power are non-technical and have to do with current energy policies and electricity markets. In Chapter 5, the committees examine this landscape, comparing and contrasting policy approaches in the United States and China. Although policy has been a critical element in sustaining the development of renewables in both countries, for various reasons the United States and China have taken different approaches and offered support at different stages. In general, the U.S. approach has been characterized by tax credits that support project development but not necessarily manufacturing, and state-led initiatives to create markets for renewable power. By contrast, China has enacted national policies and targets to support the development of renewable energy, most directly through the 2005 Renewable Energy Law, with provincial and local support being directed to encourage manufacturing. However, in practice, some of China's policies and mandates have not been fully implemented because the detailed rules for implementing the 2005 Renewable Energy Law have yet to be promulgated.

Legacy energy policies, regulations, and subsidies are key determinants to the success or failure of clean-energy initiatives and the achievement of renewable-power goals. The most prominent policy in both China and the United States has been price supports, and both countries set subsidy values specific to particular resources (wind, solar, and so forth). In Chapter 5, the committees explore how outcome-based incentives in both countries could help overcome barriers and promote the rapid, sustainable development of renewable power.

Energy policies in both countries have placed a high priority on domestic energy security, especially reducing dependence on petroleum, and have only indirectly supported efforts to develop electricity from renewables. However, other advantages of renewable power are sometimes included in national priorities. China, for example, has been quick to embrace the renewables industry as part of a clean-energy economic "pillar." The United States has been arguably slower to seize that opportunity, although President Obama alluded to it in a speech on the energy revolution:

> We can hand over the jobs of the future to our competitors, or we can confront what they've already recognized as the great opportunity of our time: The nation that leads the world in creating new sources of clean energy will be the nation that leads the 21st-century global economy.[2]

In Chapter 5, the committees also analyze challenges associated with the commercial deployment of renewable technologies, particularly as these industries mature and increase in scale. The United States and China face a number of

---

[2] May 27, 2009, speech by President Obama at Nellis Air Force Base in Las Vegas, accessed June 2009 at *http://www.solarfeeds.com/the-green-market-blog/7306-obamas-renewable-energy-revolution-speech.html*.

market and logistical barriers to the commercial deployment of renewable energy. For example, bottlenecks in the supply of some materials, such as steel for wind turbines or polysilicon for PV cells, may temporarily interfere with growth; but they might also spur innovations in resource conservation or the use of alternative materials. In addition, growing renewables industries will require a skilled workforce, both in the manufacturing sector and to meet downstream requirements and training for installation, operation, and maintenance jobs. Finally, despite government investments in both countries in 2008 and 2009, financial risks continue to hamper investments in the renewables sector.

CHALLENGES OF SCALE

As is shown in Table 1-1, the effects of scale on the electrical enterprise should not be underestimated. Today, renewables represent a rapidly growing, but still small, share of overall electrical generation. In 2008 China and the United States accounted for 19 percent of the 280 gigawatts (GW) worldwide installed capacity of non-hydro renewable power (REN 21, 2009). To put this in perspective, worldwide *generation* of all non-hydro renewable power in 2007 (EIA, 2010) could have powered the United States for only six weeks. Considering that the relative contributions of hydropower are expected to decrease over time, the share of wind, solar, and other power resources will have to increase dramatically for renewables to achieve predominant penetration of the market.

The overall energy infrastructure and longer term prospects for renewables are the subjects of Chapter 6. In the United States, change is being driven by a desire to reduce GHG emissions, reduce dependence on foreign sources of energy,

TABLE 1-1 Installed Capacity and Net Generation from Renewable Resources, 2009

	China		**United States**	
Generation Technology	Installed Capacity (GW)	Generation (TWh)	Installed Capacity (GW)	Generation (TWh)
Conventional hydropower	196.79	574.7	77.93	272.13
Wind	16.13[a]	26.9	33.54	70.76
Solar PV	0.3	0.45[b]	1.25	0.81[b]
Solar thermal	—	—	0.43	
Biopower	4.0	20.0	11.35	54.34
Geothermal	—	—	2.35	15.21
Subtotal	*217.12*	*622.05*	*126.85*	*413.25*
Entire electrical system	874.0	3663.9	1131.58	3953.11

Sources: CEC, 2010; EIA, 2010a-d; NEA, 2010; REN 21, 2010; Sherwood, 2010.

[a] Cumulative, reflecting installations that were completed and brought on-line by the end of 2009.
[b] Data is for grid-connected systems.

and replace aging infrastructure. China shares the first two concerns, but its main priority is to meet its rapidly increasing demand for electricity while shifting its energy structure to be less reliant on coal. It has taken 125 years to build the U.S. energy infrastructure. China's infrastructure has developed much more rapidly, based on marginal improvements to the model developed in the United States and other industrialized countries. As both countries look ahead, there will be many opportunities to accelerate development in ways that will bring renewables on line more quickly.

COOPERATIVE COMPETITORS

The United States and China are entering a pivotal period during which they will be both collaborators on critical global challenges and major participants in the marketplace. Nowhere is this more apparent at the moment than in the areas of energy and climate change. In Chapter 7, the committees review the historical context of U.S.-Chinese cooperation on energy and climate change, the new era of U.S.-Chinese cooperation ushered in by Presidents Hu and Obama, the role of each country in international discussions on energy and climate issues, and how cooperation can be significantly expanded in the coming years.

The development of renewable sources of energy is one of the main options for both China and the United States to reduce GHG emissions and promote a sustainable energy future. Although other countries have led the way so far, the United States and China are poised to become the largest markets for renewable energy deployment in the coming years. In 2008, they became the two largest wind power markets in the world, and they are expected to remain so for years to come. The United States is ahead of China in solar deployment, but China is ahead in solar PV production and has recently shown a commitment to expanding domestic use of PV technology. In short, renewable energy is an area in which both the United States and China can lead the world and can benefit from cooperation.

Cooperative efforts can lead to significant increases in the scale of renewable energy deployment and associated cost reductions in technology and facilitate a shared commitment to transitioning to a low-carbon economy in the face of global climate change. More comprehensive collaboration can also support the rapid, widespread deployment of renewable sources in both countries.

Industrial and economic competition are often barriers to scientific and technology cooperation between the United States and China, and these concerns can only be alleviated through mutual understanding and trust. On balance, U.S.-Chinese cooperation on renewable energy can help build a stronger, more productive foundation for Chinese-American relations, arguably the most important bilateral relationship in the world.

2

Resource Base

Both the United States and China have significant renewable energy resources. In this chapter, the committees describe the more developed non-hydro resources—wind, solar, and biomass—that could contribute significantly to the electricity supply in both nations. This is followed by summaries of the geothermal and hydrokinetic energy sources under development in the United States that may have applicability in China. China is at a comparatively early stage of assessing its renewable resources for power production, and so the balance of the chapter presents additional information on what has been done in the United States, which should be instructive as China improves its own capacity in this field.

ASSESSING RENEWABLE RESOURCES

Assessing the quality and quantity of renewable resources is a complex but necessary step in determining the potential of a particular resource. The question of potential has multiple answers depending on whether an assessment measures the technical, economic, or regional characteristics of a resource.

Theoretical potential is the upper boundary of the assessed value. For instance Lu et al. (2009) estimated theoretical wind energy potentials for the United States and China to be 320 exajoules[1] (EJ) and 160 EJ, respectively.

Technical potential is expressed as an inventory of a resource that could be developed by any and all appropriate conversion technologies without regard to cost. An assessment of technical potential takes into consideration geographic

[1] An SI unit of energy equals 10^{18} joules.

restrictions (e.g., terrain, weather, environmental conditions, ecological limitations, cultural issues, etc.). As technologies and methodologies for defining the technical potential of a renewable resource improve over time, uncertainties in assessments are reduced and confidence in the results increases.

Economic potential is expressed as a supply curve showing the quantity of a resource available at a specific cost. Methodologies for calculating the economic potential of a renewable resource have variable degrees of complexity by source and include considerations of energy, environmental, economic, existing and new infrastructure, and social factors.[2] When sustainability factors are included, economic potentials can be refined into a "sustainable potential" for a specific region. Sustainability factors can be local, national, or international (e.g., changes in land use caused directly or indirectly by the expansion of energy or other economic activity [see Chapter 4]).

Regional potential assessments include the potential of multiple resources in a geographic area (multiple inventories in a certain region). A regional potential assessment can be combined with geographic information of the existing infrastructure (e.g., conventional electricity generation and transmission) and economic information to support integrated resource planning and development for policy makers, industry, and project developers. As costs for renewable energy technologies come down, regions with lower quality wind and solar resources may be able to reassess their economic potential.

Most renewable electricity generation must be located near the source of the renewable energy flux (i.e., the rate of energy transfer through a unit area). This means that even if a source does not contribute significantly to total (national) electricity generation, it could still provide a substantial contribution to regional power generation (NAS/NAE/NRC, 2010a). Biomass, for example, can be stored and made available to meet specific demand, although there are limitations to this, including the distance the biomass can be economically transported and the ability of the power generation technologies to cycle on or off (i.e., to meet peak or intermittent demand).

In the following sections, advances in quantitative characterizations of wind, solar, and biomass, with examples of technical and economic potentials, are highlighted. Some information on geothermal and hydrokinetic energy is also provided. Table 1-1 from the previous chapter can be used as a reference point in drawing comparisons to present installed capacity (in GW) and electrical generation (in terawatt hours [TWh]) in the United States and China.

[2] The Intergovernmental Panel on Climate Change defines economic potential as: "The portion of the technical potential for GHG emissions reductions or energy-efficiency improvements that could be achieved cost-effectively in the absence of market barriers. The achievement of the economic potential requires additional policies and measures to break down market barriers." Available online at *http://www.gcrio.org/ipcc/techrepI/appendixe.html*.

TABLE 2-1 Contiguous U.S. Windy Land Characterization and Wind Energy Technical Potential for Wind Classes ≥ 3 and Gross Capacity Factors ≥ 30 Percent (without losses)

Windy Land Characterization			Key Variables		Wind Energy Technical Potential			Reference
Total million km^2	Excluded million km^2	Available million km^2	Hub height m	Spatial resolution km	Installed capacity at 5 MW/km^2 GW	Annual generation million GWh	EJ	
2.57		1.04	50	5 × 5	5,200	11.4	40	Elliott et al., 1991
2.57			80	0.2 × 0.2 to 5 x 5	7,000–8,000	15–20	50–60	Elliott et al., 2010
2.57	0.47	2.10	80	0.2 × 0.2	10,500	36.9	135	AWS Truewind, LLC and NREL, 2010

WIND POWER IN THE UNITED STATES

In a seminal work by Elliott et al. (1991), the total estimated electricity technical potential of wind in the continental United States was 11 million gigawatt hours per year (GWh/yr) from regions with winds rated as Class 3 or higher[3] and a turbine hub height of 50 meters (m). In energy units, 11 million GWh represents 40 exajoules (EJ), or approximately 40 percent of primary energy demand for 2007. By 2010, as a result of advances in wind turbine technology, the characterization and use of windy lands, and increased hub heights, the technical potential improved significantly. As Table 2-1 shows, technological improvements, a 25-fold increase in spatial resolution (from 5.0 × 5.0 kilometers [km] down to 0.2 × 0.2 km), and an 80 m hub height tripled the technical potential to 37 million GWh, or 135 EJ of energy. Figure 2-1 shows the significant changes in technical wind resource potential with changes in turbine hub height for the state of Indiana; hub height was raised from 50 to 100 m, which increased wind-speed intensities in a large portion of the state.

Extractable Potential

Continent-scale simulations indicate that high levels of wind power extraction could affect the geographic distribution and/or the inter- and intra-annual variability of winds, or might even alter the external conditions for wind development and climate conditions. Thus, model calculations suggest that, in addition to limiting the efficiency of large-scale wind farms, the extraction of wind energy from very large wind farms could have a measurable effect on weather and climate at the local, or even continental and global scales (Keith et al., 2004; Roy et al., 2004).

However, it is important to keep in mind that empirical and dynamical downscaling modeling results vary greatly (Pryor et al., 2005, 2006). Large-scale wind modeling is a nascent field of research, and global and regional climate models (GCMs and RCMs) do not fully reproduce historical trends (Pryor et al., 2009). Recent analyses (e.g., Kirk-Davidoff and Keith, 2008; Barrie and Kirk-Davidoff, 2010) have suggested that higher vertical resolution would improve modeling results, by allowing for more analysis of large-scale wind farms as elevated momentum sinks, rather than surface roughness anomalies.

Several studies (e.g., Pryor et al., 2005, 2006) suggest that mean wind speeds and energy density over North America will remain within the range of interannual variability (i.e., ~15 percent) for the next century, but we will need more detailed, meso-scale models and measurements to determine total U.S. extractable wind energy potential and how much of that potential can be extracted without causing significant environmental impacts. Models are also being developed

[3] Wind class, a measure of wind power density, is measured in watts per square meter and is a function of wind speed at a specific height from the ground.

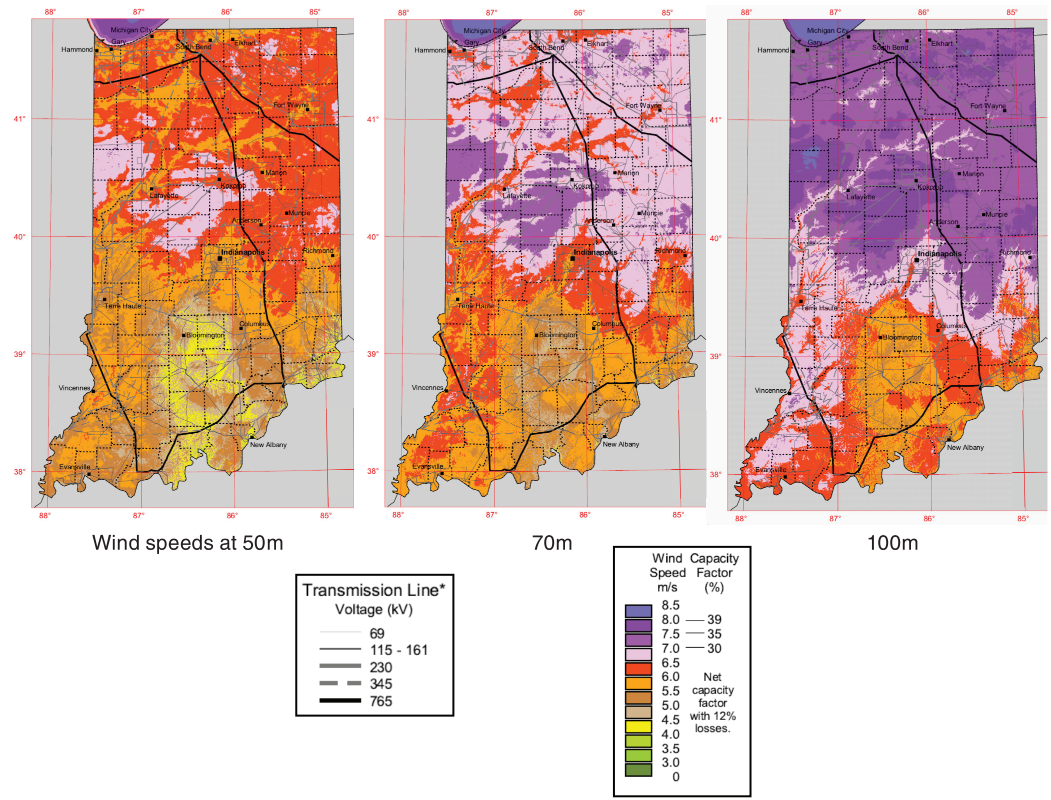


FIGURE 2-1 Comparison of the wind energy resource at 50 m, 70 m, and 100 m for the state of Indiana, United States. Source: DOE, 2008c.

to determine the optimal distance between wind farms to minimize power loss (Frandsen et al., 2007).

Assuming an estimated upper limit of 20 percent extraction of the energy in a wind field both regionally and on a continental scale and a total U.S. onshore wind electricity value of 11 million GWh/yr, an upper value estimate for the extractable wind-generated electricity potential would be about 2.2 million GWh/yr, more than half the electricity generated in the United States in 2007 (NAS/NAE/NRC, 2010a).

However, based on the 2010 estimates of technical potential, the extractable potential would be 7 million GWh/yr using only Class 3 and higher wind-speed areas in the contiguous United States (AWS Wind, LLC and NREL, 2010). This level of electricity generation would surpass the 5.8 million GWh/yr electricity demand projected for 2030 by the U.S. Energy Information Administration (EIA, 2007a). To reach the extractable potential (using only onshore wind resources) would require using an average of 5 percent of the contiguous land area of the United States, although the physical footprint of the turbines themselves would occupy a small fraction (< 5 percent) of this land area. This estimate, excludes protected lands (national parks, wilderness, etc.), incompatible land-use areas (urban areas, airports, wetlands, and water features), and other locations, which have a combined total of about 17 percent of the continental United States (AWS Wind, LLC and NREL, 2010).

Economic Potential

To estimate supply curves, scenarios can be formulated for a specific level of renewable resource penetration at a future time using a combination of models that take into account the following factors: the resource inventory; future deployment of renewable electricity products, including manufacture, installation, and operations; required capital investments and economic development in the presence (or absence) of specific policies; integration of renewable electricity into existing production, distribution, and end-use systems and required infrastructure changes; and market penetration. Production costs would be projected based on learning curves for specific generation technologies.

Comparing the overall costs of this renewable scenario with a baseline scenario with no renewable electricity penetration (e.g., using net present value) provides valuable information for governments, industries, and other organizations involved in developing investment strategies in renewable resources and policy decisions that take into account social and private costs and benefits. As the full discussion of the methodologies involved with the evidentiary basis for the development of economic potentials are described in Chapter 7 of the *Electricity from Renewable Resources: Status, Prospects, and Impediments* report (NAS/NAE/NRC, 2010a), this report will illustrate results for selected renewable technologies.

One estimate of the economic potential of wind energy resources was made by the U.S. Department of Energy (DOE), two national laboratories (primarily the National Renewable Energy Laboratory [NREL] and Lawrence Berkeley National Laboratory [LBL]), the American Wind Energy Association, Black and Veatch Engineering and Consulting, and collaborators. The modeled scenario, "20 percent by 2030," indicated a goal of 20 percent wind energy market penetration by 2030 in the United States (DOE, 2008a) and estimated costs of electricity to provide 1.2 million GWh/yr, or 20 percent of projected U.S. electricity generation (EIA, 2007a). The estimate took into account the challenges and needs in the areas of technology, manufacturing and employment, transmission and grid integration, markets, siting strategies, and potential environmental effects to reach this level of penetration.

The data analysis and model runs described in the report, which were based on 2006 data, concluded in mid-2007. In this first effort, no sensitivity analyses were performed**.** The technical potential modeled from these studies was better than 8,000 GW (in terms of installed capacity), a number that falls between the two estimates in Table 2-1, as expected, because the resource data resolution was 1 km × 1 km, and, in some cases 5 km × 5 km.

Figure 2-2 shows the "20 percent by 2030" estimated supply curve (economic potential) for onshore and offshore wind energy in the United States based on the 2007 model. The onshore lowest cost electricity comes from wind Classes 5 to 7 and supplies the first 50 GW of installed capacity. Classes 3 and 4 resources add an additional 750 GW at increasingly higher costs. Using wind turbines at 50 m hub height to generate 1.1 million GWh/yr was projected to require 300 GW of installed capacity. The affordable-to-harness installed capacity (economic potential) of land-based wind energy in this scenario was 800 GW.

The actual footprint of land-based turbines and related infrastructure in this model was estimated at about 1,000 to 2,500 km^2 of dedicated land (an area about the size of Rhode Island). Thus, the turbines and associated infrastructure would physically occupy only 2 to 5 percent of the land being used for projects, meaning that some agricultural land could be used to produce energy as well as crops and rangeland products.

Critical assumptions in this scenario included a 35 percent reduction in operations and maintenance costs (to mitigate investment risk) and the extensions of incentives (e.g., production tax credits) to maintain investors' confidence. The transmission system was estimated to require 19,000 miles of additional line to support about 300 GW of additional variable-output capacity. The plausible, high-voltage distribution system shown on Figure 2-3 is part of the significant infrastructure development that would be required over a period of 20 years.

Offshore Wind Energy Capacity

The available offshore wind capacity in the United States was initially estimated at 907 GW for distances of 5 to 50 nautical miles offshore (Musial and

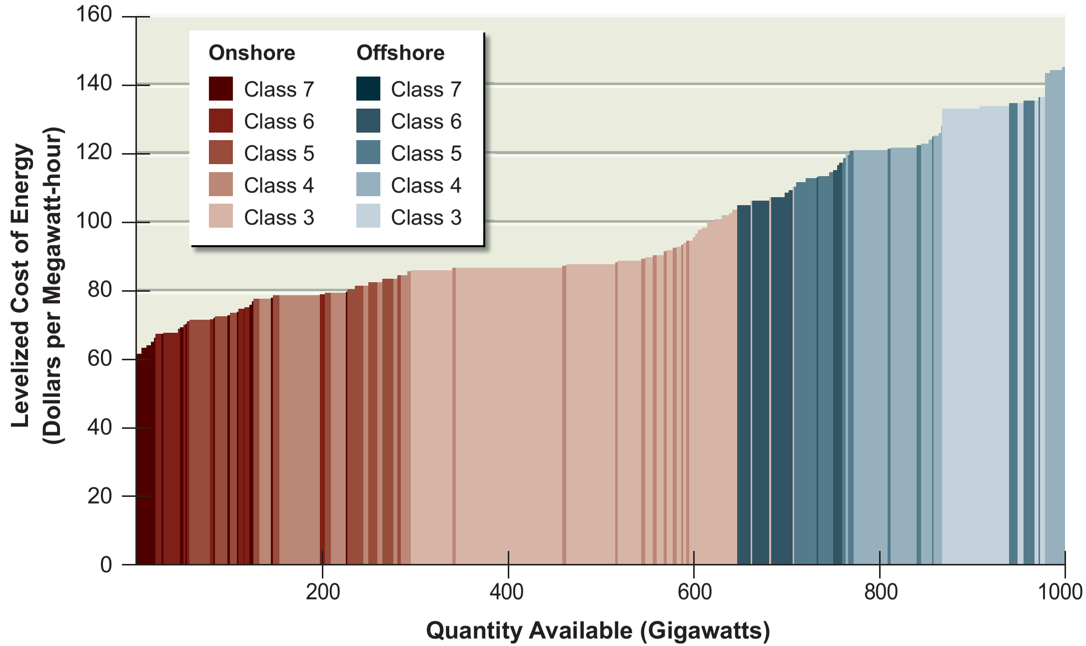


FIGURE 2-2 Modeled economic potential of wind resources in the United States shown as a supply curve in which energy costs include connection to 10 percent of existing transmission grid capacity within 500 miles of the resource. Production tax credits are not included. Source: DOE, 2008a.

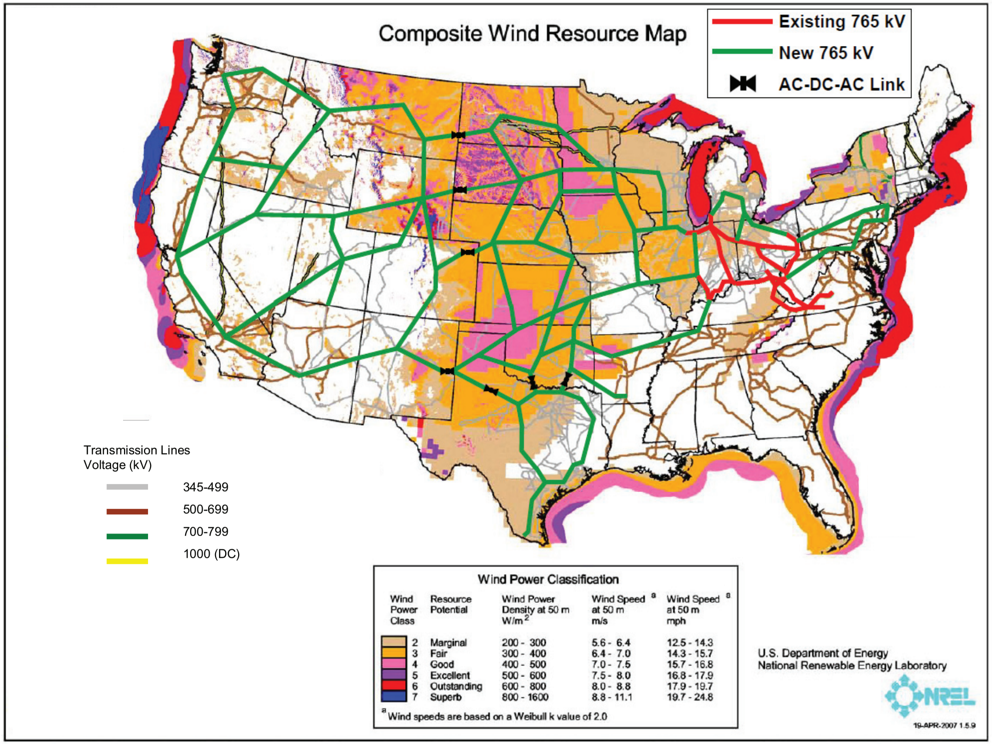


FIGURE 2-3 A concept of transmission with one technically feasible transmission grid of 765 kV overlayed on wind resource data combining low- and high-resolution datasets used to model the 20 percent wind scenario using NREL's Regional Energy Deployment System (ReEDS)

Butterfield, 2004). The depth of the water at these locations varies from about 30 to more than 900 m (NAS/NAE/NRC, 2010a). Schwartz et al. (2010) point out that this was a conservative assumption, excluding many regions (e.g., within 5 nautical miles of coastline) that subsequent analyses now include. More recent data from the "20 percent by 2030" scenario projects a technical potential, including shallow- and deep-water generation, of about 4,000 GW, or half the technical potential from the land-based, contiguous United States (AWS Wind LLC and NREL, 2010). The modeled economic potential in Figure 2-2 shows an overlap between offshore and onshore supply curves of about 50 GW.

Combined Onshore and Offshore Wind Resources

The "20 percent by 2030" scenario included 50 GW offshore and 250 GW onshore wind resources to provide 1.2 million GWh/yr, reductions in capital costs of 10 percent over the next two decades, and capacity increases of about 15 percent (corresponding to a 15 percent increase in annual energy generation by each wind plant). These optimistic assumptions were offset, at least partly, by higher technical potentials and additional resources that could become available at a hub height of >80 m, which would increase the low-cost supply of energy and expand its projected economic potential.

Modeling efforts will have to be expanded to include multiple scenarios and new data, improve and validate sub-models, and perform sensitivity and uncertainty analyses (using Monte Carlo, multivariate methods, or other methods). In addition, because a large percentage of the population lives along the coasts of the continental United States, offshore wind could be a renewable resource located close to population centers. Several states are focusing on developing offshore wind resources in areas where onshore wind resources are already well developed. However, some offshore projects, such as the proposed wind farm off Cape Cod, Massachusetts, have been plagued with controversy.

Europe has begun to develop offshore resources, and many large and small projects are already installed, under construction, or in the planning stages. The EU-27 countries have 1.5 GW offshore capacity from a total wind installed capacity of 64.9 GW (IEA, 2008).

WIND POWER IN CHINA

Wind Resource Assessments

With its vast area and long coastline, China has abundant wind resources and great potential for wind-generated electric power. From 2006 to 2009, the Center for Wind and Solar Energy Resources Assessment (CWERA) developed a wind resource map for China (Figure 2-4). This map includes land-based and offshore resources, at a resolution of 5 km × 5 km, and at several different heights. The

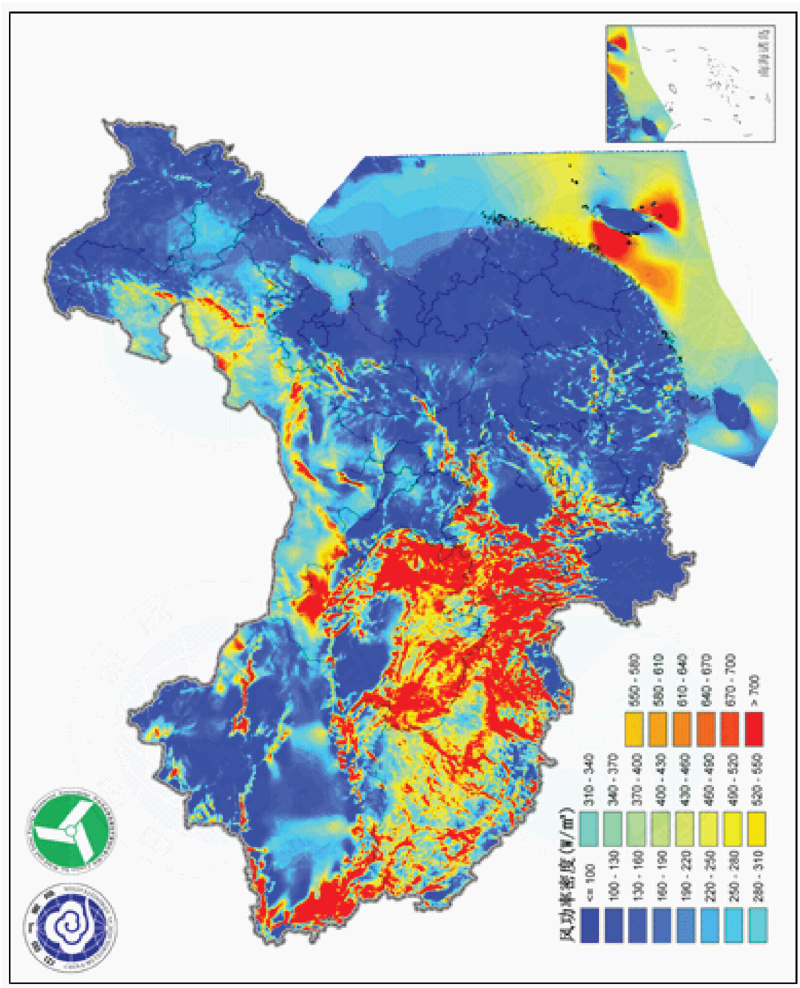


FIGURE 2-4 Distribution of wind power density in China at 50 m above ground. Source: China Meteorological Administration.

information was generated through numerical simulations based on historical observations from the period 1971 to 2000 (CAE, 2008; Zhu et al., 2009). Technical potential was analyzed using geographic information systems (GIS) to combine geospatial data (terrain, land use) and exclude certain areas not suitable for development (CWERA/CMA, 2010). Table 2-2 summarizes the parameters and results of this modeling. Basic farmland was also excluded because of China's strict policy of controlling and protecting farmland. Lands with slopes greater than 4 percent were not considered available for wind power development, and lands with slopes of less than 4 percent have an estimated potential installed capacity of 0–5 megawatts (MW)/km^2.

Table 2-2 illustrates that China's total wind resources for Class 3 and higher are comparable to that of the United States. However, due to exclusions, primarily for altitude, China's available resources and thus technical potential is much smaller, approximately half the total of the United States'. A large proportion of China's wind resources are located in Tibet and Qinghai provinces, which are excluded from calculations because of their high (> 3,500 m) altitude.

In 2008, grid-connected installed capacity for wind turbines totaled 9.4 GW, and grid-connected generation was 14,800 GWh/yr, which corresponds to a mean of 1,580 utilization hours per turbine (Li and Ma, 2009). The average capacity factor of ~18 percent for wind power projects in China was lower than expected (Li and Ma, 2009).

Based on the onshore technical capacity potential of 2,380 GW (Table 2-2) and a capacity factor of 25 percent, the estimated technical potential generation is 5.2 million GWh/yr, more than 1.5 times China's total electrical generation (3.2 million GWh) for 2007. Thus, the extractable potential (20 percent of the technical potential) is 1.04 million GWh/yr, or 30 percent of China's electricity production in 2007. Indeed, this is probably a low estimate, because the data spatial resolution was low and turbine hub height was only 50 m. At a height of 80 m, the extractable potential could increase by about 30 percent (Table 2-1). If the resolution were also increased, which would reveal areas previously unrecognized as having high wind potential, the overall estimate would increase again.

In 2009, CWERA/CMA assessed offshore wind resources once again based on numerical simulations. Based on the guidance "Marine function zoning and planning of China" issued in 2002, offshore regions for port and maritime activities, fisheries, tourism, and engineering are divided according to their potential use, and 60 offshore regions were established for ocean energy as well (such as wave, tide, etc.), leaving only 20 percent of offshore regions open for the development of wind power. The end result (see Table 2-3 and Figure 2-5) shows about 200 GW of offshore wind energy technical potential, for winds of Class 3 or higher, at a height of 50 m above sea level, at depths of 5 m to 25 m (CWERA/CMA, 2010).

TABLE 2-2 Windy Land Characterization and Wind Energy Technical Potential in Mainland of China for Wind Classes ≥ 3 and Gross Capacity Factors ≥ 30 Percent (without losses)

Wind Land Characterization			Key Variables		Wind Energy Technical Potential		
Total Million km^2	Excluded Million km^2	Available Million km^2	Hub Height (m)	Spatial Resolution (km)	Installed Capacity at 5 MW/km^2 GW	Annual Generation Million GWh	EJ
1.46	0.69	0.77	50	5×5	2380	5.2	19
3.60	2.81	0.79	70	5×5	2850	6.3	23
4.19	3.14	1.05	110	5×5	3800	8.4	30

Source: CWERA/CMA, 2010.

TABLE 2-3 Offshore Wind Power Potential of China (unit: GW)

Grade of Wind Resource Zoning	Wind Resource > Class 4 Wind Power Density ≥ 400 W/m^2	Wind Resource > Class 3 Wind Power Density ≥ 300 W/m^2
Offshore coverage within 50 km	234	376
Offshore coverage within 20 km	68	140
Offshore coverage between 5 and 25 m isobaths	92	188

Source: CWERA/CMA, 2010.

Development of Wind Resources

The most important factors that influence wind resources and their development are: weather, climate, terrain, and interaction between land and sea. Because wind resources have regional boundaries and temporal inconsistencies, it is important to identify the richest resources for wind power development (Table 2-4). The richest wind resources in China are mainly in the north and along the southeastern coast (CMA, 2006). The poorest wind resource areas are around the Sichuan Basin; in mountainous areas, such as southern Shanxi, western Hunan, western Hubei; mountain areas in Qinling and southern Yunnan; the Yalutsangpo River Valley in Tibet; and the Tarim Basin in Xinjiang (Figure 2-5).

Areas of the northern resource base were selected for development based on five criteria: (1) stable prevailing winds, northerly in winter and southerly in summer; (2) rapid increases in wind speed with height above ground level; (3) not much wind with destructive force; (4) flat terrain, convenient transportation, and good geological conditions for engineering; (5) mainly desert, grassland, and degraded grassland where no crops are grown.

Coastal regions in China offer stable prevailing winds, moderate temperatures, and short distances to load centers. Unfortunately, these areas also have serious disadvantages. First, the coastal area available for wind power development is very small because the regions with the richest wind resources are subject to a 3 km shoreline exclusion. In addition, coastal regions in southeast China have complicated terrain, are subject to turbulent winds and typhoons, and have complicated engineering-geological conditions. Finally, wind power development in these regions would have serious ecological and environmental implications.

The northern Tibetan plateau has more favorable conditions—sparse population, richer wind resources, and thinner air. As an electricity grid and transmission capabilities are created in that region, the wind resources there could be developed.

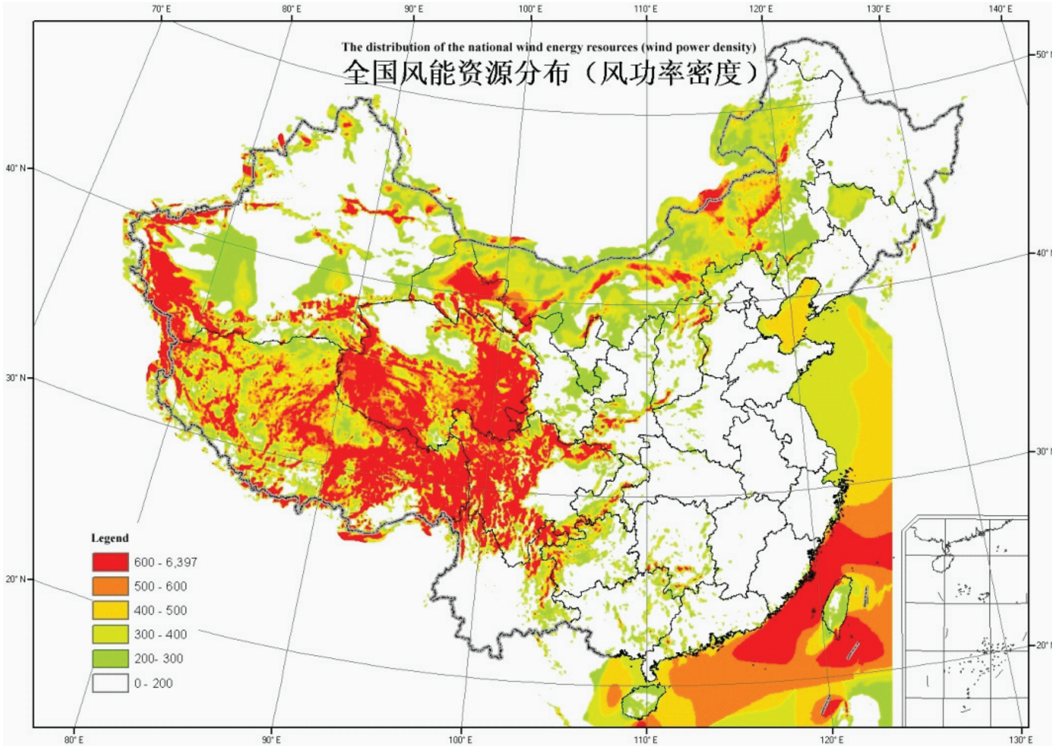


FIGURE 2-5 2006–2009 wind resource data at 50 m hub height and 5 km × 5 km spatial resolution using numerical simulation models. Correspondence of wind power density (wind class) is > 600 W/m^2 (> Class 6); 500–600 W/m^2 (Class 5); 400–500 W/m^2 (Class 4); 300–400 W/m^2 (Class 3); 200–300 W/m^2 (Class 2); < 200 W/m^2 (Classes 1 and 0). Source: China Meteorological Administration.

TABLE 2-4 Standard of Wind Resource Zoning (unit: W/m^2)

	Richest	Richer	Moderate	Poor
Annual mean wind power density at height of 50 m above ground level	> 150	150–100	100–50	< 50

Source: CWERA/CMA, 2010.

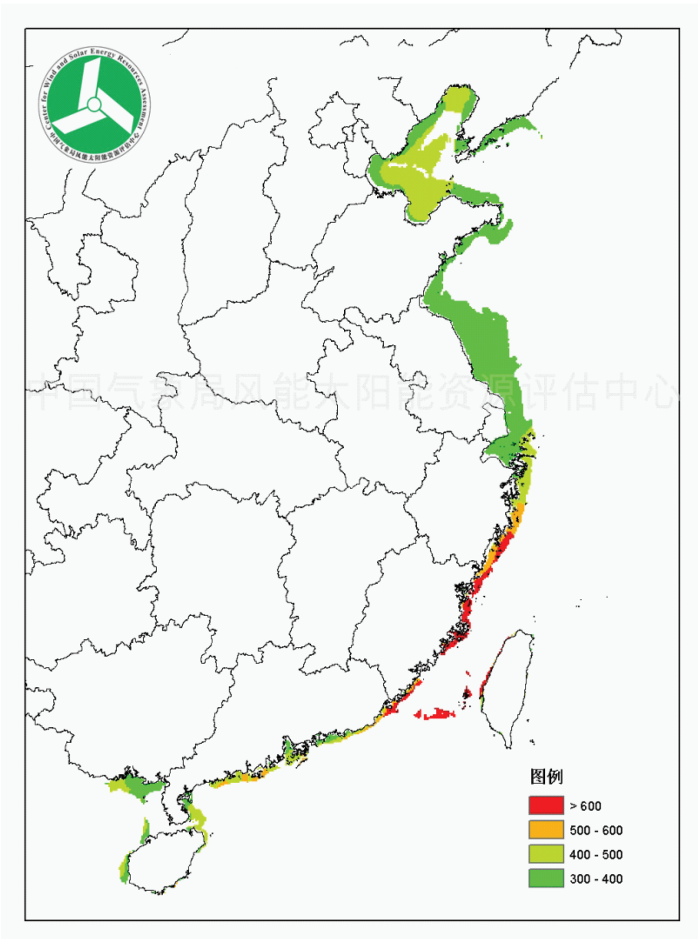


FIGURE 2-6 Offshore wind power potential by numerical methods at 50 m hub height excluding areas subjected to strong and super typhoons in the past 45 years. Correspondence of wind power density (wind class) is > 600 W/m^2 (> Class 6); 500–600 W/m^2 (Class 5); 400–500 W/m^2 (Class 4); 300–400 W/m^2 (Class 3); 200–300 W/m^2 (Class 2); < 200 W/m^2 (Classes 1 and 0). Source: China Meteorological Administration

Summary

China has rich wind resources suitable for development, especially in Inner Mongolia, Jiuquan in Gansu, Hami and Tulufan in Xinjiang, Zhangbei and Chengde in Hebei, Jilin province, western Liaoning province, and along the coast. In total, the wind power potential on the mainland is richer than it is off-shore. Regions with good prospects for development of the electric grid, increased transmission capability, and wind power include Yili in Xinjiang, the area around Qinghai Lake, central Gansu, Tongliao and Chifeng in Inner Mongolia, Shaanxi, and Shanxi. Regions with good prospects for developing small-scale, off-grid wind power include Gansu, Ningxia, Shanxi, Henan, Yunnan and Guizhou, and Heilongjiang, southeast Liaoning, and the central mountain area in Shandong.

China also has rich offshore wind resources, all of which have Class 3 or higher winds and are suitable for the development of grid-connected wind farms (Figure 2-6). The offshore regions with the richest wind resources are located in Fujian, southern Zhejiang, and eastern Guangdong. The richest offshore wind resources are in western Guangdong, Hainan, Beibu Gulf in Guangxi, northern Zhejiang, and Bohai Bay. Regions with water less than 25 m deep that are suitable for development are located in Jiangsu, Bohai Bay, and Beibu Gulf. Offshore regions more vulnerable to damage from typhoons are Quanzhou in Fujian, Maoming in Guangdong, the western side of Leizhou Peninsula, and Hainan, Taiwan.

Wind power potential on the mainland for Class 4 winds and higher is 1,130 GW and from Class 3 and higher 2,380 GW. Offshore wind power potential from Class 4 and higher is 92 GW and from Class 3 and higher 188 GW. Overall, the wind power potential is 1,222 GW from Class 4 and higher, 2,568 GW from Class 3 and higher, and 3,940 GW from Class 2 and higher (CWERA/CMA, 2010).

SOLAR POWER IN THE UNITED STATES

The United States has an abundance of solar energy resources. If we use 230 W/m^2 as a representative mid-latitude, day/night average value for solar insolation,[4] and 8×10^{12} m^2 as the area of the continental United States, the yearly averaged, area-averaged, power generation potential is 1.84 million GW (Pernick and Wilder, 2008). Thus, annually, solar power could provide the equivalent of about 16 billion GWh of electricity. Of course, realistic deployment of the technologies to harness this potential is constrained by a variety of factors, including the quality of insolation where facilities are sited, the ability of the grid to accommodate for solar's variable output, and the presence of other power generation sources in a given area.

[4] Solar insolation is the amount of solar energy that strikes a flat surface per unit area per unit of time.

Solar Photovoltaic Power

Resource Potential

Flat-plate photovoltaic (PV) arrays effectively use both direct and diffuse sunlight, thus enabling deployment over a larger geographic area than is possible with concentrating solar power (CSP) systems. Although the yearly average total insolation varies significantly across the continental United States, the regional variation is approximately a factor of two (see NAS/NAE/NRC, 2010a, Figure 2-2).

Estimates of the rooftop area suitable for the installation of photovoltaic systems have been made for each state. The Energy Foundation and Navigant Consulting (Chaudhari et al., 2004) analyzed rooftop area suitable for PV. This analysis provided estimates for each state, and included flat roofs on commercial buildings, but not steep residential roofs (or roofs not generally facing south). The analysis concluded that 22 percent of available residential rooftop space and 65 percent of commercial building rooftop space was technically suitable for the installation of PV systems.

Combining this estimate of available rooftop area with state-by-state values for average insolation yields a technical solar PV-based peak capacity of 1,500 to 2,000 GW (if conversion efficiencies ranged from 10-15 percent). Assuming a 20 percent capacity factor (slightly more than 5 hours of sunlight per day averaged over the year), this could provide 13 million to 17.5 million GWh/yr of electricity (NAS/NAE/NRC, 2010a). More conservative estimates indicate that existing suitable rooftop space could provide 0.9 million to 1.5 million GWh/yr of PV-generated electricity (ASES, 2007), suggesting that a substantial portion of U.S. electrical demand could be met by solar PV without having to set aside new land for PV development.

Concentrating Solar Power

CSP systems use only the focusable, direct-beam portion of incident sunlight and are thus limited to sites that have abundant, direct normal solar radiation, such as the southwestern United States. Figure 2-7a shows that, despite variations in radiation intensity, all six states there have high levels of insolation. A 2006 analysis by the Western Governors' Association (WGA) and subsequent refinements by NREL narrowed down suitable land to areas with average insolation of more than 6 $kWhm^{-2}day^{-1}$; land areas with a slope greater than 1 percent or less than 1 km^2, national parks, nature reserves, and urban areas were all excluded (Figure 2-7b) (WGA, 2006a).

This analysis concluded that the southwestern United States has a CSP electricity peak-generation capacity potential of 7,000 to 11,000 GW in the 225,000 km^2 of land that has no primary use (Figure 2-7b). With an average annual capacity factor of 25 to 50 percent for CSP (toward the higher end if thermal storage is used), the technical potential of this land area is between 15 million and 40 million GWh of electrical energy per year.

Assuming that 20 percent of the technical potential could become economically feasible, 3 to 8 million GWh could be produced. The current installed CSP capacity in the United States is 0.43 GW. As of March 2010, a total of 8 GW of new capacity was in various stages of development in the United States, with completion expected in 2010 to 2014. These and other international projects are described in the international database SolarPaces, a collaboration among the 16 member countries of the International Energy Agency (IEA) Implementing Agreement on Solar Power and Chemical Energy Systems (IEA, 2010d). Data is available on operational plants and plants under construction or under development.

SOLAR POWER IN CHINA

Resource Assessment

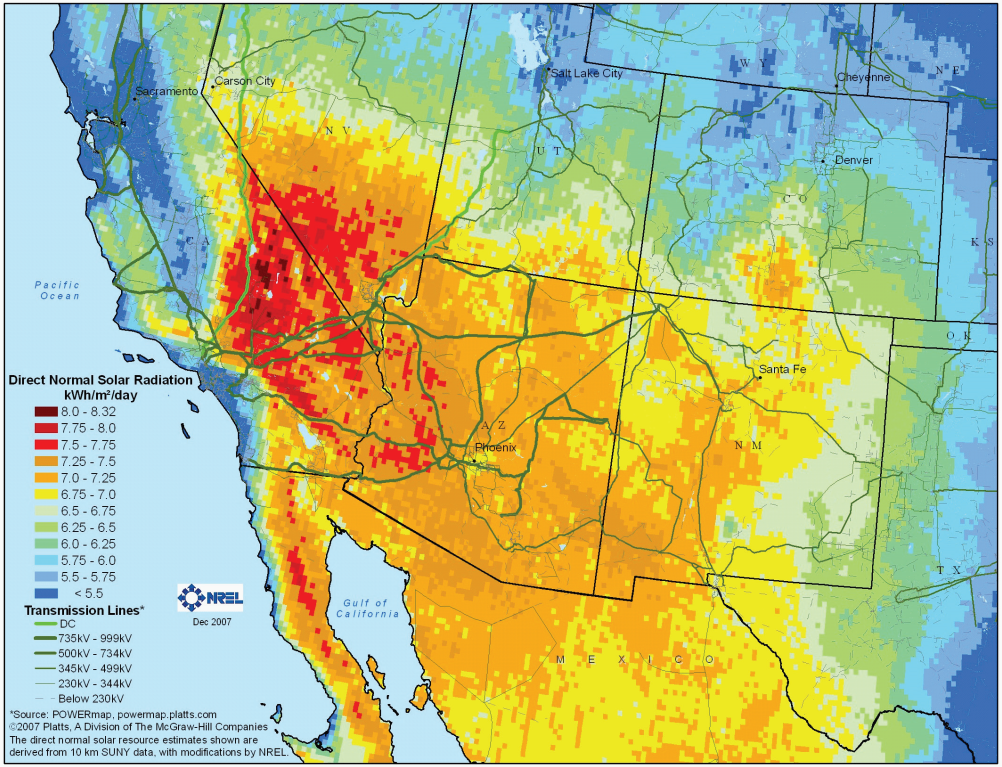
According to the Solar Energy Resource Assessment (CMA, 2008), which is based on radiation data for 1978 to 2007 for more than 700 surface stations, China has ample solar energy resources (see also CAE, 2008). The annual direct and diffuse (collectively referred to as "global") solar radiation is 14 billion GWh, which is equivalent to 1.7 trillion tons of coal equivalent (tce); the annual direct radiation is 7.8 billion GWh (or 1.0 trillion tce) (CAE, 2008). The distribution of direct radiation is shown in Figure 2-8.

At a modest 10 percent average conversion efficiency, annual global solar radiation would provide 1.4 billion GWh/yr of electricity. Also at a 10 percent conversion efficiency, only 0.23 percent of the land area of China would be required to generate the 3.2 million GWh of electricity generated domestically in 2007. To facilitate the development of solar energy resources, according to the spatial distribution of the annual global solar radiation, China has established four zones based on strength of the resource (Figure 2-9 and Table 2-5).

At present, total rooftop area in China is almost 10 billion m^2. About 2 billion m^2, 20 percent of that, could accommodate solar PV systems. In addition, solar PV power generation systems could be installed on just 2 percent of the Gobi and other desert land (i.e., 20,000 km^2), with a capacity of about 2,200 GW, assuming the same modest 10 percent conversion efficiency for modules. Thus annual solar power generation could total 2.9 trillion kWh, assuming 3.6 hours per day of sun averaged out over a year.

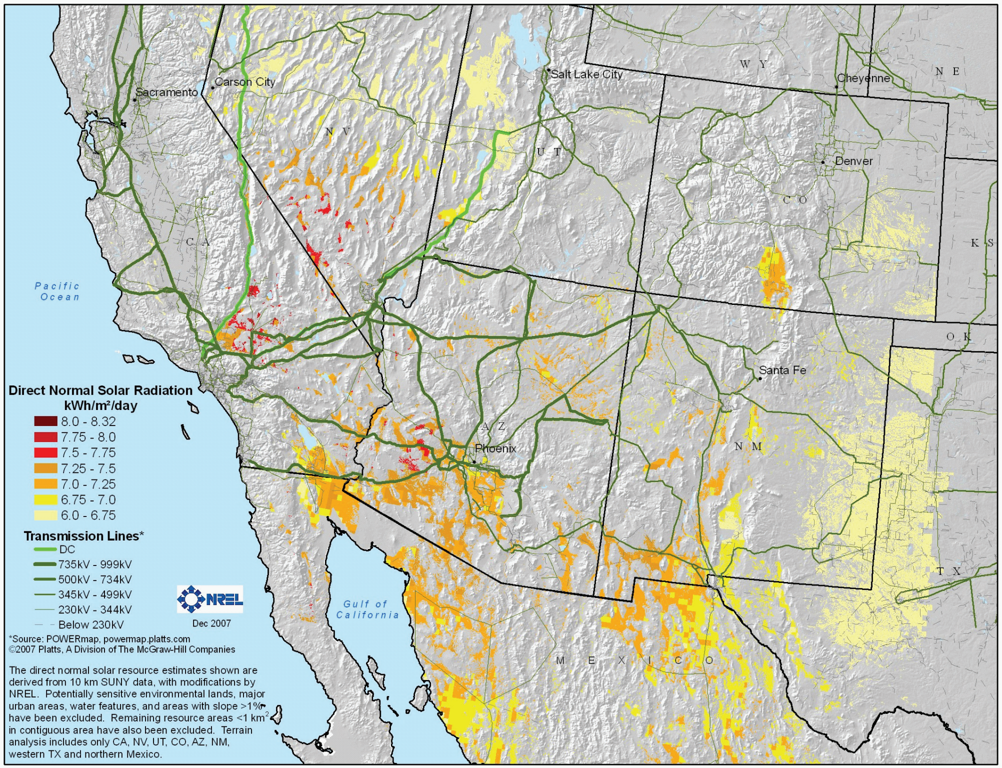
Economic Assessment

The cost of developing and using solar energy resources is directly related to the technology used. At present, China has commercial solar energy utilization



a

FIGURE 2-7 (a) Total direct normal solar radiation in the Southwest, the most suitable region for concentrated solar power, is shown on the left. Source: National Renewable Energy Laboratory resource analysis upgraded from WGA, 2006a.



b

FIGURE 2-7 (b) Direct normal solar radiation, excluding areas with less than 6 kWh/m^2/day. Land and slope exclusions are shown on the right, for which the technical concentrated solar power potential of the region is 15 to 40 million GWh (with capacity factors of 25 to 50 percent). Source: National Renewable Energy Laboratory resource analysis upgraded from WGA, 2006a.

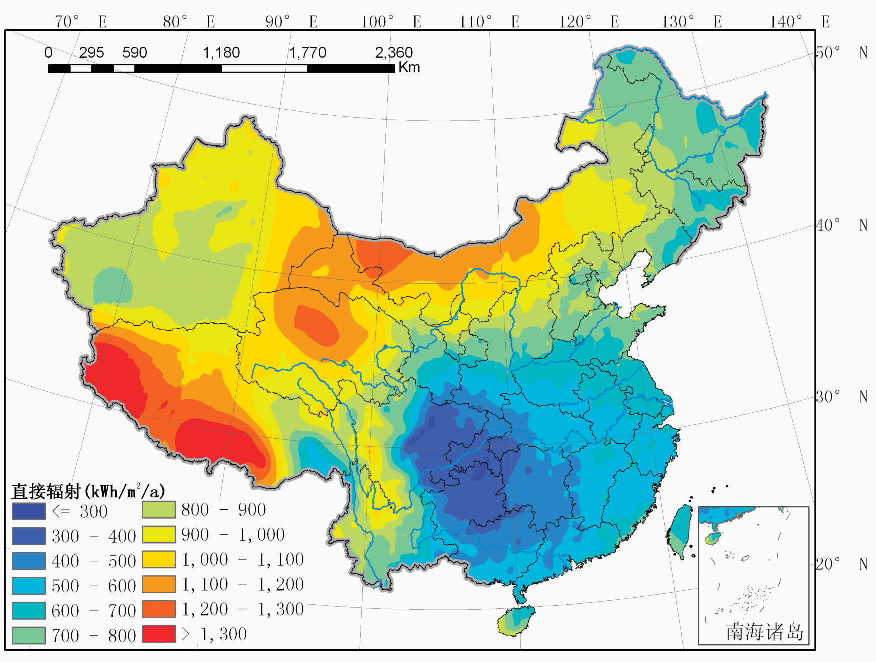


FIGURE 2-8 Annual mean distribution of direct radiation (unit: kWh/m^2). Source: China Meteorological Administration.

technology, such as solar water heaters and crystalline-silicon PV technologies. However, solar thermal power generation technologies are in still in the development and demonstration phases.

According to an assessment of solar water heater cost and practical use, by Beijing Tsinghua Solar Applied Technology Co. Ltd, the expected cost of solar water heaters is between 0.05 and 0.2 Yuan/kWh, depending on the level of internal consumption and export markets, with an average level of about 0.13 Yuan/kWh. Costs for power generation are an order of magnitude greater—presently, the cost of solar PV-generated power ranges from 1.5 to 3.0 Yuan/kWh, depending on solar energy resource zoning (Table 2-6).

BIOMASS FOR BIOPOWER

Biomass is an umbrella term that encompasses a variety of resources, each with its own characteristics (e.g., solid vs. liquid vs. gas; moisture content; energy content; ash content; emissions impact). The types of biomass for energy production fall into three broad categories: (1) wood/plant waste; (2) municipal solid waste and landfill

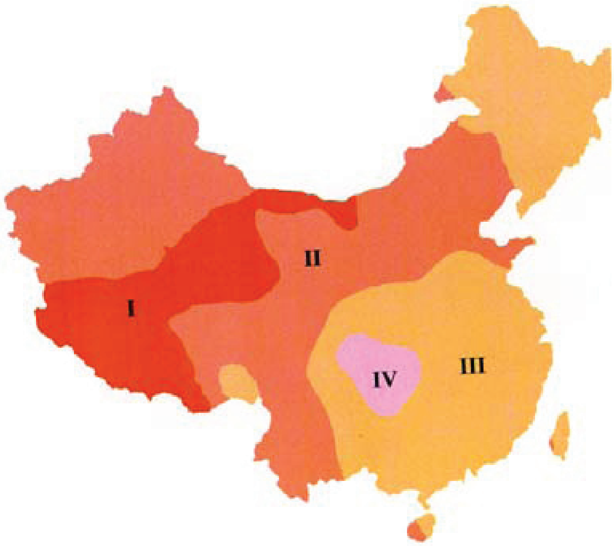


FIGURE 2-9 Solar energy zones characterized in Table 2-5.

TABLE 2-5 Solar Energy Zoning and Distribution

	Zone	Mean Solar Radiation ($kWh/m^2 \cdot a$)	Percent of China's Territory	Distribution
Richest	I	≥ 1,750	17.4	Most of Tibet, south of Xinjiang, west of Qinghai, Gansu, and Inner Mongolia
Richer	II	1,400~1,750	42.7	North of Xinjiang, northwest of China, east of Inner Mongolia, Huabei, north of Jiangsu, Huangtu Plateau, east of Qinghai and Gansu, west of Sichuan, Hengduan mountain, coastal of Fujian and Guangdong, Hainan
Rich	III	1,050~1,400	36.3	Hilly county in southeast of China, the reaches of Hanshui River, west of Sichuan, Guizhou, and Guangxi
Moderate	IV	≤ 1,050	3.6	Parts of Sichuan and Guizhou

NOTE: Regions with rich solar energy, including richest, richer, and rich zones, account for more than 96 percent of China's territory.

TABLE 2-6 Estimated Production Costs and Prices of Solar Energy Power Generation and Estimated Potential Capacity of the Chinese Solar Resource

Solar Energy Zoning	I	II	II-III	III
Total solar radiation (kWh/m^2·a)	2,250	1,740	1,400	1,160
Annual utilization hours of solar power[a]	1,700	1,300	1,050	870
Estimated price (Yuan/kWh)	1.5	2.0	2.5	3.5
Estimated production cost[a] (Yuan/kWh)	1.3	1.7	2.1	3.0
Solar power potential (thousand GWh)	700	670	620	210

[a] After the 1.5 Yuan/kWh subsidy for grid-connected solar power.

gas (LFG); and (3) other biomass products, such as agricultural by-products, biofuels, and selected waste products, such as tires. Crops dedicated to energy production currently represent an insignificant portion of the U.S. and Chinese biomass energy supplies. However, growing interest in using biomass to produce alternative liquid transportation fuels (biofuels) is beginning to change the methodology of documenting biomass usage. A particularly attractive feature of biomass is that, as a chemical energy source, it is available when needed. This feature also makes it attractive for competing applications, such as for the production of transportation fuel.

BIOPOWER IN THE UNITED STATES

Biomass Resources

A U.S. Department of Agriculture (USDA) and Department of Energy (DOE) study (2005) identifies the potential for using 1.3 billion dry tons (1 dry ton = 1,000 kg) per year of biomass for energy without adversely affecting food production. This estimate involved 448 million acres (1.8 × 1,012 m^2) of agricultural land, both croplands and pastures, and 672 million acres of forestland (2.7 × 1,012 m^2) (USDA/DOE, 2005). Collectively, the total area assumed to be available for biomass is slightly more than 57 percent of the total land area of the lower 48 states (NAS/NAE/NRC, 2010a).

However, the amount of land actually used for biomass production will be substantially less than the total available. For example, at 2.5 tons/acre/year and at 5/tons/acre/year, the land area required for 1.3 billion tons/year would be 423 million acres and 260 million acres, respectively. As discussed below, when supply projections based on the cost are used, the estimates are significantly less than the theoretical potential. Economic supply potential in 2025 ranges from 500 to 700 million tons/year, which would require 100 million acres (500 million tons at 5 tons/acre/year) to 280 million acres (700 million tons at 2.5 tons/acre/year).

The amount of biomass that can sustainably be removed from domestic agricultural lands and forestlands is 190 million dry tons annually, with about

142 million dry tons coming from forestland and the remainder coming from cropland. Only about 20 percent of this is now being used for biomass production. The USDA/DOE report projected that approximately 370 million tons (twice the present biomass production) could be made available sustainably from 672 million acres of forestland. However, this would require (1) using wood instead of burning it for forest management, (2) using pulp residues, and (3) using logging residues for power generation.

The USDA/DOE report also projected that in 35 to 40 years agricultural lands (cropland, idle cropland, and cropland pasture), which produce approximately 50 million tons of biomass per year, have the potential to yield nearly 1 billion dry tons of biomass. This would be a 20-fold increase in the yield of sustainable biomass. Of the projected 1 billion dry tons, 300 to 400 million tons would come from crop residues, and 350 million tons would result from replacing other land uses on some 40 million acres with high-yield perennial biomass crops.

The estimate in the billion-ton study by USDA/DOE was for future potential biomass resources. Another study by NREL (Milbrandt, 2005) shows a different geographical distribution of the biomass resource base (Figure 2-10). The NREL study, based on currently available biomass resources, includes county-level assessments of (1) agricultural and forest residues, (2) urban wood (secondary mill residues, municipal solid waste [MSW] wood, tree trimmings, and construction/demolition wood), and (3) methane emissions from manure management, landfills, and domestic wastewater treatment facilities.

According to the USDA/DOE study, a yield of 1.3 billion dry tons per year of biomass would require increasing the yields of corn, wheat, and other small grains by 50 percent; doubling residue-to-grain ratios for soybeans; developing more efficient residue harvesting equipment; managing croplands with no-till cultivation; growing perennial crops primarily dedicated to energy purposes on 55 million acres of cropland, idle cropland, and cropland pasture; using animal manure not necessary for on-farm soil improvement; and using a larger fraction of other secondary and tertiary residues for biomass production. Attaining these increased crop yields and collecting these materials would require new technologies, such as genetic engineering.

The billion-ton estimate was based on the assumption that agricultural lands in the United States could potentially provide more than 1 billion dry tons of sustainably collectable biomass, while continuing to meet food, feed, and export demands (NAS/NAE/NRC, 2010a). This included 446 million dry tons of crop residues, 377 million dry tons of perennial crops,[5] 87 million dry tons of grains used for biofuels, and 87 million dry tons of animal manure, process residues, and other residues.

Another estimate was provided by the Panel on Alternative Liquid Transportation Fuels, part of the America's Energy Future project of the National

[5] The perennial crops are crops dedicated primarily to energy and other products and will likely include a combination of grasses and woody crops.

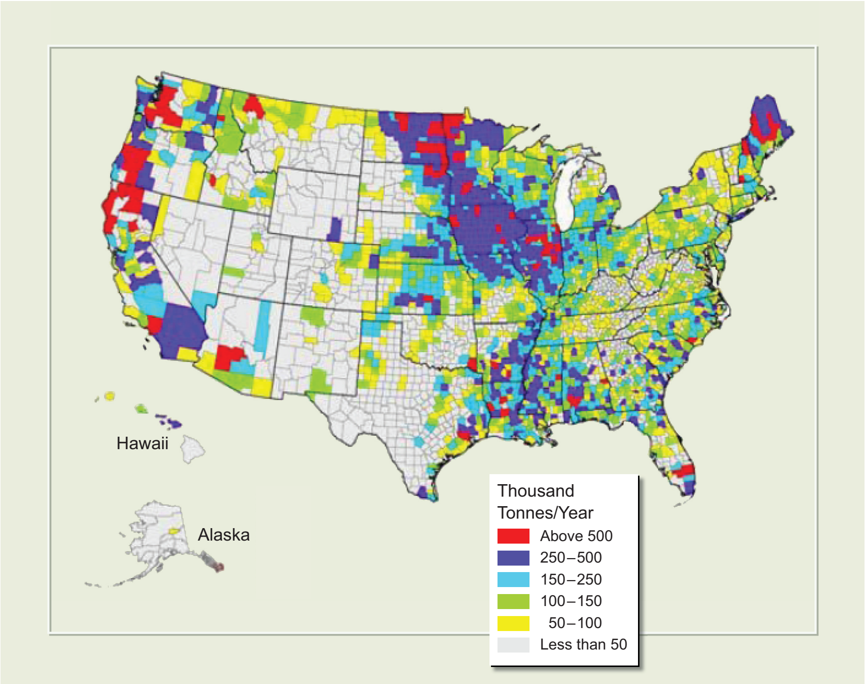


FIGURE 2-10 Total biomass available in the United States by county. Source: Milbrandt, 2005.

Academies (NAS/NAE/NRC, 2009b). Similar to NREL projections, this estimate projects an annual supply of 400 million dry tons of lignocellulosic biomass sustainably produced using technologies and management practices available in 2008. The panel projects that the supply could be increased to about 550 million dry tons by 2020 from dedicated energy crops, agricultural and forestry residues, and municipal solid waste with minimal impacts on U.S. food, feed, and fiber production and with minimal adverse environmental impacts. The panel also considered sustainability factors, such as maintaining soil carbon levels and crop productivity in subsequent years.

Economic Assessment

As discussed above, a number of studies have provided estimates of biomass availability and costs. In a review of these studies by Gronowska et al. (2009), the authors differentiated between inventory studies of existing and potential biomass resources and economic studies that take into account the cost of supply, generally referred to as biomass supply curves. Inventory studies provide estimates ranging from 190 to 3,850 million dry tons annual biomass yield. Supply curve estimates range from 6 to 577 million dry tons annually, depending on feed category and price. Gronowska et al. noted that in most studies, future biomass supplies are projected to be a mix of agricultural residues and dedicated crops, with smaller amounts of residual woody materials. Estimates by Oak Ridge National Laboratory (ORNL) (Perlack et al., 2005; Walsh et al., 2000), NREL (Milbrandt, 2005), the National Academies (NAS/NAE/NRC, 2009b), EIA (Haq and Easterly, 2006), and M&E Biomass (Walsh, 2008) are compared in Figure 2-11. It is unclear whether agricultural practices using bioengineered plants will be sustainable, even if photosynthesis can be enhanced through genetic modification. Even with today's candidate energy crops (e.g., willow, miscanthus, poplar, switchgrass) it is not clear what fraction of biomass must be left in the fields to ensure soil health, although a trend toward conservation tillage, that is, leaving at least 30 percent of the soil covered with residue, would reduce the amount of biomass available for other uses (NRC, 2010b).

Supply curves to estimate electricity from biomass ($/kWh versus kWh/yr) have yet to be developed. A sample supply curve from the M&E Biomass study (Walsh, 2008) is shown in Figure 2-12. Walsh (2008) relied on default biomass supply costs from the NREL (Milbrandt, 2005) study.

NREL has also developed a Bio-power Tool,[6] an interactive geospatial application that enables users to view biomass resources, infrastructure, and other relevant information and to query the data and conduct initial screening analyses. Users can select a location on the map, quantify the biomass resources available in a defined radius, and estimate the total thermal energy or power that could be generated by recovering a portion of that biomass. This tool is useful for refining the site-identification process but does not eliminate the need for on-site resource evaluation.

Electricity Generation from Biomass

Based on 2005 biomass production levels, full use of the 190 million dry tons of sustainable biomass produced in the United States, at 17 GJ (1 GJ = 1 × 109 J)/dry ton, and at 35 percent efficiency for the conversion of heat from biomass combustion into electrical energy, would provide 1.1 EJ of energy.[7] In other words, 100 percent of the sustainable biomass produced domestically in 2005, if used entirely for electricity generation, would produce 0.306 million GWh/yr of electricity, or 7.3 percent of the 2007 U.S. domestic electricity generation. Using a resource average value of ~500 million tons of biomass (NAS/NAE/NRC, 2010b), a total of 0.8 million GWh/yr of electricity could be produced, or 19 percent of 2007 U.S. electricity generation. Increasing available biomass to 1 billion tons and using it solely for electricity generation would produce 6 EJ, which is equal

[6] Available online at *http://rpm.nrel.gov/biopower/biopower/launch*.
[7] 1.9×10^8 tons × (1.7×10^{10} J/ton) at 35 percent electric generation efficiency.

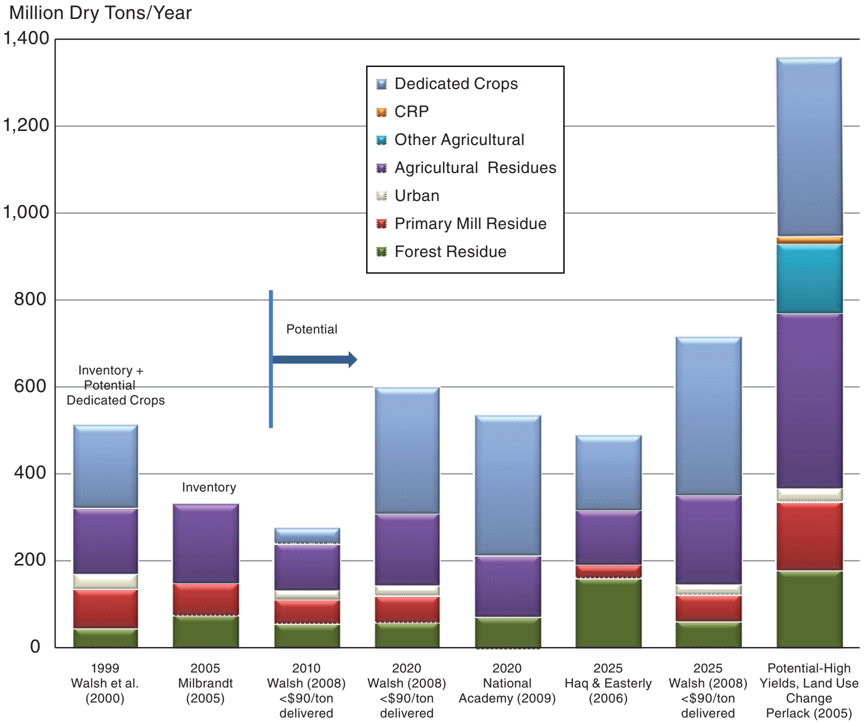


FIGURE 2-11 Past and current inventories and potential supplies at specific prices for various types of biomass in the United States. CRP = Conservation Reserve Program. Source: Walsh, 2008.

to 1.6 million GWh/yr of electricity, representing approximately 40 percent of domestic electricity generation for 2007.

However, a plausible scenario might be that 75 percent of this biomass would be used to produce cellulosic ethanol or other biofuels, and only 25 percent would be available for electricity generation. In that case, 250 million tons of biomass, which is projected to be potentially available in 35 to 40 years if more than 60 percent of the land area of the continental United States were dedicated to producing biomass, would produce 0.416 million GWh of electricity, 10 percent of the 2007 U.S. electricity generation. This represents more than 7 times the actual electricity generation from biomass in 2005 (0.054 million GWh, which accounted for slightly more than 1 percent).

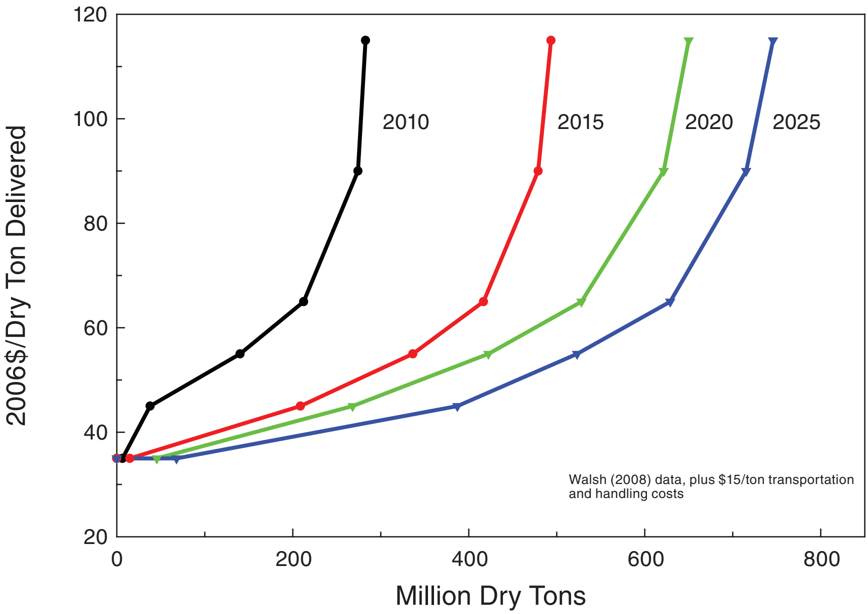


FIGURE 2-12 Biomass supply curves indicating how much feedstock can be delivered to a conversion facility at a certain price for various scenarios from today to 2025. Source: Walsh, 2008 (plus $15/ton transportation and handling costs).

BIOPOWER IN CHINA

China's biomass energy resources include straw and other agricultural wastes, forestry and forest product processing waste, animal manure, dedicated energy crops, organic effluents from industry, municipal wastewater, and municipal solid waste (MSW). Of about 600 million tons of crop straw produced every year, nearly 300 million tons (or around 150 million tons of coal equivalent (tce)), could be used as fuel (NDRC, 2007). Of about 900 million dry tons of waste from forestry and forest product processing available every year, nearly 300 million tons (or about 200 million tce) can be used for energy production. In addition, there are large areas of marginal lands in China that could be used to cultivate energy crops and plantations. Biogas and MSW are also biomass resources with good potential for development. At present, China's total annual biomass resource suitable for energy conversion is roughly equivalent to 1,300 TWh, or approximately one-third of China's total electricity consumption in 2009. When accounting for further development (improved collection methods for agricultural waste, increases in industrial and municipal effluents), this resource base could eventually double.

TABLE 2-7 Differences in Geothermal Electric Power Production Assessments Conducted by the U.S. Geological Survey

	1979	2008
Temperature and depth	> 150°C and <3 km	> 90°C and up to 6 km (Alaska 75°C)
Number of identified systems	52 high temperature	241 high and moderate temperature
Characterization of identified systems	Poor	Abundant exploration and production data
Treatment of reservoir performance	Idealized	Improved models with Monte Carlo analysis for uncertainties
Undiscovered resources	Rough estimates	Better quantitative estimates
Enhanced geothermal systems	Mentioned but not estimated	Included; analysis and methodological development continues

Source: Williams and Pierce, 2008.

GEOTHERMAL POWER IN THE UNITED STATES

Hydrothermal Energy

Geothermal energy exists as underground reservoirs of steam, hot water, and hot dry rocks in Earth's crust (NAS/NAE/NRC, 2010a). In its first national assessment of geothermal energy, the U.S. Geological Survey (USGS, 1979) focused on two categories of hydrothermal resources: (1) identified systems with the electricity generation potential of 0.18 million GWh (23 GW), which were geologically assured and economical (called reserves) or could become economical in time; (2) undiscovered resources with an electric power potential of 0.8 million GWh (~100 GW); these resources were technically recoverable and could become reserves over time. Taken together the resources in these two categories represent one-quarter of the electric power generated in the United States in 2007.[8]

Some 30 years later, in a new assessment using improved science and technology, USGS found an even greater potential (Williams et al., 2008). Results of the 2008 assessment (Table 2-7) indicate a mean electric power capacity potential of 9 GW from identified geothermal hydrothermal systems in 13 states. The estimate ranges from 3.7 GW with 95 percent probability to 16.5 GW with 5 percent probability. Twenty percent of the systems with reservoir temperatures of more than 150° C account for 80 percent of the power potential; most systems have less than 5 km^3 of reservoir volume (Figure 2-13).

The full development of just the conventional, identified systems would increase geothermal power capacity by approximately 6.5 GW. By comparison, the 2005 installed geothermal capacity of 2.5 GW grew to 3 GW in 2008, adding

[8] Geothermal power capacity of 1 MWe generates 7.8 GWh/yr at 90 percent capacity factor.

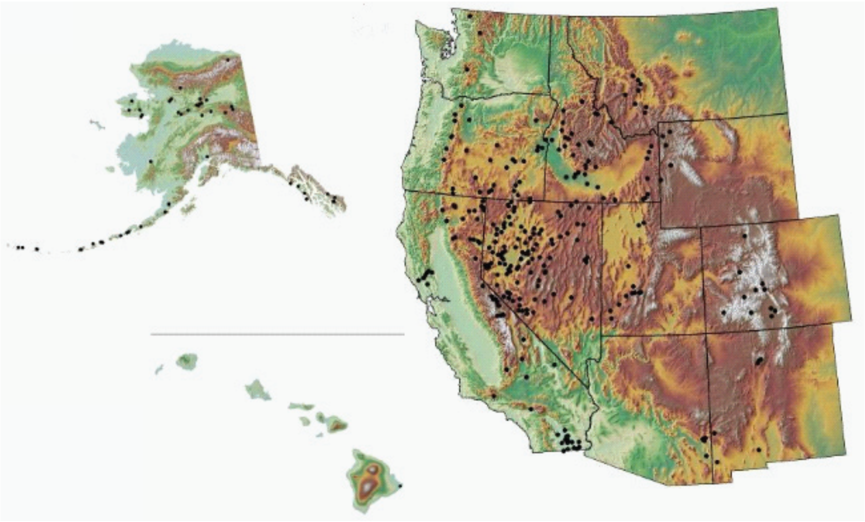


FIGURE 2-13 Map showing the location of identified moderate- and high-temperature geothermal systems in the United States. Each system is represented by a black dot. Source: Williams and Pierce, 2008.

0.11 GW in 2008 alone. The geothermal baseload power generation was 15,000 GWh (Cross and Freeman, 2009).

The 2008 USGS assessment estimated that the mean capacity potential of undiscovered geothermal systems was 30 GW, ranging from 7.9 GW (95 percent probability) to 73 GW (5 percent probability) (Figure 2-14).

Prior assessments for the western states identified 13 GW of potential electric power capacity from 140 sites (WGA, 2006b). With advances in geothermal technology, development, and power-generating operations, 5.6 GW of this potential was considered viable for commercial development by 2015. A nationwide panel of experts estimated that the shallow hydrothermal resource base had an availability of 30 GW, with an additional potential of 120 GW from unidentified hydrothermal resources that have no surface manifestations (Green and Nix, 2006). The panel of experts estimated that 10 GW could be developed by 2015.

These estimates were characterized as having significant uncertainties and did not constitute a resource assessment. Nevertheless, they clearly indicate that geothermal resources can be a significant domestic source of energy in the United States. The geothermal power capacity potential for identified resources from the WGA study is well within the range of the 2008 USGS assessment.

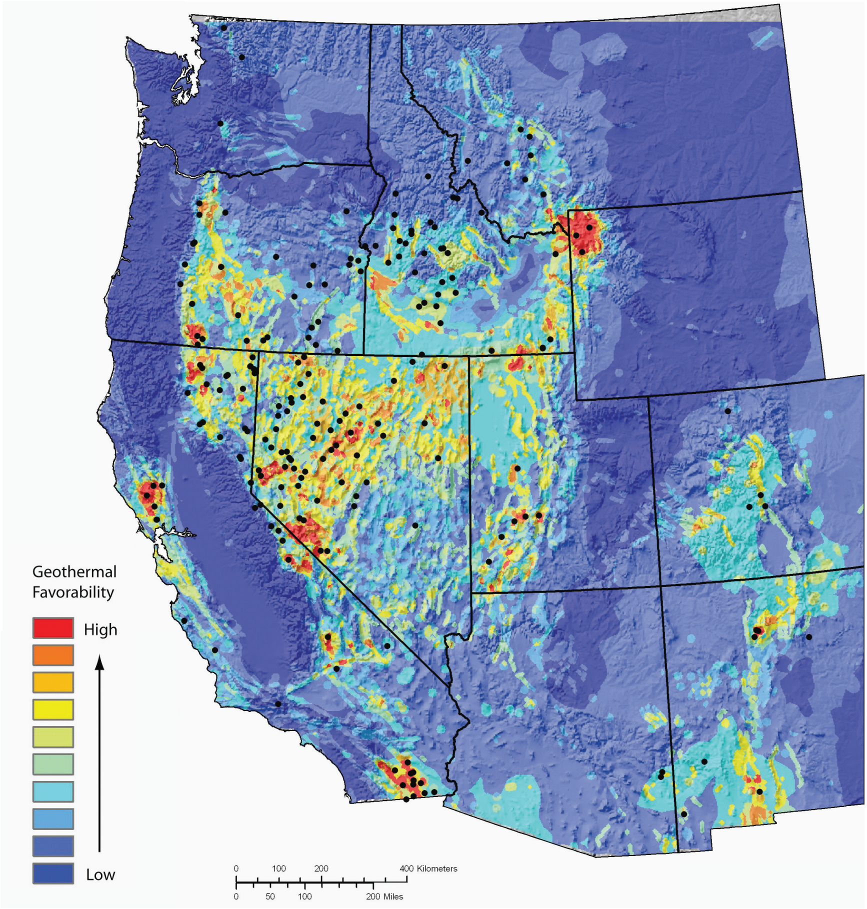


FIGURE 2-14 Sample map (from a series of 28 spatial models) showing the relative favorability of occurrence for geothermal resources in the western contiguous United States. The other models differ in details but show generally similar favorability patterns. Warmer colors equate with higher favorability. Identified geothermal systems are represented by black dots. Source: Williams and Pierce, 2008.

Enhanced Geothermal Systems

Enhanced geothermal systems (EGSs) are engineered reservoirs created to extract heat from low-permeability and low-porosity rock formations. Permeability is enhanced by causing existing fractures to slip and propagate or by increasing fluid pressure to create new cracks. EGSs tap the vast heat resources available from temperature gradients between the surface and depths of up to 10 km.

The 2008 USGS resource estimate for unconventional EGSs is more than an order of magnitude larger than the combined estimates for both identified and undiscovered conventional geothermal resources (Figure 2-14). If successfully developed, EGSs could provide an installed geothermal electric power generation capacity equivalent to about one-half of the currently installed electric power generating capacity in the United States. The mean electric power capacity potential from unconventional geothermal resources (high temperature, low permeability) EGSs is 518 GW, with a range of 345 GW (95 percent probability) to 728 GW (5 percent probability). The mean electric power generation potential corresponds to 4 million GWh/yr, as much power as was generated in the United States in 2007.

When USGS used a different methodology to test its results, the studies confirmed the large potential of EGS in the United States. The geothermal energy resource base located beneath the continental United States (total amount of heat at a depth of 10 km) is estimated to be in excess of 13 million EJ (3.6 trillion GWh), with an extractable portion of 200,000 EJ (MIT, 2006). At a conversion efficiency rate of 15 percent, the extractable geothermal resource could then, in principle, provide 30,000 EJ of electric energy (NAS/NAE/NRC, 2010a). Significant research and development will be necessary to develop the technology to take advantage of this energy source and to improve measurements of its potential.

The rate of extraction will be an important factor in how well we use this resource. The mean geothermal heat flux over land at Earth's surface is approximately 100 mW/m^2 and in many areas is significantly less. The NAS/NAE/NRC (2010a) study estimated the extractable electric power density from the geothermal resource on a renewable basis (i.e., heat being drawn down is restored by the natural geothermal flux) to be about 10 mW/m^2, and so producing even 100 GW would require land area in excess of the entire continental United States.

In practice, the in-place geothermal heat would have to be extracted at rates in excess of the natural geothermal heat flux (NAS/NAE/NRC, 2010a). In the MIT (2006) analysis of resource potential, heat mining was limited by assuming that geothermal reservoirs would be abandoned when the temperature of the rocks fell by 10 to 15°C, reservoirs were assumed to have a lifetime of 30 years, with periodic re-drilling, fracturing, and hydraulic simulation and were estimated to be able to recover to their original temperature conditions within 100 years of abandonment. Thus, if 10 percent or less of the stored heat is mined at any one time, EGS could be considered a renewable resource (NAS/NAE/NRC, 2010a).

GEOTHERMAL POWER IN CHINA

A preliminary estimate of the capacity of high-temperature geothermal resources in China is 5.8 GW, and the capacity of low-temperature geothermal resources is 14.4 GW. Although China is a leader in direct thermal use of geothermal resources, with 3.7 GWt (a measure of thermal [not electric] power, equivalent to 12.6 TWh/yr), and has the rock formations for these systems, EGSs have not been assessed (Bertani, 2005).

The most important geothermal plant in operation, with a capacity of 25 MW, is located in Yangbajain, Tibet. Energy is generated from a shallow reservoir (depth 200 m) that covers about 4 km^2; the temperature is 140 to 160°C. The annual energy production of this plant is approximately 100 GWh, about 30 percent of the needs of the Tibetan capital, Lhasa. This field also has the potential of producing 50 to 90 MW from deep reservoirs (250 to 330°C at a depth of 1,500 to 1,800 m) beneath the shallow Yangbajian field (Bertani, 2005). Another plant with a capacity of 49 GW is under construction in the Tengchong area, Yunnan province.

HYDROKINETIC POWER IN THE UNITED STATES

Wave, Tide, and River Energy

Hydrokinetic energy is energy associated with the flow of water, such as waves and water currents, including tides, rivers, and oceans. In general, these resources would only be sufficient to meet a small percentage of overall U.S. demand. The Electric Power Research Institute (EPRI) assessed total U.S. wave energy potential (EPRI, 2005) and found that all the wave energy off the Pacific coast could produce 0.44 million GWh/yr, and the wave energy from the Northeast and Mid-Atlantic coast could produce 0.12 million GWh/yr (Figure 2-15). When factoring in generation losses (10 to 15 percent), the total electric generation potential is about 0.07 million GWh for the entire continental U.S. wave energy resource (NAS/NAE/NRC, 2010a). The largest U.S. wave resource is off southern Alaska, which has an estimated resource base of 1.25 million GWh/yr (EPRI, 2005), but collecting and transmitting this as electrical energy to consumers in the lower 48 states represents a significant challenge.

The EPRI study also examined tidal energy potential from sites in Alaska, Washington, California, Massachusetts, Maine, and New Brunswick and Nova Scotia (Canada). The total combined resource was estimated to have an annual average electricity generation potential of 152 MW, which corresponds to an annualized electricity production of 1,300 GWh/year (EPRI, 2005). Another EPRI study (EPRI, 2007) focused on the electric energy potential of river currents and estimated a value of 0.11 million GWh/year.

The resource potential for theoretical, technical, and practical energy extraction from all of these sources will have to be characterized more comprehensively. Like wind energy and technology, the interplay between these resources and new technologies might lead to the identification of more resources.

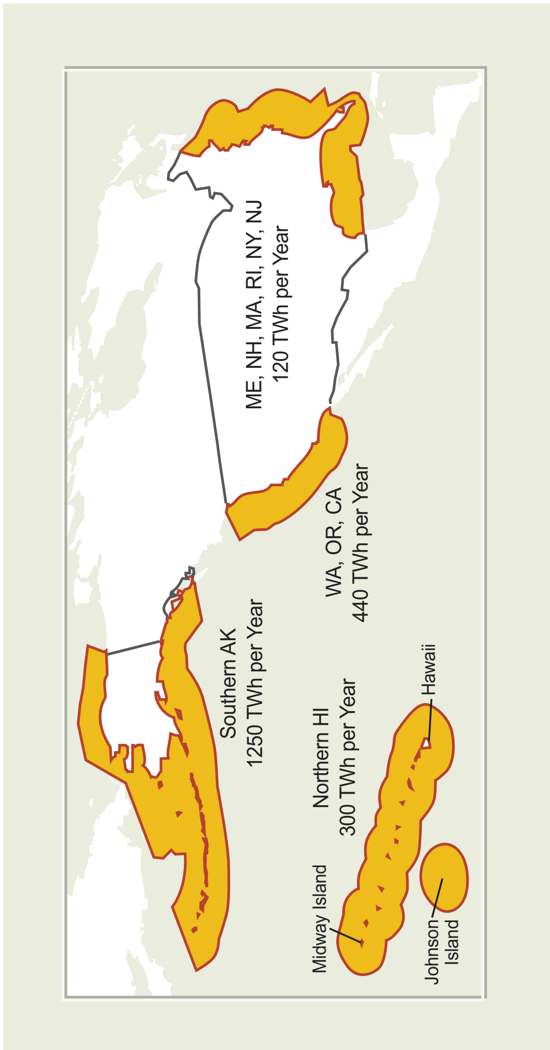


FIGURE 2-15 U.S. wave-energy resources. Source: EPRI, 2005.

HYDROKINETIC POWER IN CHINA

Up to now, China has only developed eight small-scale, tidal-energy stations with total installed power of 6 MW. The largest, Jiangxia tidal station in Zhejiang Province, constructed in 1974, is also the largest one in Asia and the third largest in the world. With six machines, this station has a total of 3.9 MW installed power. Additional tidal barrage plants in Baishakou and Haishan provide up to 640 kW and 150 kW, respectively. Many demonstration-stage wave-power stations of several tens to hundreds of kW are used for light navigation in coastal areas. In the near future, ocean power research and development will be increased and practical applications could be expanded, but still for small-scale power supply.

INTEGRATED RESOURCE PLANNING

Clean and Diversified Energy for the West, a project of the U.S. WGA is identifying ways to increase renewable energy, energy efficiency, and clean energy technologies in the mix for meeting the overall energy needs of the western United States.[9] Since 2006, WGA has used multiple resource assessments to inform its decisions about the development of 30 GW of clean energy by 2015.

In the first phase of the project, Western Renewable Energy Zones (WREZ), “hubs” that have the potential to contribute to a Western Interconnection, were identified for the purpose of evaluating interstate transmission lines for future phases of the initiative. Figure 2-16 shows the WREZ Initiative Hub Map with graphical representations of regional renewable resource potentials sized in proportion to the total amount of electricity (in TWh) that could be produced over the course of a year from resources in the Qualified Resource Areas (QRAs) (Pletka and Finn, 2009). Resource estimates do not include environmentally and technically sensitive areas, and they discount the remaining resource potential to account for unforeseen development constraints.

In some cases, the energy generating potential of a QRA is reduced to account for certain environmental sensitivities identified by state wildlife agencies, but little consideration is given to construction logistics or costs, permitting, or cultural and other land-use concerns related to specific sites. These factors are considered in other phases of the project, which includes a public consultation process (WGA, 2009). All resources that meet the minimum quality thresholds defined by the Zone Identification and Technical Analysis Working Group are shown on the map.

According to the WGA (2009, p.1) report:

> The resources quantified in each hub include only the highest quality wind and solar resources as well as geothermal sites, biomass, and hydropower with known commercial potential. Because the quality criteria for minimum wind and solar resource quality vary

[9] See WGA Policy Resolution 06-10 available online at *http://www.rnp.org/news/PR_PDF_files/WGA/clean-energy.pdf*.

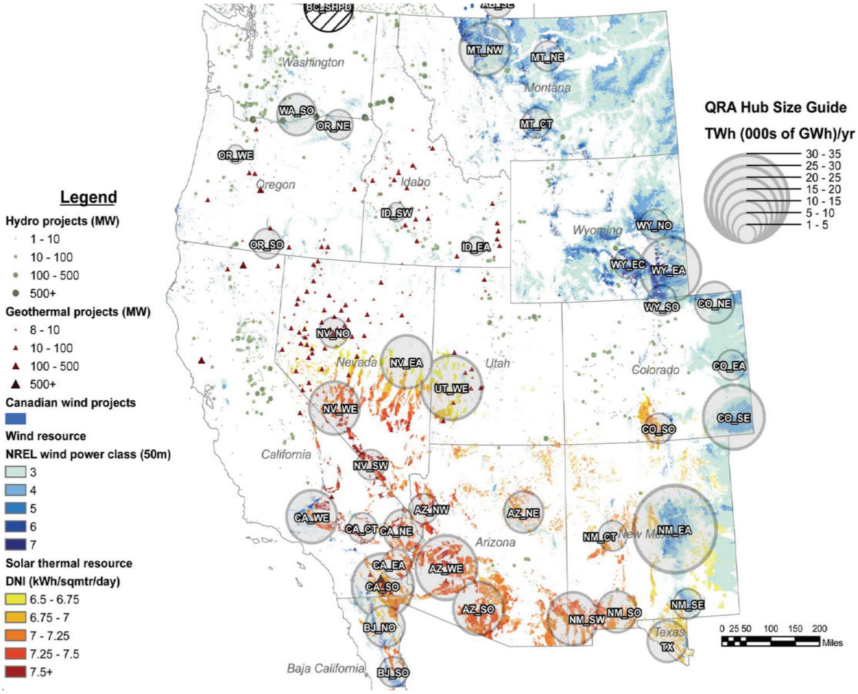


FIGURE 2-16 QRAs showing potential for electricity generation from a variety of renewable sources (biomass is not shown; only some part of the Canadian QRAs shown). Maps like this one were the first step in planning for renewable electricity and new transmission and distribution on a regional basis with input from the public. Source: WGA, 2009.

> from state to state, resources that did not meet the state's general quality thresholds were labeled "non-WREZ" resources. These include low-quality wind, solar thermal, solar PV, undiscovered conventional geothermal potential, enhanced geothermal systems, and other viable renewable resources. Thus, the assessment of conventional geothermal resources was limited to British Columbia, California, Idaho, Nevada, Oregon, and Utah which have known high-potential conventional geothermal resources. Biomass resources are also quantified as part of the WREZ supply curve analysis for each QRA, but they are not shown on the map.

WGA has also developed a transmission model and is proceeding to facilitate construction of utility-scale renewable energy plants and transmission systems. In this phase, multi-layer maps are being prepared to visualize technology-specific filters to refine QRAs and capture best sites; map layers show land use and areas excluded for wildlife protection and other environmental and ecological reasons. An interactive tool is under development that will enable planners to take these and other criteria into consideration and identify barriers to development. All phases of the process, results, and models are available on the WGA web site (WGA, 2009).

FINDINGS

Both the United States and China have significant renewable energy resources that have the potential, in principle, to provide more electric power than the total existing installed peak capacity and more electric energy annually than the total amount of electricity consumed in each country in 2009. This resource base is spread widely across the both countries.

Solar and wind renewable resources have significantly more total energy and power potential than other domestic renewable resources. Although solar intensity varies across both nations, land-based solar resources provide a yearly average of more than 10 million terawatt hours, which exceeds, by several thousand-fold, present annual U.S. or Chinese electrical energy demand. Hence, even with modest conversion efficiency rates, solar energy is capable, in principle, of providing enormous amounts of electricity without stress to the resource base. Land-based wind resources are capable of providing at least 20 percent, and in some regions more, of current electrical energy demand in both countries. Other (non-hydroelectric) renewable resources can also contribute significantly to the electrical energy mix in some regions.

The United States is conducting increasingly comprehensive and higher resolution assessments of the technical potential of its renewable resources. These assessments often include initial estimates of economic potential, combining supply curves with cost of delivered electricity for a certain amount of resource. Some Chinese resources have only been assessed at the inventory level, mostly at low resolution. Assessments that link **high-resolution knowledge of a resource base and technological progress for wind power and other renewables would be helpful to China. A reassessment of China's wind resources using higher resolution wind resource data and higher turbine hub heights could help to identify new wind development sites.** A similar assessment in the United States led to a reevaluation of wind resource potential in many states. Additional areas where the United States could lend expertise include measurements of direct normal incidence radiation (for CSP potential) and EGS mapping. In both instances, these assessments should include regional water availability, since it is a potential limiting factor in the large-scale deployment of CSP or EGS.

Scenario modeling (combining geographic information systems with estimated economic resource assessments, renewable technology development with time, current and possible evolution of transmission infrastructure, and balancing costs) is becoming increasingly important for planning and rational development of both traditional and renewable energy resources. It requires the use of coupled models that enable exploration of a large number of scenarios and the consequences of their deployment. **China and the United States can collaborate in**

this area to identify ways to reduce implementation costs through integrated resource planning and scenario modeling efforts.

Biomass resource assessment collaborations among U.S. DOE and the Chinese government, academia, and industry are ongoing for biofuels feedstock supply curve developments, but these conversion technologies are still under development. Some biopower technologies such as co-firing are the most cost effective and could be developed for appropriate regions of the country using residues if an efficient collection infrastructure is established. Mapping multiple layers of resources and infrastructure may facilitate co-development of biopower and biofuels and capitalize on the economic potential of biorefineries.

Modeling of hydrokinetic energy, which is just starting in both countries, has great uncertainties because of weather-related disasters and unpredictability. Offshore resources are also subject to weather changes and disasters. To ensure that resource assessment models include risk assessment for severe weather conditions, the United States and China could collaborate to develop and test best locations and minimize financial risk.

RECOMMENDATIONS

- China and the United States should collaborate on mapping integrated resource and development options at regional scales. Such multi-resource maps and evaluation can help identify options for distributed generation, potential resource constraints (e.g., water availability for thermoelectric power), and least cost routes for needed transmission.
- Researchers, modelers, and systems operators from both countries should collaborate on developing the software and computer models to support more integrated supply models.

3

Technology Readiness

A major hurdle to the mass deployment of renewables in China and the United State is their relatively high cost. Both countries are working to reduce those costs and, over time, have developed strategies to overcome that hurdle by taking advantage of each country's unique circumstances—namely, U.S.-led innovations have contributed to improved performance for a variety of technologies, and more recently, China's entry into the manufacturing space has helped reduce product costs for wind turbines and PV modules.

In this chapter, several technologies for renewable electricity generation and the technological readiness of the electrical system for increasing the share of energy from renewables are described. This is followed by an overview of the salient technological changes that might affect the widespread proliferation of renewable energy in both countries. This chapter does not analyze costs of each type of renewable generation, but these costs are analyzed in some detail in NAS/NAE/NRC (2010a) Chapter 4. Renewable power system costs are dynamic and highly influenced by location-specific conditions (e.g., quality of the resource, availability of transmission). "All-in" cost analysis should include all items required to reliably serve customer load with the generation resource, such as: the direct capital and operating costs of the renewable generation resource; costs for required transmission; and costs of other incremental resources required to integrate the renewable generation resource into the overall grid system (e.g., balancing services or backup generation). These are typically reflected in the levelized cost of electricity (LCOE) for a given project. Ultimately, it is the LCOE that must be competitive with alternative sources of power, and this competitiveness is influenced by the factors listed above, as well as the projected costs for fossil-fuel generation.

WIND POWER

Wind power generation involves using wind turbines to generate electricity from the kinetic energy of moving air. This mature technology has achieved good economic performance and is ready for widespread implementation.

Status of Technology

Many of the negative perceptions about wind power are based on early-generation wind turbines. Modern turbines have technological improvements to control low-voltage ride-through and output/ramp rate and provide volt-ampere-reactive support. With these capabilities, turbines can remain connected to the grid during voltage disturbances, mitigate their draw on the grid's reactive power resources, and maintain continuous real-time communications and data exchange with the control area operator.

Wind farms in the United States generated an estimated 70,760 GWh of electricity in 2009, which represented about 1.2 percent of the U.S. electricity supply (EIA, 2010c [Renewable Energy Consumption and Electricity Preliminary Statistics]). The U.S. wind power capacity spans 34 states and totaled 33.5 GW of capacity in 2009 (EIA, 2010d). At the end of 2009, there were approximately 300 GW of proposed capacity additions in transmission interconnections queues, nearly nine times current installed capacity, although not all of these projects are likely to be installed (Wiser et al., 2010). The state of Texas is currently home to two of the largest wind farms in the world—Roscoe Wind Farm (780MW) and Horse Hollow Wind Energy Center (735MW).

China has the largest industry and market for mini- and micro-wind generators in the world. From 1983 to 2009, 609,039 small- and medium-sized turbines were produced in China. In 2009, 34 manufacturers produced 100,318 sets, of which 47,020 were exported (CWEA, 2010). China set initial goals of 5 GW of installed wind capacity by 2010, and 30 GW by 2020 (NDRC, 2007). The 2010 goal was quickly revised to 20 GW, and China still reached the goal a year earlier than planned (2009 instead of 2010) and more than doubled its installed capacity from 2008 to 2009 (12.2 GW to 25.8 GW) (CWEA, 2010). The latter goal of 30 GW will likely be reached by the end of 2010, and the revised 2020 goal of 100 GW installed capacity may be further revised to 150 GW. To put this in perspective, global installed capacity as of 2009 was 158 GW (GWEC, 2010), and China would *annually* be installing capacity that is greater than total installed capacity of the UK, Portugal, and Denmark (as of 2009). To achieve this goal, China will have to expand its production capabilities to produce not only 1.5 MW units, but also 3 to 5 MW units. Figure 3-1 shows how wind deployment has evolved over the years in the United States, China, and the rest of the world.

One aspect of wind energy projects that must be taken into consideration is the capacity factor, that is, the measure of a wind turbine farm's productivity. In the United States, the capacity factor increased from 22 percent for projects

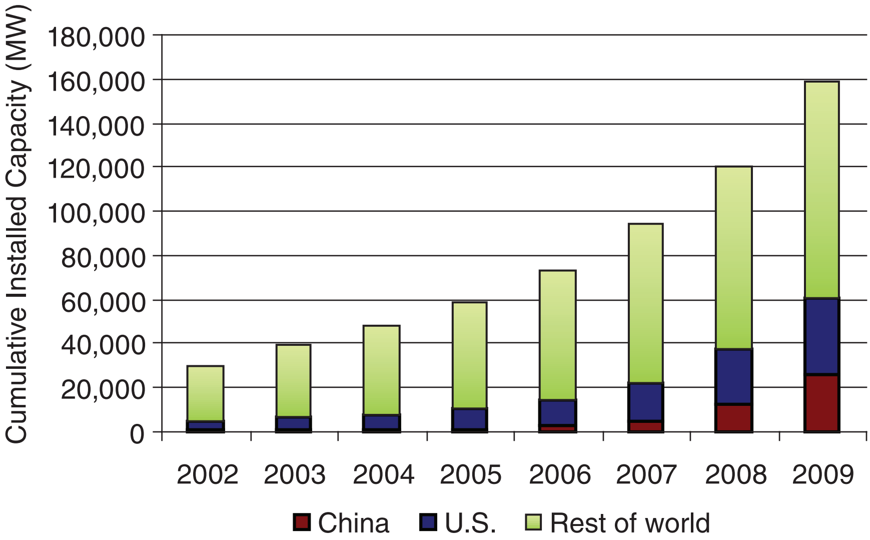


FIGURE 3-1 Deployment of wind turbines in the United States, China, and the rest of the world. Sources: AWEA, 2009, 2010; GWEC, 2010.

installed before 1998 to roughly 30 to 33 percent for projects installed from 1998 to 2003 and roughly 35 to 37 percent for projects installed from 2004 to 2007 (DOE, 2008a). The increased capacity factor is partly the result of a better understanding of wind resources and their availability.

Another aspect to consider in wind deployment is that most wind resources are relatively far from urban centers and other sources of electricity demand. In the United States, wind resources are particularly abundant in the Midwest; in China, the strongest winds blow in the Inner Mongolia region. Further deployment of wind resources must therefore be concurrent with the development of the transmission and distribution system, particularly the deployment of low-loss, high-voltage transmission lines (750 kV and higher).

Compared to Europe, the deployment of offshore wind turbines in the United States and China has been somewhat slow. Nine projects are in various stages of development in U.S. state and federal waters, but in addition to technical risks and high costs, the projects have been slowed by social and regulatory challenges (DOE, 2008a; NAS/NAE/NRC, 2010a; Wiser et al., 2010). China is interested in offshore wind development but faces the additional hurdle of deploying wind turbines that are resilient to typhoons and other severe weather events, because their most abundant offshore wind resources are in coastal areas prone to typhoons. This is partially reflected in the standards being discussed in China for turbines suitable for extreme weather conditions (typhoons and cold/ice conditions).

In June 2010, 34 wind turbines in the Shanghai Donghai Daqiao wind farm were brought on-line in China's (and Asia's) first offshore wind project, totaling 102 MW of installed capacity. China will begin an offshore wind power concession program in late 2010, and there are plans for two additional offshore projects of 300 MW each and two more inter-tidal projects (at depths of less than 5 m of water) totaling 200 MW each (CWEA, 2010).

Key Technological Opportunities

Goals for improved turbine components include building taller towers and larger rotors, developing better power electronics, and reducing the weight of equipment at the top of the turbine and the cables coming down the tower. Improvements in rotor technology might be achieved with airfoil-shaped rotors instead of designs based on helicopter blades. Efforts have also focused on improving gearboxes by incorporating more rare-earth, permanent magnets in the generator design and investigating single-stage drives with low-speed generators and distributed drive trains with a rotor to power several parallel generators. To improve the tower design, some researchers are investigating the potential of self-erecting towers and on-site blade manufacturing.

For onshore facilities, once the prime high wind speed sites are developed, more attention is likely to turn to sites with lower wind speeds (NAS/NAE/NRC, 2010a). Efficiently harnessing energy at lower wind speeds will likely require taller towers and larger rotors made from lighter, stronger materials. Table 3-1, from the DOE (2008a) study, summarizes these and other incremental improvements currently under consideration.

Summary of Wind Power Technological Assessment

The United States leads the world in installed capacity, although deployment in China is expanding rapidly and outpaced U.S. deployment in 2009. Although technological breakthroughs are unlikely in the wind energy sector in the short term (out to 2020), incremental improvements are certain to occur. Likely breakthroughs in wind technology are more for offshore wind turbines that must be resistant to the harsh marine environment and extreme weather events. In 2010, a U.S. company (American Superconductor Corporation) and Chinese company (Dongfang) established a partnership to jointly design and develop a next-generation 5 MW offshore wind turbine.

Ongoing deployment, increased manufacturing capability, and incremental improvements in component technologies are likely to drive down the cost of wind turbines in both the United States and China. It is significant to note that no enhancing technologies in particular are necessary for wind to provide approximately 20 percent of U.S. electricity generation (DOE, 2008a). However, concurrent with the deployment of turbines, there will have to be an emphasis on

TABLE 3-1 Potential Advances in Wind Energy Technology

		Performance and Cost Increments (Best/Expected/Least Percentages)	
Technical Area	Potential Advances	Annual Energy Production	Turbine Capital Cost
Advanced Tower Concepts	Taller towers in difficult locations New materials and/or processes Advanced structures/ foundations Self-erecting, initial, or for service	+11/+11/+11	+8/+12/+20
Advanced (Enlarged) Rotors	Advanced materials Improved structural-aero design Active controls Passive controls Higher tip speed/lower acoustics	+35/+25/+10	-6/-3/+3
Reduced Energy Losses and Improved Availability	Reduced blade soiling losses Damage-tolerant sensors Robust control systems Prognostic maintenance	+7/+5/0	0/0/0
Drivetrain (Gearboxes and Generators and Power Electronics)	Fewer gear stages or direct-drive Medium-/low-speed generators Distributed gearbox topologies Permanent-magnet generators Medium-voltage equipment Advanced gear tooth profiles New circuit topologies New semiconductor devices New materials (gallium arsenide [GaAs], SiC)	+8/+4/0	-11/-6/+1
Manufacturing and Learning Curve	Sustained, incremental design and process improvements Large-scale manufacturing Reduced design loads	0/0/0	-27/-13/-3
Totals		**+61/+45/+21**	**-36/-10/+21**

Source: DOE, 2008a.

the implementation of distribution infrastructure to connect areas of generation with urban centers.

SOLAR PHOTOVOLTAIC POWER

The efficiency of PV technologies has steadily improved in the past 30 years. Today's commercial modules typically offer 10 to 15 percent conversion efficiency, with China's Suntech reaching a record 15.6 percent efficiency in 2009, a record eclipsed later that year by a Kyocera module with a reported 17.3 percent efficiency (Green et al., 2010). Research laboratories are producing cells that, although more expensive, achieve efficiencies upwards of 50 percent greater than their commercial counterparts. Figure 3-2 shows the historical progress of the highest reported solar cell efficiencies. It is worth noting that conversion efficiency is not necessarily the primary way to reduce overall costs. In a study of PV cost reductions from 1980-2001, efficiency gains accounted for approximately 30 percent of overall reductions, while manufacturing plant size accounted for more than 40 percent of reductions and other factors, such as lower-cost input materials, had substantial impacts as well (Nemet, 2006).

Status of Photovoltaic Technology

A solar cell generally consists of two layers of materials. The first layer absorbs light, and the second controls the direction of the current flowing through an external circuit. Using different materials or combinations of materials in the first layer of the solar cell produces different levels of conversion efficiency.

Over 80 percent of commercial solar cells are flat-plate PV fabricated with crystalline silicon wafer technology (SolarBuzz, 2010). The typical efficiency of these cells is 12 to 18 percent. Further development will be necessary to increase efficiency and lower production costs (DOE, 2007c). The other main type of PV technology relies on thin films. Typically 1 μm to 20 μm in thickness, thin film cells require only 1 to 10 percent of the expensive semiconductor material used in flat-plate PV and can be fabricated using a relatively low-cost deposition process. These advantages may compensate for their generally lower conversion efficiencies (upwards of 10 percent) (DOE, 2007b). Cadmium Telluride (CdTe) cells represent the largest share of the commercial thin film market, but thin films can also be made with amorphous silicon or "CIGS cells" so-called because they use Copper, Indium, Gallium, and Selenide as their semiconductor metals.

Some of the most efficient solar cells are multi-junction CIGS cells. A triple-junction structure has been shown to have a conversion efficiency of 41 percent at up to 454 suns intensity (Dimroth et al., 2009; Guter et al., 2009). However, cells of this kind are expensive and therefore are not advantageous to use in a panel configuration. Concentrated photovoltaic (CPV) systems can use these more expensive cells because the area required to produce a given amount of power in

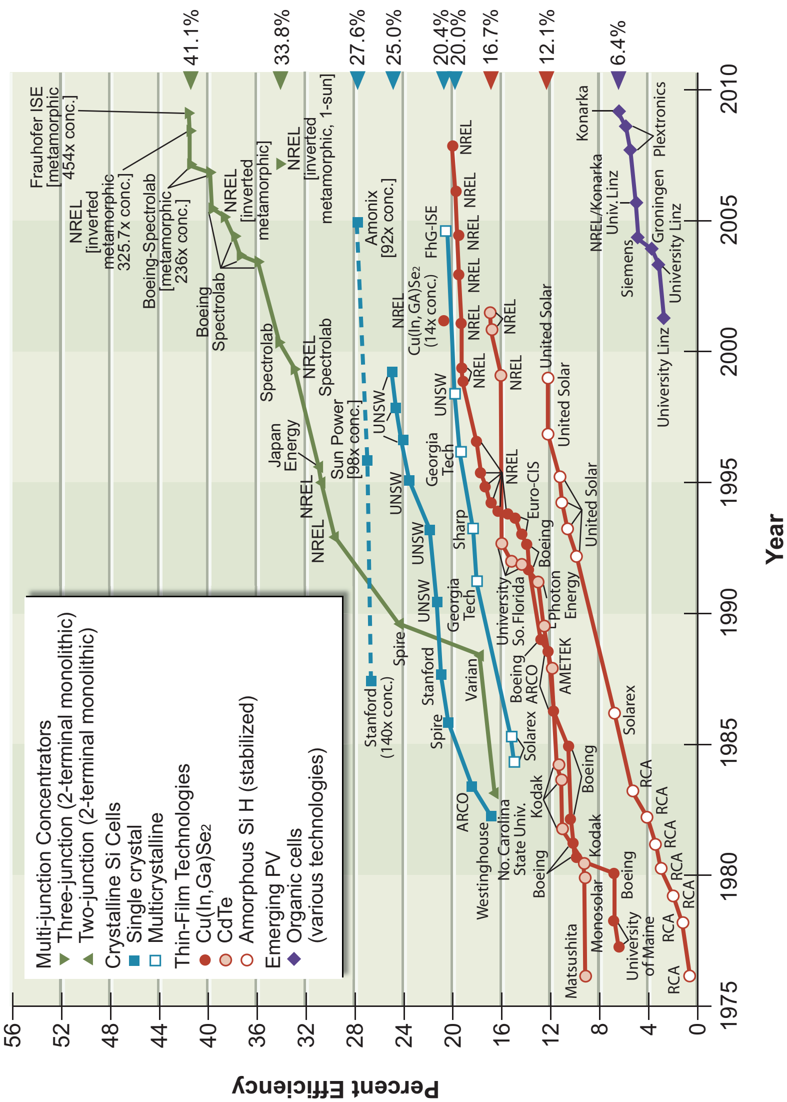


FIGURE 3-2 Historical progress of PV cell efficiency. Source: NREL.

these systems is reduced by the concentration ratio (typically between 10 and 50). High-concentration PV (HCPV) systems use two-axis trackers with concentration ratios of 200 to 500. Current research is focusing on enhancing the efficiency of cells using II-VI alloys (Carmody et al., 2010; Du et al., 2010).

Figure 3-3 shows the evolution of PV production from 2000 to 2009 in different parts of the world. It is evident that China has rapidly surpassed PV manufacturing in the United States and is now the largest producer of PV cells in the world by a large margin, although this progress in PV manufacturing has been based, in part, on cooperation with companies and research personnel from outside of China. By the end of 2007, the stock exchanges in New York, London, Hong Kong, Singapore, and China listed about 20 Chinese-owned companies. More factories are under construction, and production capability could reach 8,000 MW by 2010. In attempting to reach this goal, China has increased its silicon production capability from 400 tons(t)/year in 2005 to 4,310 t/year in 2007, and it could reach 44,700 t/year by the end of 2010 (Yan, 2009).

Deployment of PV has not always been proportional to production rates. As shown in Figure 3-4, China's PV production in 2009 was greater than 10 times its installed capacity, while U.S. PV production was roughly half of installed capacity. China's trade surplus of PV cells suggests that having access to the international export market is an important factor in its renewable energy strategy. In order to establish a domestic market for PV deployment, China established a PV power concession program in 2010, including 13 PV power station projects ranging in size from 20-30 MW each and 280 MW in total, all in the northwest

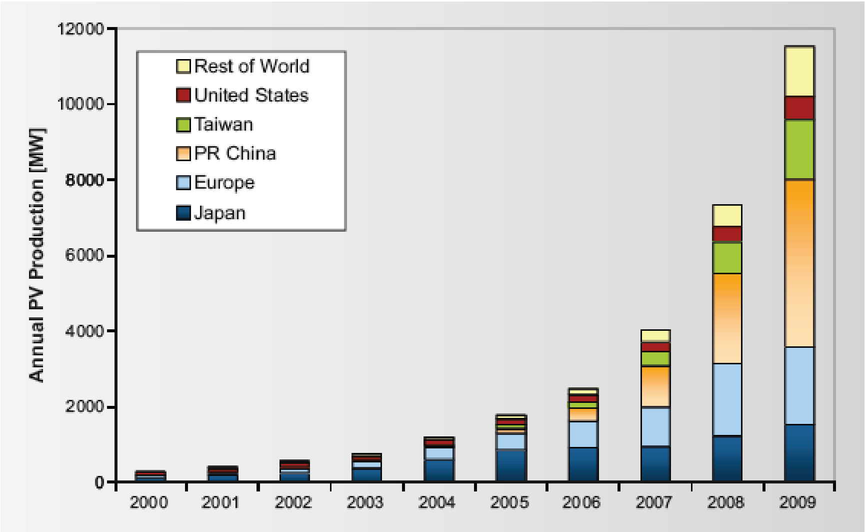


FIGURE 3-3 Production of photovoltaics in the world, 2000–2009. Source: JRC, 2010.

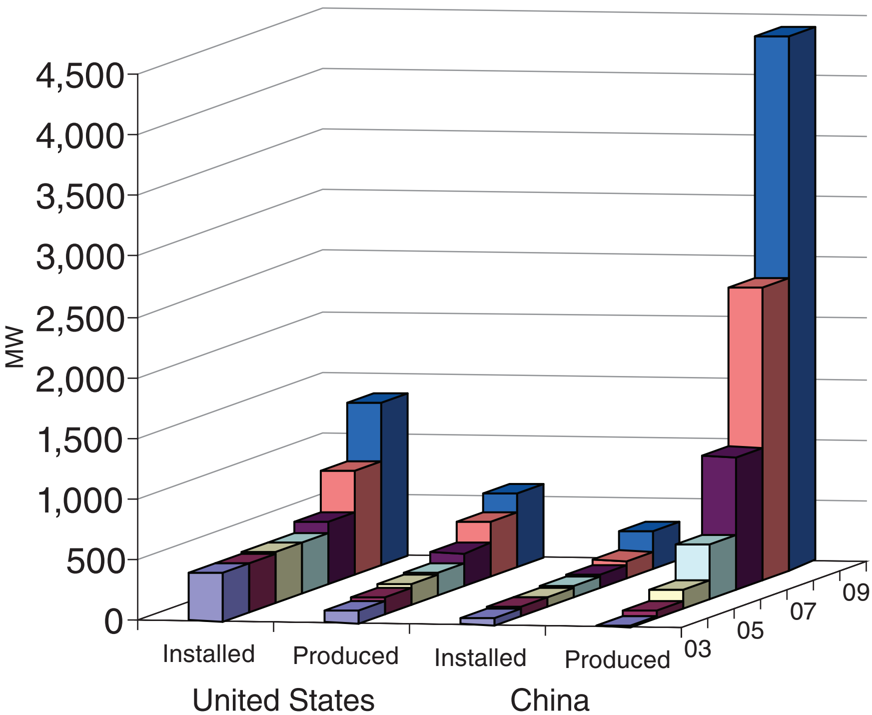


FIGURE 3-4 Annual production of PV modules and cumulative installed capacity of PV in the United States and China, 2003–2009. Sources: EIA, 2010d; JRC, 2009, 2010.

part of the country. Developers are selected by a bidding process. Preliminary prices were low—approximately US $1.4/W for multi-crystalline modules and US $0.15/kWh for electricity generated.

Potential Technology Development

Achieving ultra-low costs in solar technology will likely require a combination of learning-curve-based cost reductions and scaling opportunities, as well as the development of future generations of PV materials and systems to increase efficiency. Thin-film technologies have the potential to bring down costs substantially over current wafer-based crystalline silicon methods because thin-film processes require less material (due to direct band gaps), fewer processing steps, and simpler manufacturing technology for large-area modules. Thin-film technologies are also high throughput and have a continuous production rate, and some technologies require lower temperatures for processing (and thus lower energy inputs). Another advantage thin-film technologies (especially amorphous silicon) typically display over crystalline silicon panels is a higher energy yield in hazy climates. This is an important factor in coastal areas where PV might be deployed (see Chapter 2 on resource base).

Even lower costs may be possible with plastic organic solar cells, dye-sensitized solar cells, nanotechnology-based solar cells, and other new PV technologies. Organic cells, for example, which can be about 10 times thinner than thin-film solar cells, present opportunities for lower costs because they have low-cost constituent elements, require less material, include materials with high-conversion efficiency, and can be manufactured with high-volume production techniques.

It is interesting to note that reductions in deployment costs could also result from streamlining deployment by capturing efficiencies related to large-scale deployment or from producing lower cost structures that support solar panels (commonly referred to as the balance-of-system and sometimes comprising 50 percent of total costs). Opportunities for cost reductions could also result from a better understanding of the impact of distributed PVs on distribution systems and electricity demand. The performance and operation of existing installed systems could be monitored to provide data for future optimization as the industry expands.

Summary of Potential for Solar Photovoltaic Technology

The level of development of different solar PV technologies varies. Silicon (Si) flat-plate PV technologies are mature and are widely deployed today. China has developed a manufacturing capacity to produce these types of solar cells relatively cheaply compared to the United States. Continued reductions in cell production costs and increases in conversion efficiency and module reliability could make Si PV cells even more attractive to customers. Thin-film technologies, which have great potential to reduce costs, are in a relatively mature stage of development in the United States, although further research and testing are required (NAS/NAE/NRC, 2010a). Other competing technologies, such as dye-sensitized PV and nanoparticle PV technologies are at an earlier stage of development and will require further technological improvements before they become commercial.

CONCENTRATING SOLAR POWER SYSTEMS

Concentrating solar power (CSP) systems turn solar energy into high-temperature heat, which is then used to produce electricity or drive chemical reactions (syngas or hydrogen). CSP technologies are categorized by three types, namely parabolic troughs, power towers (also known as central receiver concentrators), and dish-Stirling engine systems (also known as parabolic dishes). The differences between these technologies are in the optical system and the receiver that absorbs the concentrated solar radiation. These differences define the potential plant size, from the smallest (dish-Stirling concentrator) to the largest (parabolic troughs and power towers).

Status of Technology

The parabolic trough combined with a conventional Rankine cycle uses concave mirrors to focus direct-beam radiation on a linear receiver containing synthetic oil. The heated oil is used to superheat steam, which in turn drives a conventional turbine/generator to produce electricity. These plants can incorporate solar energy storage capabilities (e.g., concrete, molten salt, or thermocline storage) that can extend power generation capabilities for several hours. Solar-to-electric conversion efficiency at these plants typically ranges from 12 to 25 percent, with capacity factors of 26 to 28 percent (not including storage) (NAS/NAE/NRC, 2010a).

Power towers and dish-Stirling technology are similar in that they employ two-axis tracking. Power towers consist of many two-axis mirrors (heliostats) that track the sun and direct the incoming beam radiation to a receiver located at the top of a tower. Dish-Stirling technology uses a two-axis parabolic dish to concentrate solar energy into a cavity receiver where it is absorbed and transferred to a Stirling heat engine/generator (Mancini et al., 2003). There is no large-scale solar dish-Stirling plant at this time to provide operational experience, but annual solar-to-electric efficiencies are expected to be 22 to 25 percent (NAS/NAE/NRC, 2010a).

CSP technologies are now commercially available, with trough systems dominating the U.S. market. Some of the more recent plants for CSP in the United States include the 64 MW Nevada One Plant (developed by Solargenix and operational since 2007), the 1 MW Saguaro Plant in Arizona, and the 5 MW Sierra Power Tower in Lancaster, California. The CSP industry estimated in 2006 that it could provide approximately 13.4 GW of additional peak capacity by 2015, if the market could absorb that much capacity (WGA, 2006a). This was not a projection of demand; it was meant to signal that industry production capacity could meet the needs of a much larger potential market. Signed purchase agreements for CSP were about 4 GW in the United States as of February 2009, but there is probably twice that capacity in planned projects (Mancini, 2009). Some of these large projects—the 250 MW Solana Project in Arizona and the 440 MW power tower project in Ivanpah, California—benefitted from federal loan guarantees in 2010, which allowed them to proceed with construction. Data on CSP projects around the world, including projects that are under development, under construction, and already operational, are being compiled by the International Energy Agency and made available through its SolarPACES program (see solarpaces.org).

CSP in China is still under development. A national program to build a 1 MW experimental solar tower was approved in 2006 and is scheduled for operation in 2010, and solar thermal power has been included in the national renewable development program. Beyond the 1 MW tower, there is also a 100 MW station planned for 2015 and a 300 MW plant for 2020, and by some estimates China could increase its installed capacity to 100 GW by 2025 (Wang, 2009). Overall, the United States has relatively more experience with this type of technology and therefore could aid in ramping up production of CSP in China.

Key Technology Opportunities

In the short term, incremental improvements in design are likely to drive down costs and reduce uncertainties in performance predictions. Costs could be driven down further as more systems are installed and manufacturers take advantage of economies of scale. In terms of specific components, cost reductions are anticipated for increasing the reflector size of the concentrator (heliostat or dish), low-cost structures, better optics, and high-accuracy tracking. Improvements in receiver technology are also expected.

A key opportunity for improvement is in storage technologies, such as concrete, graphite, phase-change materials, molten salt, and thermocline storage. Molten-salt tanks can provide storage for a number of hours, but improved pumps and valves are likely to lengthen storage time. Molten-salt receivers, which provide storage at about 550°C to power a turbine, can extend storage time to 12 hours. There are no molten-salt receiver plants in commercial operation today, although the Solar I project in California (a 10 MW pilot plant built in 1981) used molten-salt storage in an updated configuration from 1995 to 1999. Several are planned, however, as part of projects under development in Spain.

BIOPOWER

Status of Technology

The vast majority of biomass-fired power plants operate on a steam-Rankine cycle in which the biomass feedstock is directly combusted to create high-pressure steam that drives an electric generator. With a gaseous fuel, a more efficient turbine engine (operating on the gas-Brayton cycle) can be used, similar to natural gas-fired power plants. A gas-reciprocating engine is also frequently used for small-scale (<5 MW) installations where it is more cost-effective than a turbine engine.

A key difference between dedicated biomass power plants and plants powered by fossil fuels is the size of the power plant. Wood-based biomass power plants (accounting for about 80 percent of biomass electricity) are usually smaller than 50 MW (average size of 20 MW), as compared to the 100 to 1,500 MW range of conventional coal-fired power plants (NAS/NAE/NRC, 2010a). Landfill gas (LFG) power plants have capacities in the 0.5 to 5 MW range, whereas those operating on natural gas are on average about 100 times larger, in the 50 to 500 MW range.

The small size of biomass plants is partly the result of the high cost of shipping low-energy-content biomass. Typical wood has a moisture content of about 20 wt-percentage and an energy content, even after drying, of about 9,780 Btu/lb (18.6 MJ/kg), as compared to about 14,000 Btu/lb (25 MJ/kg) for coal (NAS/NAE/NRC, 2010a). It is worth noting that the heat content for much of the coal used in the United States and China is lower than this unit value (and closer to the unit value for dried biomass), thus making biomass a suitable candidate for co-firing in many locations. As a consequence of their small size, dedicated biomass power plants are typically less efficient than their fossil-fuel-fired counterparts (in the low 20 percent range as opposed to high 30 percent range for coal), because the cost of implementing high- efficiency technologies is not economically justified at the small scale.

LFG power plants can be located directly at the landfill site, which eliminates shipping costs, and the size of the plant is determined by the rate of LFG production, which, in turn, is determined by the overall size of the landfill. Co-location and size matching are also characteristic of biomass power plants operated on black liquor, the lignin-rich by-product of fiber extraction from wood.

Co-fired power plants for which coal is the primary fuel source and solid biomass is the secondary source are relatively large, and therefore enjoy higher efficiencies. With optimal design, co-fired plants can operate over a range of coal-to-biomass ratios, allowing operators the flexibility to adjust the fuel mix based on the lowest-cost inputs (NAS/NAE/NRC, 2010a). Furthermore, co-firing tends to produce lower SO_x and particulate emissions and have less ash residue than coal-fired power plants, although NO_x emissions can be higher due to the presence of nitrogen in the biomass. Emissions reductions are an important driver for biomass co-firing, and this extends to GHG reductions as well. The emissions profile from co-fired plants depends largely on the specific characteristics of the biomass. In addition, the impact of biomass co-firing on the effectiveness of selective catalytic-reduction technologies is an important issue that must be resolved.

Although municipal solid waste (MSW) contains significant amounts of energy, it is not universally recognized as a renewable fuel source because a large fraction of the carbon in waste products derives from petroleum resources, and storage of that carbon in landfill sites can be considered "carbon sequestration" (NAS/NAE/NRC, 2010a). As a consequence, several U.S. states exclude MSW from their renewable portfolio standards. Nevertheless, the process of MSW electricity production is comparable to a typical biomass power plant, often relying on direct combustion to create steam that subsequently powers a generator.

LFG, the gaseous product that results from the anaerobic decomposition of solid waste, contains about 50 percent CH_4, 50 percent CO_2, and trace components of other organic gases (NAS/NAE/NRC, 2010a). In contrast to solid waste, LFG is not "sequestered" in the landfill, and the methane that is naturally released is about 20 times as potent as CO_2 as a greenhouse gas.

In the United States, biopower use increased substantially after the Public Utilities Regulatory Policy Act (PURPA) of 1978 guaranteed small electricity producers (< 80 MW) would purchase surplus electricity at a price equal to the utilities' avoided cost of producing electricity. The passage of PURPA, along with various state incentives, resulted in a three-fold increase in grid-connected biopower generating capacity from 1980 to 1990. The certainty of these contracts propelled industry investment to $15 billion dollars and the creation of 66,000 jobs (Bain et al., 2003). However, by the early 1990s, the biopower industry began to stall for many reasons, including increased costs for feedstock because of inadequate infrastructure and the absence of explicit accounting for the environmental benefits in utility regulation or market costing and much higher new generation costs compared to natural gas combined cycle. In addition, avoided-cost contracts signed under PURPA (contracts that required utilities to purchase renewable power from independent producers at the cost of what the utilities would have spent to build new fossil plants) were expiring, and utilities were unsuccessful in petitioning to buy back the contracts.

In recent years, biomass has accounted for about 10 percent of renewable electricity capacity in the United States, second only to hydroelectric power (see Table 1-1). In 2007, the generation capacity of 10.72 GW came from about 7 GW of forest product residues and agricultural industries, and about 3.75 GW from MSW residue.

The use of LFG for electricity production can be expected to increase in the near future, because it not only yields electricity in settings close to demand points (i.e., urban areas), but also reduces the release of methane, an extremely potent greenhouse gas (NAS/NAE/NRC, 2010a). As of July 2010, approximately 518 LFG energy projects were operational in the United States. These projects generate approximately 12 billion kWh of electricity per year (and deliver 285 million cubic feet per day of LFG to direct-use applications), amounting to just under 20 percent of biomass electricity generation. The Environmental Protection Administration (EPA) has identified approximately 520 candidate landfills with a total annual electricity generating potential of 10 billion kWh (EPA, 2010).

China had 3.14 GW of biomass power generation capacity at the end of 2008, including: 1.7 GW bagasse, 603 MW waste combustion, 592 MW non-waste direct combustion, 173 MW biogas combustion, 50 MW rice mill (small-scale off-grid systems), and 18 MW biomass gasification. The costs for power generated at these plants is typically not competitive with coal-fired power, but it is worth noting that between 30 and 50 percent of the costs of biomass power generation are in the transportation and storage of biomass feedstocks. China's first direct combustion biomass power plant was commissioned in late 2006, and growth in this sector has been rapid. From 2004 to 2007, the Chinese government approved approximately 87 biomass power plants with a combined capacity of 2,200 MW, and in 2008 over 600 MW of capacity was installed.

Biomass gasification for power generation is a technology suitable for China—the Chinese Academy of Sciences developed a circulating fluidized bed gasification facility that is currently operational. This initial project, which uses a gas engine-driven generator, has an installed capacity of 5.5 MW and was completed in 2006. Four additional projects are complete or nearing completion and will total 18 MW of installed capacity. By contrast, electricity generation from biogas has developed rapidly in China since 2005. Of the 173 MW of installed capacity noted above, 79 MW make use of waste streams from light industries (e.g., breweries and distilleries, paper mills), 45 MW use MSW and LFG, and 31 MW use biogas from livestock.

As mentioned above, biomass is also used for co-generation in thermal power plants, and for this reason it accounted for almost 50 percent of the U.S. renewable *energy* supply in 2005, the largest single source of renewable energy (EIA, 2007b). Co-generation has been slow to develop in China, primarily because of problems related to biomass supply measurement and regulation, which has impeded any attempts at subsidies. Two pilot projects currently exist, firing 20 percent biomass, with plans to increase the ratio to 80 percent.

Potential Technology Development

In the short term, technology improvements are likely to relate to biomass power plant design to ensure fuel flexibility, particularly in co-fired plants (NAS/NAE/NRC, 2010a). This will require fuel-feed and emissions-control systems that can be adapted to a range of biomass feedstocks. Fuel-mixing strategies include premixing coal and biomass in a single feed system or providing separate coal and biomass inlets.

Technological developments in the medium term are likely to focus on a pretreatment step that converts biomass to a gaseous or liquid fuel, which is more suitable than solids for power generation. Solid fuels cannot be directly used in gas turbine engines, which have relatively high operating efficiencies; thus the fuel must be converted to a gas or liquid using a method generically called gasification. Lower cost, high-temperature materials for both steam engines and gas turbines are also potential areas for development (NAS/NAE/NRC, 2010a).

Potential long-term breakthroughs in biopower could come from direct conversion to clean fuels (NAS/NAE/NRC, 2010a). Essentially, the high-temperature catalytic steps of gasification or pyrolysis would be replaced with ambient-temperature steps using bacteria, and the resulting biogas would be fed into an internal combustion engine to produce electricity or used directly for heating and cooking.

GEOTHERMAL POWER

Existing geothermal facilities typically produce electricity with hydrothermal resources (hot water or steam) accessible within 3 km of the Earth's surface. These facilities operate 90 to 98 percent of the time and can therefore provide base load electricity. Although the use of this technology is expected to increase modestly, a more aggressive deployment scenario may be possible if heat stored in deeper layers of Earth's crust can be extracted. Research continues on this early stage technology, commonly referred to as enhanced geothermal systems (EGS) or "hot dry rock." One approach for EGS is hydraulic stimulation. As one example, the Iceland Deep Drilling project plans to access a high-temperature (400 to 650 °C) hydrothermal resource 4 to 5 km deep in the Krafla, Hengill, and Reykjanes geothermal fields (Stefansson et al., 2008).

Status of Technology

Geothermal steam plants either use steam directly from the source to directly drive a turbine or use flash plants to produce steam by depressurizing hot water from the source (175 to 300°C). Binary-cycle plants convert geothermal waters (normally from 90 to 175°C) to electricity by routing the hot water through a closed-loop heat exchanger, where a low-boiling-point hydrocarbon, such as isobutane or isopentane, is evaporated to drive a Rankine power cycle. Lower temperature reservoirs are far more common than steam reservoirs, so binary plants are more prevalent than steam plants. Also, binary plants can be located in areas with limited water resources. In addition, the cycle is self-contained and, therefore, produces no emissions other than water vapor.

If successfully exploited, EGS could recover the vast thermal energy stored at depths of 3 to 10 km. However, there are still technical and economic challenges to the widespread implementation of EGS because of the required drilling depths, the low permeability, and the need for reservoir enhancement.

The world's overall installed geothermal power capacity is 10,500 MW, which generates about 70,000 GWh of electricity worldwide. The United States has the largest installed geothermal energy capacity and represents nearly one-third of global geothermal power generation capacity. The United States also has the largest installed capacity.

Increases in conventional hydrothermal electricity are expected, primarily in the western United States. The Western Governors Association assessed the potential for new development of about 140 known, accessible geothermal sites and concluded that the western states share an untapped capacity of 5.6 GW that could be developed within 10 years (WGA, 2006b). The U.S. Geothermal Energy Association (GEA, 2009) has identified more than 100 geothermal projects under development in 13 states that represent more than a doubling of conventional geothermal capacity by 2020. No additional technological developments are necessary to tap into these resources, although advances in exploration and resource assessment could have an impact on the development of new plants (NAS/NAE/NRC, 2010a).

Although China is a world leader in use of low-temperature geothermal energy resources (for heating and cooling), it has limited experience with geothermal power generation. China's largest geothermal power plant, in Yangbajing, Tibet, has eight double-flash units and a total capacity of 25.2 MW (Wang and Zhang, 2008). Another plant with capacity of 48.8 MW is under construction in Yunnan province. Government targets for geothermal power are modest—100 MW capacity by 2010 and 500–1,000 MW by 2050, although these estimates do not reflect the potential of technological advances in EGS.

Key Technology Opportunities

The primary technical challenges of EGS are accurate resource assessment and understanding how to reliably achieve sufficient connectivity in fractured rock to yield commercially feasible, sustainable production rates. Other issues to be resolved include potential risks of inducing seismicity, land subsidence, and water requirements. Modeling analysis shows a large capability for EGS wells to yield significant heat (MIT, 2006). However, given the depths, experience and success in developing EGS wells at sufficient flow rates in the field have been limited.

Technology is not a major barrier to the development of conventional hydrothermal resources, but improvements in drilling and power conversion technologies could lead to cost reductions and more reliable systems. There are many ways in which EGS technology can by improved and better understood. Based on EIA projections of electricity prices, successful implementation of EGS will require sustained production of 80 kg per second (equivalent to a productive hydrothermal reservoir) at a temperature of 250 °C and generation of about 5 MW per well (DOE, 2007a).

There might also be challenges to drilling, because geothermal resources are typically found in crystalline rocks, as opposed to the much softer sedimentary rocks targeted for oil and natural gas exploration. There is also significant uncertainty in the flow rate and heat flux that can be achieved in an enhanced reservoir.

HYDROPOWER

Conventional hydropower is one of the least expensive sources of electricity. Converting energy stored in flowing water to electricity can be done with conventional hydroelectric technologies, as well as emerging technologies that can extract energy from ocean tidal currents, wave energy, and thermal gradients. Currently, the largest source of renewable electricity is energy captured from freshwater rivers (known as conventional hydroelectricity or simply hydropower). Hydropower is an important component of electricity generation in both the United States and China. China's Three Gorges Dam, the world's largest hydropower plant, has a capacity of 21.5 GW of power. Another generating station planned for 2011 will bring the Three Gorges Dam capacity to 25.6 GW. As of 2008, China's hydropower capacity was approximately 172 GW, corresponding to 17 percent of its overall electricity production. Hydropower capacity in the

United States is nearly 80 GW, representing approximately 6 percent of overall electricity production.

Status of Technology

Most hydropower projects require a dam to back up and control the flow of water, a penstock to siphon water from the reservoir and direct it through a turbine, and a generator to convert the mechanical energy to electricity (NAS/NAE/NRC, 2010a). The amount of electricity produced is a function of (1) the capacity of the turbines and generators, (2) the volume of water passing through the turbines, and (3) the hydraulic head (the distance the water drops in the penstock). Categories of hydropower include large, conventional hydropower with a generating capacity of greater than 30 MW, low-head (<65 ft) hydropower with a generating capacity of less than 30 MW, and micro-hydropower with a generating capacity of less than 100 kW.

Although the potential for new dam construction in the United States may be limited, there are opportunities for "run-of-the-river" projects—diverting water from a river, using a flowline and penstock, and returning the water to the river downstream below the powerhouse (Table 3-2). There is also increasing interest in "conduit" hydro projects that use a flowline initially constructed for a non-hydroelectric purpose (such as irrigation) to create hydroelectric power. A small fraction (~3 percent) of the roughly 80,000 existing dams in the United States are presently used to generate electricity (NHA, 2010).

Submerged turbines are used to harness tidal, river, and ocean currents, but there is no single approach to converting the energy from waves into electricity. Approaches include floating and submerged designs that harness energy directly from the impacting wave, and designs that exploit the hydraulic gradient between the top and bottom of the wave to generate power (Minerals Management Service, 2006). The latter design concentrates waves and allows them to overtop into a reservoir, which generates electricity as the water in the reservoir drains out through a turbine.

Ocean thermal energy conversion (OTEC) converts solar radiation to electric power by using the ocean's natural thermal gradient to drive a power-producing cycle. OTEC pilot plants have been in various stages of demonstration since the

TABLE 3-2 Permit Activity for Hydrokinetic Sources

	Number of Permits	Capacity in MW
Tidal	16	2,253.846
Wave	11	469.70
Inland	114	6,864.225
TOTAL	**141**	**9587.77**

Source: FERC, 2010.

1970s, and future projects may rely on improvements in offshore platforms to increase the scale of the plants. Power systems could also theoretically exploit the energy of the osmotic pressure difference between freshwater and salt water (i.e., the salinity-gradient), but designs have not yet moved beyond the conceptual stage. Although these unconventional sources of hydropower have substantive amounts of energy, significant technological and cost issues must be addressed before they can significantly contribute to electricity generation (NAS/NAE/NRC, 2010a).

Key Technology Opportunities

Many of the prime sites for large-scale conventional hydropower in the United States have already been exploited, and many of the opportunities for improvement involve mitigating impacts on aquatic wildlife, and in some cases, boosting efficiency at existing sites (O'Donnell et al., 2009). Although no breakthrough technologies are expected, a number of technological improvements for non-conventional hydropower are likely to result from learning opportunities from the implementation of large-scale demonstration projects in the next 10 to 25 years. For example, four 250 kW floating buoys recently placed in Makah Bay, Washington, will be connected to the electricity grid by a 3.7-mile-long submarine cable (Miles, 2008).

Summary of Hydropower Potential

In the United States, the public is increasingly in favor of returning river systems to free-running conditions. Although this is not likely to lead to the removal of major generating facilities, it could impede plans for substantial additions to hydropower stations. In China, despite the potential for several hundred GW of additional hydropower capacity, there are similar concerns about the impacts of large-scale projects. In addition, there are great technological uncertainties about the future of new current, wave, and tidal generators. Demonstrations of marine and hydrokinetic technologies are under way, some of which have been connected to the grid, but no uniform designs have been developed, and no one has long-term experience with these technologies.

MODERNIZING THE ELECTRICITY GRID

Modernizing the electricity grid will make it easier to integrate variable-output renewable sources into the overall power supply. Grid integration will also have other advantages, such as improving security and power quality, creating a capacity for self-healing, and making possible operation at a higher load factor with less risk of thermal overload. In addition, a modernized grid will create a dynamic, interactive infrastructure that will provide real-time power and information exchange, and, therefore, will greatly improve demand management. The two main aspects of grid integration, namely storage technologies and so-called "intelligent" technologies, are described in more detail below.

Energy Storage

Energy storage is a rapidly changing space in which new technologies are moving into the commercial arena. Storage technologies are valuable to electrical power systems regardless of the generation resource, but they provide specific attributes that are especially important for systems with large shares of wind and solar. We include a brief overview of potential storage functionality, but do not fully evaluate its uses or its latest technical developments. Fuel cells and hydrogen technologies are not discussed in this section, although fuel cells are commercially available and are capable of catalyzing renewable fuels; hydrogen technologies, although not commercially available, have generated considerable interest as a method of energy storage, particularly as related to fuel cells.

Because large penetrations of renewable electricity from wind and solar (beyond 20 percent) will potentially exacerbate the challenges of load management, developing storage technology can alleviate these challenges. Multiple-hour MW-scale storage can also be used to "shift" the availability of power from solar and wind farms to be better aligned with demand—this is particularly useful for large wind farms that are most productive in late evening hours, when demand is lowest.

Storage is a valuable component of any power system and can provide numerous benefits. Benefits of energy storage include such items as avoided upgrades to transmission and distribution infrastructure, frequency regulation, improved power quality, and avoided GHG emissions (e.g., eliminating the need for coal- or gas-fired backup). The need for storage, or the cost of intermittency, can vary widely based upon a particular region's pre-existing generation stock, demand/pricing policies, and the degree of fit between renewable generation and load patterns. It will not be necessary to "back up" or augment every variable-output generation source, nor will it be the only option available to manage intermittency.

One way to evaluate energy storage is by a flexibility supply curve. Many sources of flexibility are available in different amounts at different prices, and supply curves differ by region, based on many factors. Typically, the most readily available source of flexibility is competitive wholesale markets—fast markets, slow markets, and price-responsive load markets, for both energy and ancillary services. In areas with no available markets, flexible generation, most often in the form of gas turbine capacity or hydro capacity, is used. The most economical sources of flexibility are generally tried first, and at today's prices, new energy storage is at the end of the flexibility supply curve.

Storage technologies are characterized in terms of discharge duration vs. power (Figure 3-5) and are typically used for one of three functions: frequency

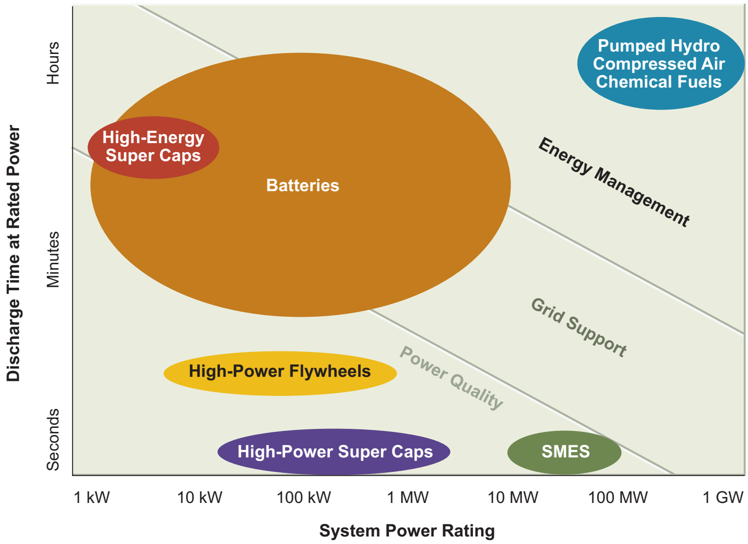


FIGURE 3-5 Capabilities of a variety of storage technologies. SMES = superconducting magnetic energy storage. Source: NAS/NAE/NRC, 2010a.

regulation, stabilization, or load-shifting. Technologies that can discharge energy rapidly are useful in frequency regulation. These technologies include super capacitors (not yet commercial) and high-power flywheels (in commercial use for frequency regulation in the New York and New England control areas of the United States). High-power approaches for multiple-hour energy storage include pumped hydropower, compressed air, some types of batteries, and devices that convert electricity into chemical fuels, such as hydrogen.

Pumped Hydropower

Pumped hydropower storage involves using energy to pump water into a hydropower reservoir and then releasing the water through a turbine when electricity is needed. This is a mature, effective technology and the only significant type of electricity storage in the United States today that can buffer fluctuations in electricity demand and supply. There are currently 40 pumped hydropower storage projects in the United States and as of late 2009, an additional 23 projects had preliminary permits from the Federal Energy Regulatory Commission (FERC), representing 15 GW of capacity. Additionally there are 15 projects, representing another 16 GW of capacity, pending Preliminary Permits from FERC (Miller and Winters, 2009). In 2006, there were 19 pumped hydro stations in operation in China with a generating capacity of 9.27 GW. China plans to have 18 GW by 2010, 32 GW by 2015, and 50 GW by 2020. However, increases in pumped hydro energy storage in the United States could be limited because of the lack of environmentally acceptable sites and because pumped hydropower is a relatively low-energy-density storage solution.

Compressed Air Energy Storage

Compressed air energy storage (CAES) is a method of storing energy as compressed air, usually in underground, airtight caverns, but sometimes in depleted natural gas fields or above-ground storage tanks. CAES works by converting electricity into mechanical energy in the form of compressed air—when the air is released, it is heated (typically by combusting natural gas) and then used to spin a turbine to produce electricity.

In a *diabatic* storage process, air is cooled before it enters a cavern and, when electricity is needed, the air is expanded by external heating applied from a modified gas turbine. Because diabatic CAES power plants are in many ways similar to conventional natural gas power plants, the two existing systems in the United States have operated reliably since they were commissioned, and the technology is considered mature (NAS/NAE/NRC, 2010a). New approaches to diabatic CAES systems are directed toward microscale systems that store smaller volumes and capitalize on underground natural gas storage or depleted gas fields.

Adiabatic CAES systems do not require combustion fuels because they store not only the mechanical energy of compression, but also the thermal energy produced when the air is compressed. Electric power generation from an adiabatic CAES system uses the hot air to operate a turbine (in the absence of combustion), which, in turn, operates an electric generator. Although most of the components of these systems are known technologies (Figure 3-5), adiabatic systems have not yet been demonstrated.

Batteries

A battery generally consists of two reactive electrode materials separated by an electrolyte membrane that allows select ions to pass through it. The battery's ability to be recharged depends on the nature of the reaction at the electrodes. Rechargeable batteries can be composed of a variety of chemical systems—commercially available batteries include lithium-ion, lead-acid, nickel-cadmium, or sodium-sulfur. These compositions have varying efficiencies, ranging between 65 and 95 percent. Sodium-sulfur batteries have proven effective and reliable for charging and discharging over many hours and in megawatt scale, and have thus been candidates for grid-scale applications. Lead-acid batteries are used in China by the hundreds of thousands for distributed grid-connected systems and to support wind and PV power generation in remote areas.

Alternatives to conventional batteries are flow batteries and regenerative batteries. Flow batteries have inert electrodes that simply collect current. The overall reaction in these batteries occurs between two chemical solutions separated by an electrolyte membrane. The energy capacity is fixed by the storage volume of the reactant solution, rather than by the dimensions of the electrodes as in a conventional battery.

Regenerative batteries, another alternative, are complex systems involving pumps, valves, and corrosive fluids. This makes them difficult to use for portable applications, but they are useful for utility-scale storage especially because the energy storage and energy delivery components of the battery are clearly separated.

It is unclear whether fundamental breakthroughs will bring revolutionary advances in conventional or flow batteries. For example, the energy density stored in gasoline is still much greater than the energy density that can be stored in current lithium-ion or flow batteries. Both the United States and China are actively involved in research, development, and demonstration projects for these types of storage systems. Research in the United States is focused especially on developing batteries for the transportation sector, but there is a growing recognition that batteries for utility-scale electricity storage are also important.

Grid Intelligence (The Smart Grid)

Energy storage is only one technological solution to facilitating the integration of renewables into the electrical grid. Other technologies will be useful to ensure reliability and optimize available renewable energy resources. These technologies will include smart meters (meters that can turn appliances on and off and enable time-of-day pricing), power converters, conditioners, source- and load-control technologies, and improved software for forecasting and operations (Kroposki, 2007).

In general reinstrumenting the grid will increase the available grid information and allow a more realistic scheduling methodology that will in turn provide for better utilization of the existing grid components. These benefits will then cascade from the transmission, distribution, and generation down to the fine tuning of residential, commercial, and industrial loads. In the United States, electricity markets provide some of this information today, but their operation will be greatly enhanced by the information generated in the smart grid.

Although the modern grid is not thoroughly defined as yet, it is likely that it will include devices such as the following:

- Synchrophasors and other monitoring equipment will be installed to monitor grid status in many locations enabling the recognition of congestion at critical spots across the grid. This will let new, more sophisticated control algorithms to optimally dispatch transmission, generation, and demand resources to resolve congestion. Additionally, the momentum provided by these responsive resources will provide a more reliable grid capable of smoothing the output of an increasing number of volatile generation resources.

- Smart meters, currently being deployed in the United States, will relay information on pricing and/or grid conditions so that smart resources can respond.
- Controllers will be installed (many exist today) on many resources to enable them to alter their load profile based on smart meter output. Those may include small generators, motors, pumps, load shifting air conditioners, storage devices, variable speed pumps, and almost any other load that is capable of intermittent or variable operation.

Advanced Metering and Demand Response

Advanced metering (or smart meters) refers to electricity meters that (1) provide the consumer with detailed profiles of electricity consumption and (2) allow for more demand management. Smart meters could help shave peak load by allowing certain devices to cycle off in periods of high demand. Advanced meters would also provide consumers with pricing signals that reflect the real-time availability and cost of energy. This could be especially useful in systems with large wind loads in the evening—devices (e.g., dishwashers) could be programmed to operate only when sufficient wind power is available.

Demand response is a general approach to managing consumer consumption of electricity based on supply conditions and is frequently used by utilities to help reduce peak demand. However, demand response can also be used as an approach to smoothing the integration of variable-output technologies like wind and solar, by reducing load at times of low renewable generation and "dispatching" demand when a resource like wind is available (to reduce the need for curtailment).

Software/Modeling Support

New grid-operating tools will help in the reliable incorporation of renewable energy resources into the electricity grid. Operating models and system-impact algorithms could make the transient and intermittent energy from renewables more manageable. Specifically, software algorithms that can better predict fuel source availability, whether it is wind or solar, and modeling tools for predicting how the system will react both in steady state and dynamic conditions, could help operators adjust to higher penetrations of wind and solar in the generation portfolio. In addition, improved visualization techniques, new training methodologies, and advanced simulation tools could give operators a better understanding of grid behavior.

FINDINGS

In the near term (to 2020), wind, PV, CSP, conventional geothermal, solar thermal applications, conventional and low-head hydro, and some biopower technologies are technically ready for expanded and accelerated deployment. China has emphasized PV over CSP for planned large-scale power plants, even though CSP has been proven at utility scale (mostly in the United States). **CSP could be a suitable technology for large-scale solar energy bases, particularly if it is coupled with low water-use and storage technologies.** Wind turbines for onshore deployment have matured and now incorporate technology that addresses past concerns about turbine reliability. These new turbines are therefore ready for large-scale deployment. Continued developments for turbines will include designs for offshore applications that are resilient to storms and typhoons.

Other technologies, particularly hydrokinetic (ocean, wave, and tidal) technologies, look promising as locally available baseload generation options. However, they will require further development. Biomass production has the advantage of reliability, but concerns about land use, especially about replacing food production, must be addressed. Improvements in biomass yields and conversion technologies might lead to liquid fuels.

As both countries continue and accelerate the build out of renewable power generation facilities, it would be highly beneficial if a mechanism can be established to rapidly exchange information. Although learning and cost reductions have already been achieved from deployment in the United States, **the rapid growth of renewable energy projects in China is likely to expand learning opportunities.** China is now moving ahead of the United States in terms of offshore wind development and has plans to begin deploying next-generation 5 MW wind turbines. Readily available information on these developments could enhance technology evolution and make renewable technologies more accessible globally, especially in developing nations. Cooperation will require settling some potentially contentious issues, such as sharing intellectual property or protected business data, which will be important for continued improvement in renewable technologies.

Unlike fossil or nuclear energy, renewable energy resources must be located at the source of the energy flux they exploit. They are also inherently intermittent, which has complicated their integration into the transmission and distribution system. Issues related to power-system management will become increasingly important as renewable energy provides a larger share of total energy. Ensuring the viability and continued expansion of renewable energy will call for a contemporaneous overlaying of unified "intelligent" electronic controls and communication-system technologies throughout the power delivery infrastructure. Improvements in the grid could not only facilitate the integration of renewable electricity, but could also simultaneously improve system reliability, provide significant capacity and cost advantages, and reduce the need for backup power and storage.

Further deployment of renewables will be more likely as the cost of existing renewable technologies come down as a result of learning and scale opportunities. However, dominant penetration of renewable energy into the electricity system will require technologies that have yet to be developed, or that have yet to become available at sufficiently low cost. In addition, further deployment will eventually require large-scale, distributed, cost-effective energy storage, new methods of cost-effective, long-distance electricity transmission, and the management of large amounts of dynamic data.

To a large extent, major deployment of renewable power generation is constrained by location and intermittency issues. In addition, technologies to harness these resources are modular (allowing projects to easily be scaled up or down), and some resources are more amenable to distributed and off-grid applications. Given these conditions, it is clear to the committee that **China and the United States will need to transform power delivery systems to accommodate and integrate large amounts of variable-output renewable electric power.** Both the United States and China are making sizeable public investments (greater than $7 billion each for 2010) in next-generation grid technologies, with China spending nearly 10 times that amount ($70 billion from its economic recovery package) on new high-voltage transmission infrastructure. This presents a tremendous opportunity for China and the United States to learn from one another. **Specific issues that deserve attention are grid stability, load management, system flexibility including MW-scale multiple-hour storage, and compatibility with an electrified transportation infrastructure.**

In addition, joint efforts could include the analysis of distributed PV options at a regional level (e.g., metropolitan areas) for both countries. **A stronger focus on deploying distributed PV could encourage rapid reduction of balance of system cost and make the overall system more cost effective.** China is a world leader in integrating solar thermal technologies for direct use in buildings, and there are lessons from this experience that could transfer well to building-integrated PV. Regional analyses would help optimize PV to best meet peak demand and take advantage of existing electrical distribution infrastructure.

RECOMMENDATIONS

- China and the United States should cooperate on defining the needs and requirements to transform power delivery systems to accommodate and integrate large amounts of variable-output renewable electric power.
- China and the United States should cooperate in developing large-scale (>50 MW) physical energy storage systems. Both countries have experience with pumped hydro and are currently investigating options to create additional capacity, which could directly benefit large wind and solar farms. The United States could also work with China to develop and demonstrate a compressed air energy storage system (CAES) in China, which currently has no experience with CAES.
- China and the United States should share information on, and consider conducting a joint analysis of, experiences with the integration of variable-output renewables (e.g., wind and solar) to gain a better understanding of what has been learned about their impacts and to look into approaches by grid operators in both their countries, and elsewhere, to manage these impacts.

4

Environmental Impacts of Renewable Electricity Generation

Fossil-fuel dominated electricity generation in the United States and China has enormous environmental consequences. In 2007, 2.4 billion metric tons of carbon dioxide (CO_2) were emitted from electricity generation in the United States, about 40 percent of the country's energy-related greenhouse gas (GHG) emissions. In the same year, electricity generation in China produced just over 2 billion metric tons of CO_2, accounting for about one-third of its energy-related GHG emissions. Fossil-fuel combustion is also responsible for the emission of other pollutants, such as nitrogen oxide (NO_x) and sulfur dioxide (SO_2). The production of electricity also puts a strain on water and land resources. In 2000, thermal power plants accounted for nearly half of total withdrawals of water in the United States (USGS, 2005) and nearly 40 percent of water withdrawals for industrialized use in China. Overall, reducing environmental impacts is a major impetus for shifting from fossil fuels to renewable energy for electricity generation.

Developing renewable energy technologies that exploit the sun, the wind, and geothermal energy is critical to addressing concerns about climate change and some environmental issues. However, using renewable energy sources will not eliminate all environmental concerns. Although renewable energy sources produce relatively low levels of GHG emissions and conventional air pollution, manufacturing and transporting them will produce some emissions and pollutants. The production of some photovoltaic (PV) cells, for instance, generates toxic substances that may contaminate water resources. Renewable energy installations can also disrupt land use and wildlife habitat, and some technologies consume significant quantities of water.

To develop sound policies, policy makers must understand the relative environmental impacts of alternative energy sources, including how the impacts of renewable energy technologies compare to those of fossil-fuel technologies and to opportunities for improvements in energy efficiency. Understanding the potential environmental impacts of renewable energy technologies is also essential for identifying and pursuing designs, manufacturing methods, project siting, utitlity operations, and so on to mitigate or offset these effects.

Environmental impacts of energy sources are commonly assessed on two scales or levels of aggregation. The first scale is the regional or national scale, which is an attempt to characterize the average impact of a typical facility or installation for the purposes of broad comparisons and planning. Life cycle assessment (LCA), for example, is an attempt to account for the full suite of impacts associated with all stages of an energy project, from the extraction of raw materials to the decommissioning of a facility and the disposal of equipment. The second scale is on the local level, where site-specific impacts, such as effects on wildlife and local water supplies, can be assessed.

The first part of this chapter provides a review of published LCAs as a basis for comparing renewable and fossil-fuel technologies in terms of emissions and energy, land, and water requirements. Detailed LCAs for selected renewable energy technologies are provided in Appendixes B-D of this report. The second half of the chapter provides a discussion of local-scale impacts and permitting and regulatory requirements in the United States and China, with examples illustrating some of the environmental concerns raised by renewable energy projects. Localized effects will warrant more attention as renewable energy deployment accelerates, especially in places where large-scale installations are being considered. The last part of the chapter identifies opportunities for collaboration by the United States and China to advance renewable energy technology by minimizing harmful effects on human health and the environment.

FOSSIL FUEL VS. RENEWABLE ELECTRICITY GENERATION

An LCA estimates resource requirements, energy use, and environmental impacts of products or services at all life stages. The estimates may be derived from detailed, “bottom-up” analyses of mining, manufacturing, transport, construction, operations, and disposal processes or from “top-down” analyses based on national-scale economic input/output models. Overall, an LCA is useful for comparing impacts of different technologies and for identifying points in the life cycle where improvements can be made.

In this section, we present results from published LCA studies compiled by the National Academies Committee on Electricity from Renewable Resources: Status, Prospects, and Impediments (NAS/NAE/NRC, 2010a). These studies provide high-level comparisons of fossil- and renewable-fueled technologies in terms of net energy production, emissions of GHGs and conventional air pollutants, water use, and land use.

It is important to note that the LCA results presented here were not adjusted for differences in underlying assumptions. Indeed, for renewable energy technologies in particular, the results sometimes depend heavily on the strength and variability of the renewable resource at the assumed site of installation. In addition, newer versions of technologies may produce electricity more efficiently and use cleaner, more efficient manufacturing methods. Differences may also be attributable to differences in geographical location. The NRC committee's (NAS/NAE/NRC, 2010a) review focused on LCA studies from Europe and the United States, so generalizing the results to conditions in China should be done cautiously. Thus, these LCA results provide a *range* of estimates that have been published in the literature.

Life Cycle Uses of Energy

An LCA is commonly reported with a net energy ratio (NER), which is defined as the ratio of useful energy output to the grid to the fossil or nuclear energy consumed during the lifetime of the project. For renewable energy sources, NERs are expected to be greater than one, indicating a positive return over the fossil-fuel energy investment. For fossil-fuel and nuclear technologies, NERs are smaller than one and essentially represent the overall life cycle efficiency of the project. NERs are strongly influenced by a number of underlying assumptions, such as plant capacity and life expectancy. For electricity generation from wind and solar energy, the strength of the resource (which will affect the capacity factor of the installed technology) is also a critical assumption. For silicon PV specifically, the NER is highly dependent upon the thickness of the wafer and the efficiency of the cell/module produced.

The highest estimated NERs are generally for wind, followed by biopower and then solar PV (Figure 4-1). Hydropower is also expected to have high NERs, although the results shown in the graph, from a single study, are not as high as anticipated. By definition, NERs for fossil fuels are all less than one, with average estimates of 0.3, 0.4, and 0.3 for coal, natural gas, and nuclear power, respectively. An LCA for a 300 MW solar power tower in Hami, Xinjiang Autonomic Region of China, presented in Appendix B, estimated an NER of 12.4 (in that example referred to as the energy balance factor). Estimates of NERs for three different biomass combustion technologies in China (direct combustion, gasification, and co-firing) are shown in Appendix C. The LCA results for these technologies, which include energy required for biomass cultivation, result in NER estimates ranging from 1.3 for direct combustion to 4.6 for co-firing. Most of the fossil energy used in these cases is associated with energy crop cultivation. NERs would be significantly higher for waste biomass.

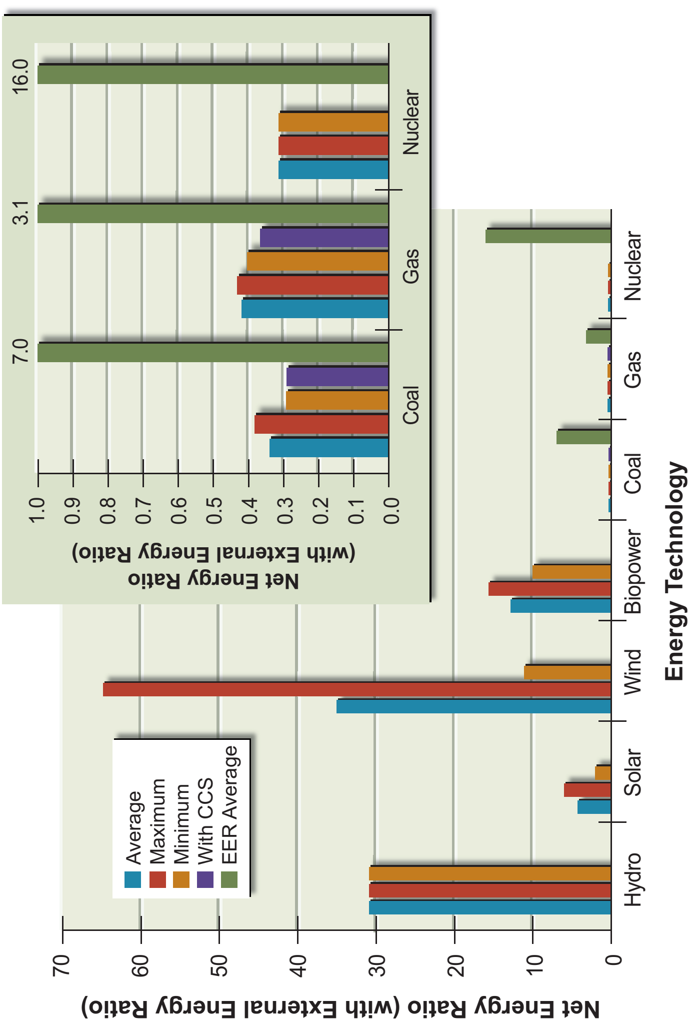


FIGURE 4-1 Net energy ratios for various renewable and non-renewable energy sources. Source: NAS/NAE/NRC, 2010a.

Greenhouse Gas Emissions

In 2007, the Intergovernmental Panel on Climate Change concluded that "warming of the climate system is unequivocal …" and that "most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic GHG concentrations." In light of these and other critical concerns about climate change, the United States and China are both taking significant steps to address emissions of CO_2 and other GHGs and are weighing further action, including new regulations.

Among the sectors that use fuel directly in the United States, electric power production is the largest source of CO_2 emissions, accounting for more than 2.3 billion metric tons in 2007, or more than 40 percent of total energy-related emissions. In China, the electric power sector is estimated to have emitted 3.1 billion metric tons of CO_2 in 2007, accounting for nearly half of that country's total.

Compared to fossil-fuel-based electricity generation, renewable energy technologies offer a major advantage in lower emissions of CO_2 and other GHGs. In addition, as shown in Figure 4-2, all forms of renewable electricity production are expected to have significantly lower life cycle GHG emissions (expressed as CO_2 equivalents, CO_2e) than electricity production from conventional coal and natural gas plants. Supplementing the results shown in Figure 4-2, the solar-power tower LCA in Appendix B estimated GHG emissions of 32 g CO_2e/kWh.

Renewable energy would have less of an advantage if carbon capture and sequestration were included with fossil-fuel power plants, or if energy storage systems, such as battery energy storage, compressed air energy storage, or pumped hydro storage, were included as part of renewable energy systems (Denholm and Kulcinski, 2003). We should also keep in mind that there are significant opportunities to improve energy conversion efficiencies and reduce fossil fuel requirements for the manufacture and transport of some renewable energy technologies, especially PV.

GHG emissions for some renewable technologies are difficult to estimate. For example, emissions from biopower vary, depending on which feedstocks are used and the assumptions about their production. Most CO_2e values for biopower range from 15 to 52 g CO_2e/kWh for biomass derived from cultivated feedstocks, excluding emissions associated with initial land conversion (NAS/NAE/NRC, 2010a). The negative CO_2e values shown in Figure 4-2 reflect estimates based on the assumption that biopower could serve as a CO_2 sink if waste residues that would otherwise decompose to produce CO_2 and methane were used as feedstock (Spath and Mann, 2004). If carbon capture and storage were added to biopower systems, there would also be large reductions in CO_2e values.

Similarly, estimates of GHG emissions from hydropower production depend on what is included in the LCAs. Although not reflected in Figure 4-2, some studies have suggested that initial flooding of biomass when a hydroelectric reservoir is filled can release large quantities of CO_2 and methane (e.g., Gagnon and van de Vate, 1997). The amount of these emissions depends on the density of the biomass and the size of the reservoir.

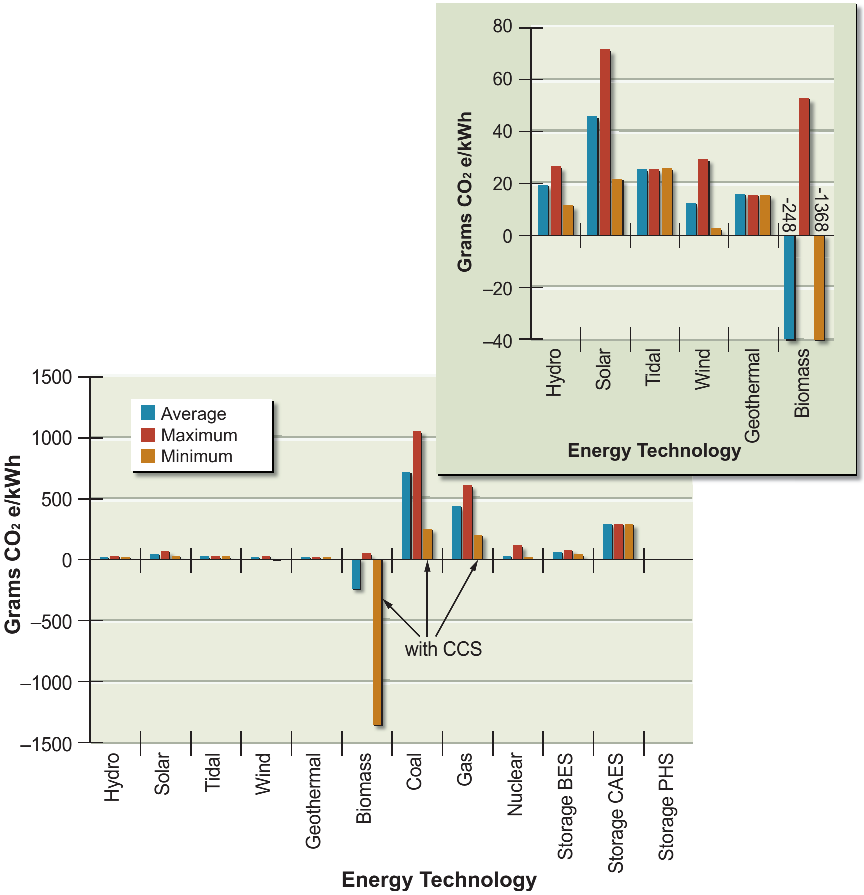


FIGURE 4-2 Life cycle emissions of greenhouse gases (in CO_2 equivalents) for various sources of electricity. Source: NAS/NAE/NRC, 2010a.

Finally, electricity production from closed-loop geothermal systems has low GHG emissions as shown in Figure 4-2 (Hondo, 2005). However, depending on the composition of the reservoir gas, if these gases are vented to the atmosphere, as can occur with flash technology, CO_2e GHG emissions can be relatively high. In the worst case, they can approach the emission levels from natural gas combined-cycle power plants (NAS/NAE/NRC, 2010a).

Local and Regional Air Pollution

Electricity generation accounts for significant emissions of local air pollutants in the United States and China. In the United States, the electric power sector accounts for 18 percent of total NO_x emissions and 66 percent of SO_x emissions (EPA, 2009). Oxides of nitrogen, which react in the atmosphere to form ground-level ozone, nitric acid, and particle-phase ammonium nitrate, contribute to human health effects, visibility degradation, acid deposition, and eutrophication. Sulfur oxides, which react in the atmosphere to form sulfuric acid and ammonium sulfate, contribute to health effects, visibility degradation, and acid deposition. In addition, coal-fired power plants account for 40 percent of direct mercury emissions in the United States and are believed to dominate direct mercury emissions in China (Wu et al., 2010).

Most renewable energy technologies have much lower life cycle emissions of conventional air pollutants than conventional coal and natural gas plants. For example, the solar power tower LCA in Appendix B estimates NO_x and SO_2 emissions of only 15 and 43 mg/kWh, respectively. One exception is electricity generation from biomass, which can produce significant NO_x, particulate matter, and hazardous air pollutants, such as polycyclic aromatic hydrocarbons (PAHs). Although biomass has lower nitrogen content than fossil fuels, a substantial quantity of NO_x is formed whenever high-temperature combustion occurs in air, through oxidation of atmospheric nitrogen (N_2) at high temperatures (see Figure 4-3). Although direct emissions of NO_x and SO_x are expected to be low for geothermal power plants, flash and dry-steam geothermal facilities can produce significant quantities of hydrogen sulfide (H_2S) from geothermal reservoirs, unless steps are taken to abate it (DiPippo, 2008).

For other renewable technologies, life cycle emissions of conventional air pollutants are mainly from the manufacturing or construction stages of the life cycle. As discussed below for PV, emissions during manufacturing depend strongly on how efficiently energy is used in the manufacturing process and the efficiency and degree of pollution control at the manufacturing site.

Land and Water Use

Land Use

Land is in limited supply in many parts of the United States and China. Hence the physical footprint of new facilities and feedstocks for electrical generation is an important consideration. In additional, the amount of land used is a rough proxy for other impacts of new development, including impacts on ecosystems, cultural and historical resources, scenery, and agricultural land.

When the impacts on land use are measured simply by the surface area they occupy during their life cycle, some renewable energy technologies appear to have heavy land-use requirements (Figure 4-4). However, this approach does not take into account the intensity of land use or whether the technology allows for simultaneous use of land for other purposes. Whereas coal-fired power plants fully occupy the sites where they are constructed, small-scale PV installations may be placed on rooftops where they cause little or no interference with the

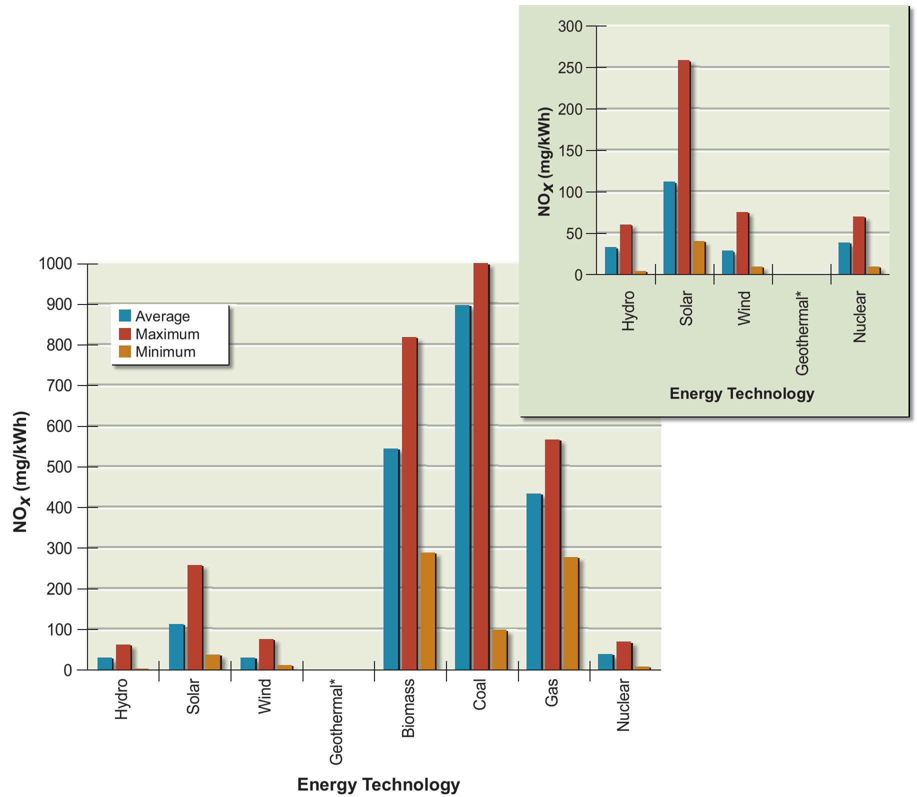


FIGURE 4-3 Estimates of life cycle NO_x emissions from various technologies. Data compiled by NAS/NAE/NRC, 2010a.

primary use of the land for commercial or residential buildings. Thus, smaller scale or distributed solar technologies may have less of an impact on land use and habitat loss than large-scale, central station plants. Land-use concerns may also be addressed by deploying renewable energy systems on previously developed sites, rather than in undeveloped areas (Mosey et al., 2007).

The high land-use requirements for biopower shown in Figure 4-4 assume that the feedstocks have been cultivated for energy production; if waste biomass is used as the feedstock, the land-use impacts are significantly lower. In China, the biomass materials likely to be used for electricity generation are mainly agricultural residues (e.g., straw, bagasse, and rice husks), forestry wastes (e.g., wood chips, sawdust, and bark), and municipal solid waste. Plants grown for energy are expected to comprise a very small proportion of biopower feedstocks in China.

The potential of waste resources available in China is estimated at about 370 million tons of coal equivalent (Tce), equivalent to about 14 percent of total Chinese energy consumption in 2007. Incremental land-use requirements for using waste materials as biopower feedstocks are insignificant. Moreover, if not used for biopower, some waste resources, such as municipal solid waste, would otherwise occupy land and could cause environmental damage if not disposed of properly.

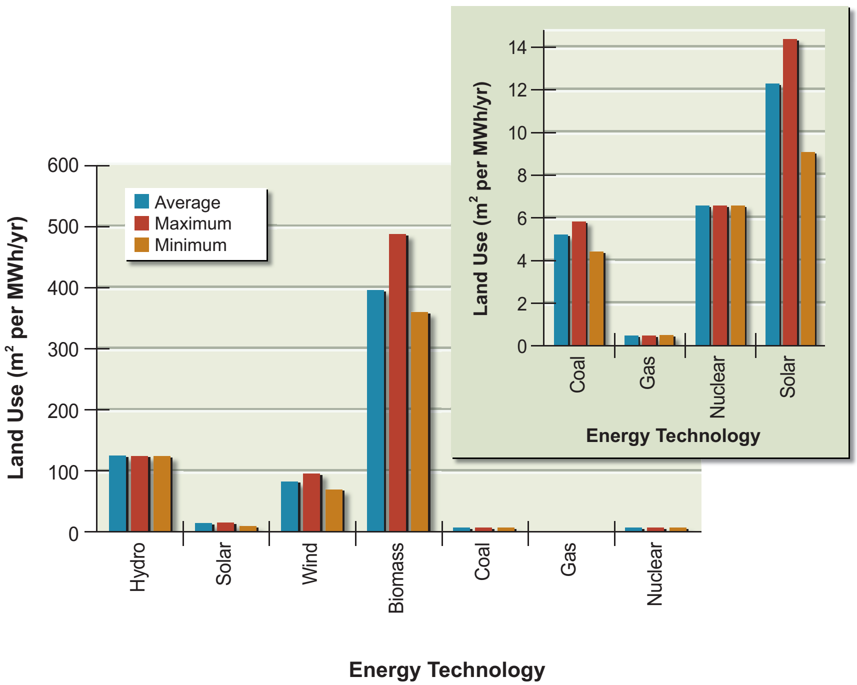


FIGURE 4-4 LCA of land use for various renewable and non-renewable technologies. Adapted from Spitsley and Keoleian (2005) by NAS/NAE/NRC, 2010a.

The hydropower estimate shown in Figure 4-4 represents land use for the Glen Canyon Dam and Lake Powell, attributing the full area of the reservoir to electricity generation (Spitzley and Keoleian, 2005); in contrast, small-scale hydropower and run-of-the river installations would have minimal land-use requirements. Land-use requirements for electrical transmission and distribution lines and facilities, which are significant for all centralized electricity generating facilities, are not shown in Figure 4-4.

Water Use

Water is a scarce resource in large portions of the United States and China. Recent global circulation model projections suggest that, if climate change proceeds as expected, under current business-as-usual scenarios, freshwater supplies will become even scarcer in some parts of the United States (Milly et al., 2005). In China, the amount of water available per capita is 2,200 m^3, only a quarter of the world per capita average. Water supply problems in China have been exacerbated because the spatial distribution of water is very uneven.

Electricity production using thermoelectric technologies requires vast amounts of water, primarily for cooling. In the United States, about 43 percent of existing thermoelectric generating capacity uses once-through cooling, 42 percent uses recirculating wet towers, 15 percent uses recirculating cooling ponds, and 1 percent uses dry cooling (Feeley et al., 2008). Water use by power plants is characterized by withdrawals (the total amount of water taken from a source) and consumption (the amount of water not returned to the source). Although consumption is sometimes emphasized over withdrawals, the latter is important, because power plant operation may be constrained by the amount of water available for withdrawal and power plant uses may compete with other demands for water (Gleick, 1994). Furthermore, water returns can be significant sources of thermal pollution and may include discharges of chemical pollutants, such as chlorine or other biocides used in cooling towers.

The U.S. Geological Survey estimates that nearly 280 billion cubic meters (BCM) of water was withdrawn in 2000 for thermoelectric power generation in the United States, accounting for nearly half of total withdrawals (USGS, 2005). Water consumption by thermoelectric facilities in the United States is much lower, an estimated 4 BCM in 1995 (estimates for 2000 are not available), but this quantity nevertheless constitutes more than 15 percent of U.S. water consumption for uses other than irrigation (Feeley et al., 2008). Water use by thermoelectric plants in China is also huge. In 2006, the quantity of withdrawals was 49 BCM, accounting for 37 percent of total industrial use. Chinese thermoelectric plants consumed an estimated 7 BCM of water.

Water consumption by geothermal plants depends on the technology and geothermal resource, as well as the cooling system. The 2,000 gal/MWh water requirement shown in Figure 4-5 reflects experience in the Geysers geothermal

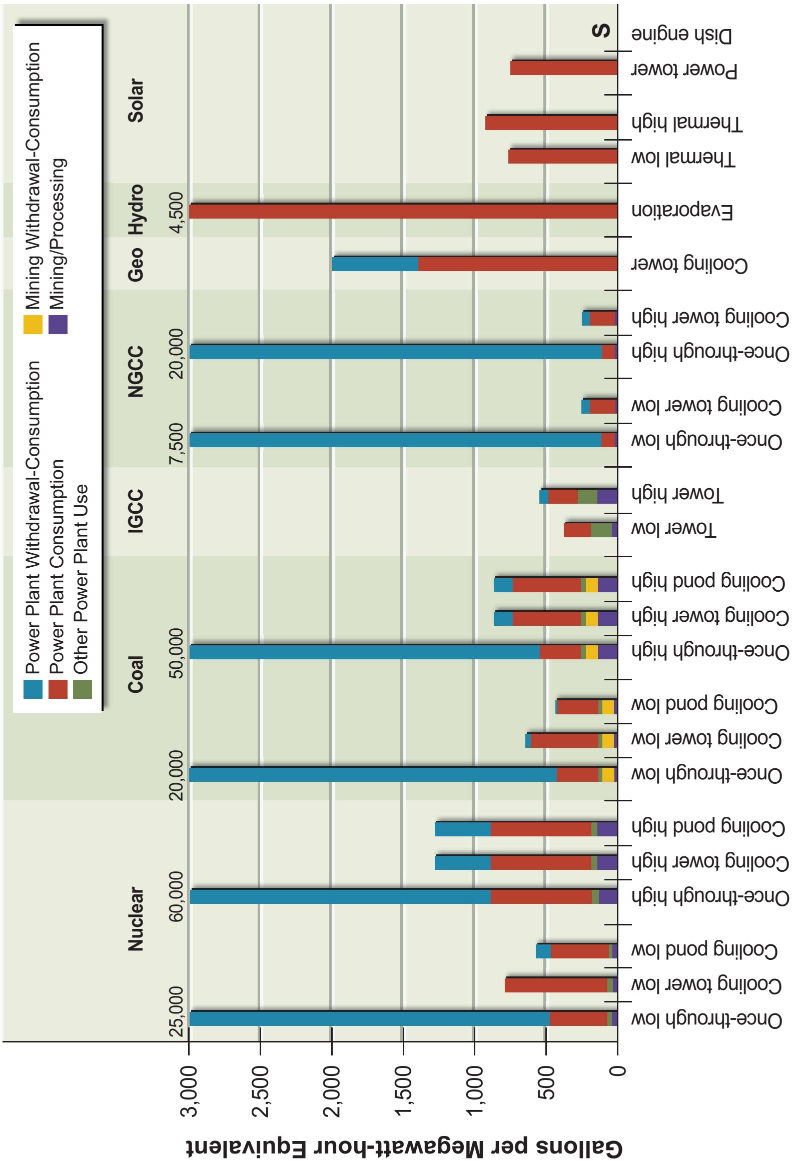


FIGURE 4-5 Estimates of water withdrawal and consumption for various electric generation technologies compiled from DOE, 2006a by NAS/NAE/NRC, 2010a.

resource area in California, where a dry-steam system withdraws 2,000 gal/MWh from the geothermal field, with 70 percent of the water consumed in an evaporative tower (Hall et al., 2006). The balance of water, for recharging the reservoir, comes from secondary-treated wastewater from a nearby community (DiPippo, 2008). Water consumption in liquid-dominated binary geothermal systems can be very high if wet cooling towers are used, but can be much lower if hybrid or air-cooled systems are used.

Wind and solar PV technologies use very little water. Water-use requirements for solar thermal plants also depend on the cooling system. Values shown in Figure 4-5 reflect operating experience with a 350 MW parabolic-trough system in the Mojave Desert, which uses evaporative cooling and consumes about 800 gal/MWh; a comparable estimate of water consumption for solar power tower technology; and a projection of negligible water consumption with an air-cooled parabolic dish system.

Finally, if evaporative losses from hydroelectric reservoirs are ascribed fully to the generation of electricity, large-scale hydroelectric power can be considered to *consume* more water per MWh electricity output than any other electricity generation technology (Gleick, 1994). However, reservoirs associated with hydroelectric power plants may have other uses, such as storage of irrigation water. Thus, evaporative losses may not be exclusively attributable to electricity generation.

Life Cycle Assessment of Solar Photovoltaic Technology

Although thin-film cadmium telluride and amorphous-silicon technologies are gaining ground in the global marketplace, most PV panels produced today are made of single or multicrystalline silicon. As discussed in Appendix D, in China, the production of high-purity polysilicon for solar cells is a rapidly growing industry, although it has high energy requirements and serious pollution problems at some facilities. To minimize these impacts, polysilicon manufacturers in China, as elsewhere, must use state-of-the-art methods to reduce energy consumption and address problems with hazardous materials and wastes. In response to these environmental concerns, especially the need to separate and recycle tail gas, China has initiated a key research project on the comprehensive use of by-products from polysilicon production.

As indicated above, although life cycle impacts of solar PV are estimated to be much lower than those of electricity generation from fossil fuels, the estimated NER and emissions impacts of PV are somewhat less favorable than for wind technology. The main reason is that production of PV panels is very energy intensive, with significant associated emissions of CO_2, NO_x, and other air pollutants.

Estimates of energy requirements for silicon PV panel manufacturing vary widely, depending in part on the vintage of the manufacturing technology and in part on the sources of process heat and electricity required. Alsema (2000) reported that estimates published up to that time ranged from 2,400 to 7,600 MJ m^{-2} for multicrystalline silicon and from 5,300 to 16,500 MJ m^{-2} for single-crystal silicon panels. To illustrate the distribution of energy requirements among the steps in the process, Figure 4-6 shows a breakdown for manufacturing of multicrystalline silicon PV modules, beginning with the production of metallurgical-grade (M-g) silicon. The fractions shown are adapted from estimates by Alsema (2000) and Alsema and de Wild-Scholten (2006). Alsema and de Wild-Scholten (2006) assumed the polycrystalline silicon is produced in part using the Siemens process and in part through a modified Siemens process, with an overall average electricity requirement of 110 kWh/kg Si and assuming 1.67 kg Si is used per square meter of PV panel. Whereas Alsema and de Wild-Scholten assumed electricity for polysilicon production was supplied from a mixture of hydroelectric and natural gas combined-cycle generation, the modified results shown here were calculated assuming electricity used at all stages in the process was produced from primary fuel with a net conversion efficiency of 31 percent. The overall estimate of the energy requirement is in the middle of the range cited by Alsema (2000). The results show the importance of electricity used at the silicon-purification stage.

If the silicon is purified using inefficient processing technology, electricity is supplied from relatively inefficient power plants, or polycrystalline silicon is wasted in wafer production steps, energy requirements can easily exceed those shown. By the same token, at some production facilities, the fossil energy required for polycrystalline silicon production has been greatly reduced by process improvements,

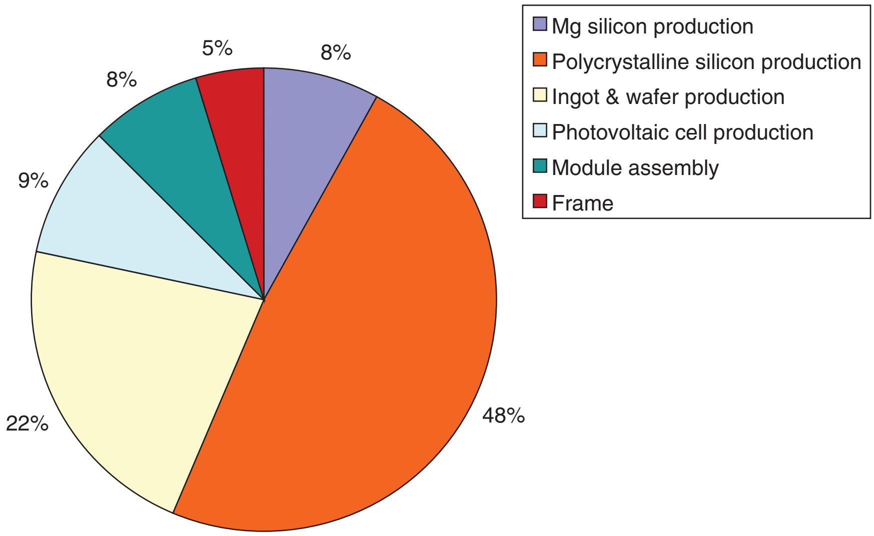


FIGURE 4-6 Breakdown of energy use in multicrystalline silicon PV module manufacturing. Adapted from estimates provided by Alsema (2000) and Alsema and de Wild-Scholten (2006).

including fluidized bed reactors for the silane decomposition step and renewable or highly efficient electricity sources.

The process of manufacturing PV panels also entails the use, or by-product production, of a number of hazardous materials that must be monitored, handled, and disposed of properly to minimize risks to workers, the public, and the environment. In addition to $SiCl_4$, these substances include silane, a highly flammable intermediate of polysilicon production, and hydrofluoric acid (HF) and other toxic gases and acids used in cleaning silicon wafers and in texturing and etching. Large amounts of acidic and alkaline wastewater are produced, so wastewater treatment and acid recycling are also critical steps.

Fluoride in wastewater poses special problems, because an excessive amount of fluoride in drinking water can cause a variety of diseases. Thus, strict standards are necessary to regulate the treatment and discharge of water containing HF. These issues are discussed in more detail in Appendix D, where research for reducing environmental and health and safety issues associated with polysilicon manufacturing are highlighted.

PROJECT-SCALE IMPACTS AND REGULATION FOR RENEWABLE ENERGY

Renewable energy facilities, like other means of electricity production, can have significant environmental and socio-cultural impacts. Depending on the technology, location, and scale of the facility, these impacts can include soil erosion or degradation, forest clearing, disturbance or loss of wildlife, air and/or water pollution, noise pollution, and impairment of scenic vistas. For renewable technologies, these impacts are often, but not always, similar to or milder than the effects of other industrial development on a similar scale. Nonetheless, locating renewable energy projects in sensitive areas can make the environmental licensing of the project difficult and more costly, and so these project-scale impacts can affect the rate of deployment.

Assessments of Ecological, Aesthetic, and Cultural Impacts

Cultural Impact

Among renewable electricity technologies, large-scale hydroelectric projects have historically had especially stark consequences, especially if they involved flooding scenic valleys or town sites. For example, when the Dalles Dam on the Columbia River was completed in 1957, the associated reservoir flooded Celilo Falls and the village of Celilo, a tribal fishing area and cultural center that archeologists estimated had been inhabited for millennia (Oregon Historical Quarterly, 2007). Like other dams on the Columbia River, the Dalles Dam serves multiple purposes, including improved navigation, irrigation, flood control, and the generation of nearly 1,800 MW of electricity. Although the Dalles Dam has provided widespread benefits, they came at great cost to the Native Americans whose community and traditions were rooted in the area (Wilkinson, 2005).

Since the Dalles Dam was completed, a web of U.S. laws have been enacted to protect natural and cultural resources from development pressures. These include the 1964 Wilderness Act, which prohibits activities that damage the character of wilderness in specified areas, the 1968 Wild and Scenic Rivers Act, which bans construction of dams and associated hydroelectric projects on protected stretches of rivers, and the 1969 National Environmental Policy Act (NEPA), which requires that environmental reviews be completed with full opportunities for public input before federal actions are taken. In part because of these protections, the pace of large-scale reservoir construction in the United States has slowed dramatically since the 1970s, and most new U.S. efforts to develop hydroelectric power plants are likely to be relatively small-scale systems. At the same time, however, as plans for utility-scale wind and solar projects move forward in the United States, advocates will have to take great care in siting and designing projects and operations that minimize environmental and social costs.

A case in Hawaii is another example of controversy surrounding the siting of renewable energy projects in locations of natural, cultural, or religious value. In 2007, Hawaiians celebrated the protection of a 26,000 acre tract of lowland rainforest on the island of Hawaii, after more than 20 years of efforts to restore public access and block the development of a geothermal power plant at the site (OHA, 2007). In the late 1980s, True Geothermal Energy Co. secured a permit to develop a 100 MW geothermal plant in the then privately held Wao Kele O Puna rainforest (Boyd et al., 2002). Native Hawaiians opposed the development because they traditionally used the area for hunting and gathering and for religious purposes. Some native Hawaiians also objected to the exploitation of geothermal resources in general because of reverence for Pele, the goddess of volcanoes in the native Hawaiian religion. The Wao Kele O Puna geothermal project was abandoned in 1994.

When the land was subsequently offered for sale, the Pele Defense Fund, a native Hawaiian group, approached the Trust for Public Land to arrange a purchase for conservation purposes. Only one geothermal power plant—the 30 MW Puna Geothermal Ventures Plant—is currently operating on Hawaii. As the Hawaiian Electric Company moves forward with plans to increase development of geothermal and other renewable resources in the state, it has recognized the need to deal with cultural and environmental concerns in advance "with openness and respect."[1]

Impact on Wildlife

After hydropower, whose impacts have been fairly well documented (e.g., ORNL, 1993), impacts on wildlife have been a particular concern for wind energy. Collisions with wind turbines have killed birds and bats; the numbers depend in

[1] See the "Environmental and Cultural Concerns" page of HECO's website, *http://bit.ly/9GKmwb*.

part on turbine technology and, very strongly, on turbine siting. In the United States, wind turbines were estimated to have killed roughly 20,000 to 40,000 birds in 2003 (NRC, 2007). Although these totals are much smaller than the hundreds of millions of bird deaths nationwide attributed to collisions with buildings, high-tension lines, and motor vehicles, localized impacts on specific bird populations can be significant. For example, raptor fatalities at the Altamont Pass wind site in California in the 1980s caused significant concerns.

Relatively limited data on bat deaths from wind turbines are available, but mortality rates at some facilities are as high as 40 recovered carcasses per MW per year (NRC, 2007). The significance of this rate of bat deaths is hard to gauge, in part because of a lack of baseline data on species' abundance. However, ecologists warn that as wind energy development accelerates in the United States, the potential for biologically significant impacts on bats is a major concern (Kunz et al., 2007).

In the past decade, the wind industry in the United States has been required to pay more attention to siting considerations and equipment modifications to reduce animal mortality rates. The Fish and Wildlife Service (FWS, 2003) has issued interim guidelines for minimizing the impacts of wind projects on wildlife, and an effort to revise and update them is currently under way.

These concerns are embodied in substantive laws that can go beyond imposing procedural requirements (as NEPA does) to sharply curtail or block development in some areas. The Endangered Species Act (ESA) of 1973 is a prime example; this law requires that federal agencies "insure that any action authorized, funded, or carried out by such agency… is not likely to jeopardize the continued existence of any endangered species or threatened species or result in the destruction or adverse modification of [critical] habitat…" (16 U.S.C. §1536(a)(2)). ESA further prohibits any person from "taking" any endangered species or listed threatened species of fish or wildlife (16 U.S.C. §1538(a)(1)) where "take" is broadly defined to mean "harass, harm, pursue, hunt, shoot, wound, kill…" (16 U.S.C. §1532). ESA requires consultation with the Fish and Wildlife Service before initiation of projects that require federal action. Even for project development on private lands, consultation is recommended to avoid incidental harm. If there is a potential for incidental harm, project developers may proceed by securing an incidental take permit, which typically entails developing and implementing a habitat conservation plan and appropriate mitigation measures.

Aesthetic Impact

Aesthetic concerns may not be specifically regulated but can be a significant issue for communities where new renewable energy projects will be located. The NRC (2007) study of environmental impacts of wind energy notes that in many countries and cultures, people form strong attachments to the place where they live that influence their reaction to new developments. Wind farms in particular are often proposed for ridgelines and other locations with a high density of wind where turbines are highly visible. Moreover, as with other renewable energy facilities, they are often proposed for locations where there has been no prior industrial development. The NRC (2007) study recommends a visual impact assessment process for determining whether a particular wind project would result in undue harm to valuable aesthetic resources and cautions that meaningful public involvement is crucial for acceptance. These same concerns would apply for transmission lines as well, and thus could become an important factor in the acceptability of large-scale renewables projects requiring new transmission.

Impact Assessment

Procedure in the United States

Under NEPA (and similar state laws), federal (or state) agencies must assess in advance the environmental impacts of their actions. Actions that fall under NEPA requirements range from the provision of loan guarantees for renewable energy projects to the granting of rights-of-way or the issuance of leases for construction of projects or transmission lines on or across federal lands. The objective of NEPA is to ensure that agencies fully consider potential environmental impacts and allow all interested parties, including the public, to provide input into the process before decisions are made.

The process typically begins with a brief Environmental Assessment (EA), the purpose of which is to determine whether the activity might impose a *significant* environmental impact. If so, the agency must prepare a full Environmental Impact Statement (EIS); if the agency anticipates little or no environmental impact, a Finding of No Significant Impact (FONSI) is issued. The majority of projects proceed with an EA, often after agreement has been reached on mitigation measures, and do not require full-blown EIS documents. However, large projects usually require a full assessment.

In recent years, the Bureau of Land Management (BLM), under the U.S. Department of Interior, has collaborated with the U.S. Department of Energy (DOE) to complete region-wide "programmatic" EISs for wind energy development (BLM, 2005) and with the U.S. Department of Agriculture Forest Service for geothermal energy development in the western United States (BLM, 2008). BLM is currently working with DOE on a programmatic EIS for utility-scale solar energy projects (DOE, 2009). BLM assessments are important because the agency administers more than 260 million acres of public land in the United States, almost all of it in the western half of the country and much of it rich in renewable energy resources.

Each programmatic assessment addresses the implications of broad policies designed to facilitate private development of renewable energy on federal lands. EIS studies examine potential environmental, social, and economic impacts on a broad scale, with the objective of assessing resource potential; identifying lands that should be categorically excluded from leasing; identifying best practices for mitigating impacts; and developing guidelines for public involvement and consultation with other agencies during subsequent project-level reviews of site-specific proposals.

As an example, the programmatic EIS for wind identifies potential impacts on soils; water resources and water quality; air quality; noise; vegetation; wildlife; paleontological resources; and cultural resources, including sacred landscapes, historic trails, and scenic vistas (BLM, 2005). Impacts on soil, water, and air quality are expected to occur principally during project construction, whereas impacts on noise, wildlife, and scenic vistas are expected to continue throughout the life of the project. Programmatic analyses have helped to streamline later assessments of individual projects but cannot supplant case-by-case analysis because impacts on natural and cultural resources are usually site specific.

Procedure in China

The Environmental Impact Assessment Law of 1979 mandates that a developer complete an environmental assessment before project construction. If not, the developer is required to complete a post-construction assessment. The Environmental Protection Bureau can fine the developer approximately $25,000 if no assessment is completed for the project. In recent years, numerous environmental disputes have arisen over the construction of waste incineration power plants. For example, protests by nearby residents against the construction of the Liulitun waste incineration power plant in Beijing had a significant social impact at the time. Since then, a mechanism for public participation has been introduced. For controversial projects that are environmentally sensitive, local governments are responsible for explaining the project to the public and for holding public hearings, if necessary.

Overview of Environmental Planning and Permitting

Planning and Permitting in the United States

Like other economic sectors, the electric power sector (generation, transmission, and distribution facilities) in the United States is covered by a wide range of land-use and environmental regulations that encompass the development and construction of new facilities, facility operation, and decommissioning and site restoration. Project developers must typically attend to layers of local, tribal, state, and federal regulations and deal with multiple agencies and permitting processes. Different project developers may be involved in the generation facilities and in the transmission/distribution facilities. Thus the complexities of planning and permitting may be multiplied in terms of approval steps and timelines due to the number of parties involved. Special protections or bans on development may apply to lands (including privately owned land) with special designations, including historic sites, prime farmland, and wilderness and roadless areas. Where federal or state action is required for project development, NEPA or parallel state laws require environmental review as part of project planning.

Federal NEPA requirements apply for any electrical generating facilities or transmission lines on federally managed public lands or offshore. Approximately 30 percent of the land in the United States is federal public land, and public lands are especially prevalent in the western United States, where significant wind, solar, geothermal, and hydropower resources are located.

The American Wind Energy Association has compiled a guidance document that outlines the types of local-scale environmental impacts that can arise and the corresponding regulatory framework that governs the development of wind energy projects (AWEA, 2008). Projects developed on private lands face an array of local, tribal, state, and federal land-use and environmental review and permitting requirements designed to ensure that potential impacts are identified and mitigated.

Siting and land-use regulations for privately owned land are usually the purview of state, tribal, or local governments, and hence vary widely across the country. In some states, public utility or state energy siting boards have jurisdiction to review and authorize new electricity generation facilities. State environmental quality and wildlife conservation agencies may implement requirements for environmental review. In other states, or for relatively small projects, siting decisions may be left to municipal or county agencies. Whether or not state-level approval is required, almost all projects on private land require local review for compliance with zoning restrictions and ordinances limiting height, setbacks, and noise.

Renewable energy projects that release contaminants into air or water or thermal pollution to surface bodies of water may also be subject to state and federal regulations. The primary laws governing air and water pollution in the United States are the Clean Air Act and Clean Water Act, both of which include direct federal regulations as well as programs that are mandated and enforced by the federal government but administered by states or tribes. Compliance with air pollution regulations under the Clean Air Act is required for biomass combustion and geothermal facilities that release pollutants to the atmosphere during operation; other renewable projects that entail clearing land or construction of new roads may also have to address concerns about vehicle or construction equipment emissions and fugitive dust. Biomass, geothermal, and solar thermal power plants that discharge cooling water to lakes or rivers face regulation for thermal pollution as well as contaminant discharges. Discharge permits may also be required for renewable energy projects that use water during exploration or production phases, including for sanitation and dust suppression.

Planning and Permitting in China

Confronted with multiple pressures, such as the need for economic development, expanded employment, and mitigation of GHG emissions, the Chinese government has promulgated policies and implemented laws on energy conservation, environmental protection, and sustainable development (see Chapter 5 for details of specific policies). However, to avoid or mitigate environmental, cultural, ecological, and scenic impacts, the development of renewable energy projects is subject to other national laws and regulations.

Specifically, projects that involve feed-in power generation from renewable energy must secure administrative permits and submit information in conformance with relevant laws or provisions of the State Council. Western China, for example, is the birthplace of Chinese civilization. Throughout history, people of many nationalities have developed and created a rich and valuable cultural heritage, and artifacts in the region are the historical testimony that people of all ethnic groups developed the region and lived there together. To protect the cultural relics in these areas, on August 31, 2000, the State Council issued the "Notice of General Office of the State Council on reinforcing cultural relic protection and management in west development by the General Office of the State Council" (No. 60 in 2000).

Since the adoption of the Renewable Energy Law, additional environmental regulations have appeared in China specifically to address environmental impacts of biomass power generation. In 2006, the State Environmental Protection Administration (now MEA) and National Development and Reform Commission (NDRC) promulgated an official document to strengthen the environmental evaluation and management of biomass power generation projects. In accordance with the new provisions, the construction and operation of waste incinerators must meet national or industry standards (such as GB13271-2001 Solid Waste Incineration Pollution Control Standard), and the quantity and quality of garbage must be guaranteed. At present, to qualify as a biomass power generation project, the proportion of conventional fuel fed into the furnace by mass must be limited to 20 percent when a fluidized bed incinerator is used to deal with solid waste. In addition, existing laws, such as the Thermal Power Plant Air Pollutant Emission Standards (GB13223-2003) and Boiler for Air Pollutant Emission Standard (GB13271-2001), regulate emissions.

Although laws and codes issued by the Chinese national government are considered to be the dominant set of rules, because of China's vast territory and numerous regional differences, implementation of a particular project on a local scale can differ from centrally established guidelines. Some local governments faced with economic development pressures, a lack of modern technology, and a shortage of capital have been lax in implementing or enforcing laws and codes, although this situation is improving. Lessons from the experience of developed countries and increased capital investment can further improve the implementation of standards. As public awareness of and interest in environmental issues increases in China, there are likely to be projects that attract public opposition.

FINDINGS

In comparison to fossil fuels, renewable sources of electricity such as solar, wind, and geothermal can offer substantial environmental benefits, especially with regard to GHG emissions. When life cycle emissions are considered, all forms of renewable electricity production are expected to have significantly lower GHG emissions per unit of electricity produced than generation from conventional coal and natural gas plants. With the exception of emissions of NO_x and carbonaceous materials from biomass combustion, rates of life cycle emissions of conventional air pollutants from renewable electricity generation are also sharply lower than from coal and natural gas plants.

Although renewable energy sources have major advantages over fossil fuels, they also raise some environmental concerns. Many renewable energy technologies are ready for accelerated deployment, but research and development are still needed to reduce their environmental impacts. While wind, solar PV, and some geothermal plants have very low water requirements, biomass, concentrating solar thermal, and some geothermal plants generally have requirements comparable to those of other thermoelectric facilities. **The United States and China would benefit from efforts to further improve cost effectiveness and efficiency of low water-use cooling systems to help expand their utilization.** Also, as a result of evaporation, water consumption associated with large-scale hydropower plants and other uses of associated reservoirs is particularly high.

LCA is a valuable method of comparing environmental impacts of alternative electricity generating technologies and identifying where improvements are most likely to pay off. LCA shows that increasing system efficiencies and operating lifetimes will reduce environmental impacts for all renewable energy technology. The life cycle GHG emissions benefits of renewable energy are generally high, but improvements are possible in some areas. In particular, research and development are needed to reduce life cycle GHG emissions for emerging storage options, such as batteries and compressed air energy storage, and to reduce GHG emissions and electricity use in PV manufacturing.

To minimize waste in the modified Siemens process for polycrystalline silicon production, the toxic silicon tetrachloride ($SiCl_4$) produced as a by-product of trichlorosilane decomposition must be recycled. Several tons of $SiCl_4$ are produced per ton of polysilicon, and unless it is recovered and sold as a by-product or recycled in the polysilicon production process, a large share of the silicon feedstock is wasted. However, because the components of the tail gas are very complex, separation and recycling are difficult. News reports (e.g., Cha, 2008) indicate some Chinese polysilicon producers have not been attempting this critical step. Additional research is needed on the life cycle impacts of thin-film technologies, which comprise different processes and inputs than silicon flat-plate PV (Fthenakis, 2009).

Both countries will need to reduce air pollution emissions from biomass combustion. As shown in the LCA section of this chapter, the majority of energy consumption and emissions associated with biomass power generation is in the plant cultivation stage. Both the United States and China are currently focusing on using waste biomass and should continue to do so. Even with waste biomass, however, pollutants are emitted during plant operation. Pollutants associated with the combustion of biomass include PAHs and nitrogen and SO_x. The combustion of municipal solid waste can produce dioxins and release heavy metals that must be captured.

Biomass has lower nitrogen content than coal, but it also has lower heating values (15 to 21 MJ/kg for biomass compared to 23 to 35 MJ/kg for coal). Therefore, some biomass fuels can produce more NO_x emissions than coal does for the amount of heat it produces. The production of NO_x from the nitrogen in biomass is not well understood, because the forms of nitrogen are different from those in coal. Therefore, research is needed to minimize pollutant emissions during biomass power generation processes.

Land use is also a significant issue with some renewable energy technologies, especially as we envision scaling them up in the future. Research will be necessary to understand the impacts that renewable power installations have on plants and wildlife in various geographies, and to develop effective ways to mitigate these impacts. **Land-use impacts can be reduced by the use of previously developed sites, co-occupation with other land uses, using military and government sites, and encouraging distributed generation technologies to minimize the need for more transmission lines.** Renewable power development will have to be restricted in areas with sensitive ecosystems or high cultural or scenic value, and public involvement will be invaluable for helping to identify these areas. Additional research is also needed to understand impacts of large-scale (e.g., 10 MW for PV, 100 MW for wind) renewable energy installations on meteorology and climate.

It is evident that, in both countries, large-scale renewable energy installations will also require new transmission infrastructure that entails environmental impacts. Siting and constructing new transmission requires similar processes, in terms of impact assessments, licensing, and permitting. Project developers may need to plan for this up front, and work with regulatory agencies, environmental and civil society groups, and transmission utilities to identify ways to mitigate transmission impacts. Opportunities include: identifying areas of common transmission corridors for use by a number of projects, addressing the need for new substations for interconnection and power transmission, and enlisting local support for transmission projects that enable more renewable energy technologies to be deployed.

Finally, recognizing that renewable energy facilities and the installed generation technologies will have a finite lifespan, both countries will have to pay more attention in the next decade to decommissioning, recycling, disposal, and site restoration.

RECOMMENDATIONS

- Scientists and engineers in both countries should work together to solve key technical challenges in waste treatment and recycling of components. Opportunities include reducing or reusing silicon tetrachloride and other toxic byproducts of polysilicon production, and recycling PV panels and wind turbine blades.
- For biomass power generation, the priority should be on reducing combustion emissions and using available waste resources (rather than dedicated energy crops), including municipal solid waste and agricultural residues.

5

Renewable Energy Policies, Markets, and Deployment in China and the United States

By reducing some of the risks perceived by the private sector, leveraging financing, and increasing capital flows for R&D, policy plays a central role in the deployment of renewable energy technologies. Beyond technological challenges are significant hurdles in the marketplace. Renewable projects will require large investments in infrastructure, which the private sector might consider risky, unless they have sufficiently funded, consistent incentives. In the form of incentives, policy can also sustain industry sales until manufacturers achieve cost reductions from learning opportunities and economies of scale. The United States and China have historically taken different approaches to policy making in the energy sector, partly because they have different needs and priorities and partly because they have different systems of government. These factors can make it difficult to comparatively analyze policies, or to find common ground for cooperation on policy-related matters. Nonetheless, given the important role that policy will continue to play in both countries' efforts to scale up the use of renewable energy, this chapter highlights the strategic approaches that China and the United States are taking,[1] and identifies some areas of common interest. It also summarizes potential constraints in the marketplace, and discusses opportunities to strengthen the market infrastructure.

[1] Campbell (2010) offers a recent, comprehensive overview of renewable energy programs and policies in China and the United States.

RENEWABLE ENERGY POLICY IN CHINA

The Role of Government

China's energy policy is developed through a two-step approach. The central government first develops broad policy goals and communicates them every five years in its *Five Year Plans*. Ministries, agencies, and the National People's Congress then use the plans to design targeted, specific policies. China's 10th and 11th *Five Year Plans* (2000-2005, 2006-2010) were the first to include goals for renewable energy development.

China's increased focus on renewable energy requires coordinated action from many entities and groups outside the central government and government agencies. In January 2010, the government announced the creation of the National Energy Commission (NEC) to streamline China's energy operations and coordinate activities by the National Energy Bureau (NEB) and the National Energy Administration (NEA), which tend to overlap with the mandates of other ministries. The NEC will also assume many of the energy-focused activities of the National Development and Reform Commission (NDRC) and the Ministry of Finance. The goals of the NEC are to devise China's energy strategy, ensure the country's energy security, and coordinate cooperative programs.

One of China's main goals in developing renewable energy has been to supply off-grid electricity to more than 2 million rural households that have no access to electricity. Another goal is to address concerns about the long-term environmental impacts of coal-fired electricity generation. China has acknowledged the potential impact of increased greenhouse gas (GHG) emissions on climate, and China has already taken several steps to reduce emissions of regionally important criteria air pollutants, such as particulates, sulfur dioxide, and nitrous oxide (NAE/NRC/CAS/CAE, 2007). Among other things, these reductions have served as a response to civil unrest in recent years to protest energy-related pollution. Even more important, however, China sees renewable energy as a potentially lucrative economic opportunity, particularly in the global market for clean technologies. In 2009, for example, more than 90 percent of photovoltaic (PV) cells produced in China were exported.

General and Targeted Policies

In China's 11th *Five Year Plan*, its broad renewable energy policy goal is to "accelerate renewable technology advancement and industrial system development . . . specifically supporting the technology breakthrough and industrialization of bio-liquid fuel, wind power, biomass power, and solar power." This goal is supported by a series of suggested measures and incentives, shown in Tables 5-1 and 5-2. Four important policies in defining China's renewable energy landscape are: Renewable Energy Law of the People's Republic of China, which outlines policy goals; Medium and Long-Term Development Plan for Renewable Energy

TABLE 5-1 Direct Renewable Energy Policies in China

Dates	Policy	Details
February 2005	The Renewable Energy Law of the People's Republic of China	Outlines mid-range policy goals of the government surrounding renewable energy. It provides only general guidance and so does not set prices. The price authorities of the State Council set them.
November 2005	Renewable Energy Industry Development Guidance Catalogue	Sets industrial development targets covering the field of wind, solar, bio, geo, ocean, and hydropower using the top performing projects in each field.
January 2006	Interim Measures for Renewable Energy Power Price and Cost-Sharing	Mandates the purchase of renewable energy over the national grid, either based upon the Government Fixed Price or the Guidance Price of the Government (awarded tariff of the bid winner). Outline pricing policies of electricity from renewable sources: 1. Applies Guidance Price to wind energy's feed-in tariff 2. Applies Government Fixed Price to solar, ocean, and geothermal power Biomass feed-in tariff shall be set by the yardstick feed-in tariff for desulpherizing coal-fired units in 2005 plus the subsidy price for biomass, which was raised to 0.35 CNY/kWh in 2008. Biomass projects shall receive the subsidy for 15 years after the beginning of production.
January 2006	Management Rules of Renewable Energy Power Generation	Assigns management bodies to approve, manage, and monitor various categories of renewable projects on a central and provincial level. Mandates detailed responsibilities of the power generating companies and the grid companies to develop renewable energy power generation.
May 2006	Interim Measures for Management of Special Fund for Development of Renewable Energy	Detailed codes for supporting key areas, such as funding, management, and assessment.
August 2007	Medium and Long-Term Development Plan for Renewable Energy in China	Mandates that the share of renewable energy consumption must reach 10 percent by 2010 and 15 percent by 2020.
March 2008	The Renewable Energy Development Planning during 11th Five Year Planning Period	Establishes priorities and targets for renewable energy development during the 11th Five Year Planning Period.
July 2009	Feed-in-tariff rates for four categories of onshore wind projects	Tariffs vary by quality of wind resource area: 0.51 CNY/kWh; 0.54 CNY/kWh; 0.58 CNY/kWh; 0.61 CNY/kWh.
December 2009	The Amendment to the 2006 Renewable Energy Law	Mandates power grid operators to buy all the electricity produced by renewable energy generators within their region.

TABLE 5-2 Indirect Renewable Energy Policies in China

Dates	Policy	Details
2006–2010	National 11th Five Year Plan for Environmental Protection	Outlines the national agenda during the 2006–2010 administrative period. The plan bases itself on the 11th Five Year Plan and the Implementation of the Scientific Outlook on Development and Strengthening Environmental Protection. Specific goals include to: 1. Reduce national sulfur dioxide and carbon dioxide emissions by 10 percent from 2005 levels by 2010. 2. Increase the number of days in which urban air quality of key cities is superior to Grade II National Air Quality Standard by 5.6 percent.
2000	10th Five Year Plan for Energy Conservation and Resources Comprehensive Utilization	Outlines the national energy resource agenda for the 2000–2005 administrative period with a focus on efficiency, energy conservation, consumption reduction, and comprehensive resource utilization. This includes: 1. Petroleum conservation and substitution technologies 2. Renewable resources recovery and utilization technologies 3. Energy-saving and clean enterprise demonstration projects
2006	11th Five Year Plan for the Development of the Environmental Protection Industry	Outlines the national agenda for the 2006–2010 administrative period with a focus on environmental protection. This includes: 1. Focus on the development of technologies that are more resource-efficient and less polluting. 2. Focus on the development of overall contract services for environmental projects, including financing, design, and equipment.

in China, which establishes thresholds for renewable energy; Interim Measures for Management of Special Fund for Development of Renewable Energy; and Policy and Price of Electricity Generated by Renewable Energy, which describes pricing policies.

Renewables, except for hydropower, are still more expensive than fossil fuels, partly because of long-term subsidies for fossil-fuel power. Pricing policies are, therefore, important to providing incentives for the increased deployment of renewables. One approach consists of feed-in tariffs that force energy utilities to purchase renewable energy at a fixed price and connect it to the grid. Another approach is tendering, a government-run bidding process for contracts that supply renewable energy. Feed-in tariffs have benefited biomass power and solar power; tendering has benefited wind power, although in 2009 tendering was replaced by a feed-in-tariff. As China expands the use of feed-in-tariffs, it may need to consider increasing the quota and rate, to encourage larger scale commercial projects. Feed-in tariffs account for the bulk (~90 percent) of China's national subsidies for renewable energy development, leaving a comparatively small percentage of national support for R&D and other "upstream" efforts to improve technologies and reduce costs.

Chinese policies address biofuel production, but overall, China's biomass policy focuses on heat and power generation rather than alternative transportation fuels. Because of concerns about the impact of biofuels on the food supply, in 2006 the government prohibited the production of ethanol from food grains. The production of ethanol from non-food feedstocks (such as cassava, sweet sorghum, Jatropha Curcas, Pistacia Chinensis, Tung, and cottonseed) continues.

Impact and Challenges

Hydroelectric projects dominate the Chinese renewable energy landscape, reflecting the long history of policies promoting electrification regardless of the energy source. The country also has the resources, the know-how to take advantage of them, and a centralized approach to policy making that is well suited to the development of large hydro projects, such as the Three Gorges Dam. The deployment of other renewable energy sources, with the recent exception of wind farms, continues to be an uphill struggle in most areas because of widely available, low-cost, fossil-fuel energy.

One of the most important renewable energy policies in China is the Medium and Long Term Development Plan for Renewable Energy. This policy has a specific goal of increasing the share of clean energy (to include large hydro and nuclear) to 10 percent of primary energy consumption by 2010 and 15 percent by 2020. Achieving or exceeding these targets will likely require China to address some related policy issues that could otherwise impede progress.

Enforcement

China will need to strengthen environmental regulations to address some environmental impacts of renewable energy production, and enhance local capacity to enforce regulations. Although the central government plays the largest role in implementing renewable energy policy, the enforcement of environmental regulations is left to provincial governments. A number of provincial leaders regard enforcement of environmental regulations as a secondary or tertiary concern. Some authorities have even exerted influence over regulatory agencies that have attempted to report inadequate environmental enforcement (Canfa, 2007). Lax enforcement of environmental regulations has several important implications for the renewable energy industry, namely: (1) the price of coal-fired power remains artificially low if pollution controls are bypassed, (2) as manufacturing of renewable energy technologies increases, inefficient and highly polluting processes could serve to undermine confidence in the fledgling industry, and (3) as renewable power plant installations increase in quantity and scale, site-specific environmental impacts, if not properly managed, could undermine support for a further proliferation of these projects.

Grid Integration

The expansion of the electricity grid has not always kept up with the construction of new renewable energy projects. The 2006 Renewable Energy Law stipulates that grid utilities must connect renewable energy developments to the electricity grid, and grid operators are awarded a subsidy based on distance: 0.01 Chinese yuan renminbi (CNY) per kWh within 50 km, 0.02 CNY per kWh for 50 to 100 km, and 0.03 CNY per kWh for distances of more than 100 km.

However, connecting with the grid requires more than just new construction. It requires training grid operators to manage the intermittency of the renewable power supply, which often requires the modernization of grid technology to make the electrical distribution system more predictable and manageable. It also sometimes requires balancing services, which in China's case frequently means additional coal-fired power (whereas the United States will typically rely on natural gas).

A relatively large portion of China's wind projects have not been connected to the main electricity grid, particularly in Inner Mongolia and Gansu. There are various reasons for this, including the lack of available transmission interconnections. However, in many cases individual wind farm project development is simply outpacing regional plans for power development and transmission. Projects are also sometimes constructed without the necessary permits and authorization—this can result in either an excess of wind capacity that must routinely be curtailed, or poorly constructed projects that are difficult and expensive to integrate without causing severe disruptions to the grid.

Social Resistance

The construction of hydroelectric projects such as the Three Gorges Dam has caused substantial population displacements in China. Hydroelectric projects have displaced millions of people in the past few decades, and hydropower projects continue to arouse resistance. In 2004, approximately 100,000 farmers staged a sit-in to denounce the building of a 186-meter high dam in Hanyuan in Sichuan Province. Although there have not been such demonstrations against wind farms or other renewables development, this could be a potentially important issue for future projects. Transmission projects, particularly long-distance corridors crossing multiple provinces, are likely to be a part of China's overall plans to develop large wind and solar bases in remote provinces. Thus, it may be useful to engage all of the affected communities at the outset of transmission planning, in order to identify potential impediments to developing these large projects.

RENEWABLE ENERGY POLICY IN THE UNITED STATES

Role of Government

As noted in Chapter 1, there are many drivers for increasing the deployment of renewable energy in the United States. Chief among these, as reflected in current policy debates, are the desires to substantially reduce GHG emissions from the power and transportation sectors and to identify more sustainable, long-term sources of energy. Within the transportation sector especially, national security concerns are another driver; the United States imports approximately 65 percent of its oil, some of it from politically unstable regions. James Jones, the U.S. National Security Advisor, has described the nation's reliance on foreign oil as "one of the most important and pressing national security challenges of this century" (Jones, 2008). Finally, job creation is another rationale for increasing the deployment of renewable energy. In policy discussions, the renewable energy sector, and its associated jobs in manufacturing, construction, and operation of facilities, constitute a portion of the so-called "green jobs" sector.

The U.S. Department of Energy (DOE) is critical to energy-related legislation in the United States and to energy-related research and conservation. DOE also supports the development of a variety of energy policies. Recent legislation related to DOE activities include the Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007, which was the last comprehensive energy bill passed in the United States. As of July 2010, comprehensive federal legislation on energy was still pending in the House of Representatives (H.R. 2454 American Clean Energy and Security Act) and the Senate (American Clean Energy Leadership Act).

The Environmental Protection Agency (EPA) is responsible for developing U.S. environmental regulations. Although EPA is not a cabinet agency, it is responsible for enforcing compliance with the Clean Air Acts and has devised a number of energy efficiency programs, such as Energy Star, as well as fuel-economy standards. In addition, in December 2009, EPA issued an Endangerment Finding, a prerequisite to finalizing proposed standards for greenhouse gas emissions. A major impact of this finding would be restrictions on the availability, and increases in the prices of, fossil fuels, especially coal. Thus, the finding would have a major impact on the development of renewable energy in the United States.

State governments encourage the adoption of renewable energy through the implementation of state programs and Renewable Portfolio Standards (RPS). In 2007, California, for example, instituted the California Solar Initiative, which initially offered a cash incentive of $2.50 (decreasing over time) per watt of PV modules installed. States have often been referred to as "laboratories" for policy experimentation, and this has been the case for renewable energy policies since the early 2000s (NAE/NRC/CAS/CAE, 2007). As of July 2010, 29 states and the District of Columbia have an RPS, while an additional 7 states have set portfolio goals. Comprehensive information on state-level incentives is available through the Database of State Incentives for Renewables & Efficiency (DSIRE, *www.dsireusa.org*).

General and Targeted Policies

Renewable energy policy in the United States is shaped at the federal, state, and local levels. The key policy tools at the federal level include the Federal Production Tax Credit (PTC), the Investment Tax Credit (ITC), and the Modified Accelerated Cost-Recovery System (MACRS). These policies have provided economic incentives and subsidies that have made the final production price of renewable energy more cost competitive with traditional fossil fuels.

Newer federal proposals may impact the U.S. renewable energy sector in the future. These include the federal RPS, carbon-pricing legislation, and regulations for electricity transmission and distribution. Combined with established fuel subsidies, the federal Renewable Fuel Standard (RFS) could be particularly effective at making alternative transportation fuels more cost competitive. Palmer and Burtraw (2005) have found that a federal-level RPS would be more cost-effective in promoting renewables than a PTC or a carbon cap-and-trade policy. Critics of a federal RPS point out that it favors renewables over other sources, notably nuclear and coal with carbon capture and sequestration (CCS), that could also deliver low-carbon electricity.

A state's RPS can be more stringent than a federal renewable energy mandate. This is significant because a state with a large consumer market that adopts relatively stringent environmental regulations can influence the enactment of those regulations on a national level. For example, a relatively stringent CAFE (fuel economy) regulation in California is a strong incentive for auto manufacturers to adopt the standard for all U.S. vehicles in order to gain access to the large California market.

On February 13, 2009, the U.S. Congress passed the American Recovery and Reinvestment Act (ARRA), commonly referred to as the U.S. stimulus package. ARRA includes economy-wide funding but does have some specific provisions that support renewable deployment. New federal funding was made available through:

- cash grants in lieu of investment tax credits under a program administered by the U.S. Department of Treasury
- loan guarantees underwritten by the U.S. Department of Energy

Approximately $43 billion of ARRA funds were dedicated to "clean energy" projects, and $36.7 billion of this is being administered by DOE. Of that sum, $4.5 billion is to be spent on smart grid applications, $4 billion for loan guarantees, $2.3 billion in manufacturing tax credits, and $2.5 billion for research, development, and demonstration within DOE's Office of Energy Efficiency and Renewable Energy.

The RPS, the most often used state-level policy to encourage renewable energy development, is complemented by tax credits and other incentives. However, some states have not mandated RPS because of scarce renewable energy resources, opposition to the federal expansion of electricity transmission, and interstate competition. Some states, notably California, have also implemented feed-in-tariffs, and a national feed-in-tariff continues to be a subject of debate but has, to date, not been formally proposed in Congress.

Green-power marketing (i.e., marketing and selling power from renewable sources to end-users) is one factor to consider when introducing a policy that targets renewables. These voluntary purchases of power represented about 0.6 percent of all electricity sales in 2008 (Bird et al., 2009). It is still unclear whether introducing new renewable energy policy will stimulate new markets for renewables or simply recapture the already present interest in this voluntary market.

Impact and Challenges

Tables 5-3 and 5-4 list policies that directly and indirectly impact renewable energy production and consumption in the United States. Figures 5-1 and 5-2 illustrate the different levels of federal incentives for energy development from 1950 to 2006. These figures demonstrate that the fossil-fuel sector (particularly oil) has historically benefitted from a range of subsidies and other government incentives. Incumbent technologies in these sectors continue to be dependent on federal incentives, with an emphasis on tax policy and regulation. Figure 5-3 illustrates the impacts of the federal production tax credit (PTC), a key driver in the U.S. renewable energy sector—it has cycled on and off, thus making it difficult to plan for large-scale projects.

TABLE 5-3 Direct Renewable Energy Policies in the United States

Dates	Policy	Level	Sector	Form	About
1997–present	Renewable Portfolio Standard (RPS)	States and territories (44)	Electricity	Command-and-control (with trading)	The standard varies significantly depending on the state (typically 10 to 30 percent) and the type of renewable energy source. Adding all the RPSs for the different states shows that 60GW of renewables will be placed online over the next decades.
1994–present	Production Tax Credit	Primarily federal	Electricity	Financial incentives	Mandates 2.1 cent tax credit per KWh of electricity generated in the first 10 years of new renewables projects.
1986–present	Modified Accelerated Cost-Recovery System (MACRS)	Federal	Electricity	Financial incentives	By allowing a wide variety of renewable electricity assets to be declared as depreciating rapidly, this system indirectly reduces the tax burden on entities building renewable energy capacity. In some cases this can be very significant. Prior to MACRS (from 1975–1983), a similar system, the Accelerated Cost Recovery System (ACRS), was in place.
2005–present	Investment Tax Credit (ITC)	Federal	Electricity	Financial incentives	This mandates a 30 percent tax credit for solar power, fuel cells, and small wind <100 kW, and 10 percent for geothermal, micro turbines, and combined heat and power. Note that the American Reinvestment and Recovery Act of 2009 allowed all PTC eligible renewable sources to receive the ITC in-lieu of the PTC.
2005–present	Renewable Fuel Standard (RFS)	Primarily Federal	Transport	Command-and-control (with trading)	The 2007 Energy Independence and Security Act mandated a substantial increase in the use of biofuels over the level established by the Energy Act of 2005. The Energy Act of 1992 gave DOE the authority to require alternative fuels, but only in certain federal fleets.
1997–present	Public benefit funds	States	Electricity	Financial incentives	Several states tax electricity and use a portion of the tax revenues to fund a wide variety of projects and subsidies for renewable power.

Dates	Policy	Level	Sector	Form	About
1978–present	Tax credits, grants, rebates, low-interest loans	Federal, states (49)	Primarily electricity	Financial incentives	Every U.S. state except Arkansas provides some form of financial assistance to renewable energy, although the nature and extent of this assistance varies considerably. Tax exemptions are a common theme.
Varies	State goals	States (5)	Primarily electricity	Goal setting	Five states that have not established binding renewable energy targets have established nonbinding goals instead.
2009	25 percent renewable energy by 2025	Federal	All	Goal	President Obama has called for the United States to meet 25 percent of its energy needs with renewable energy by 2025.
2009	Doubling renewable energy in 3 years	Federal	All	Goal	President Obama has called for the United States to double its production of renewable energy in 3 years.
1978–present	Renewable fuel subsidies	Federal	Transport	Financial incentives	Federal subsidies for renewable fuels have gone through various permutations since the Energy Tax Act of 1978. The current level is 45 cents per gallon for corn ethanol, 65 cents per gallon for cellulosic ethanol, and $1 per gallon for biodiesel.

TABLE 5-4 Indirect Renewable Energy Policies in the United States

Dates	Policy	Level	Sector	Form	About
1980–present	Subsidies for alternative fuels	Primarily federal	Transport	Financial incentives	Typically collect a small surcharge on electricity sales to use for subsidizing renewable in other ways. As of 2004, more than $300 million invested annually.
200–present	Green power purchasing	States (mandatory in 7)	Electricity	Financial incentives	Protocol by which consumers can pay a surcharge on their electricity prices to "buy" renewable power. Obvious difficulty is that utility cannot choose which electrons go to which consumers; raises questions of additionality.
2009–present	GHG controls	States/ Regional (RGGI, WCI, MGGRA)	All	Command-and-control (with trading)	Any emissions trading or carbon tax legislation would likely lead to a substantial and sustained competitive advantage for renewable power sources. If emission-trading legislation passes, one key question would be the allocation of emission permits. Depending on their distribution, renewable power could be heavily affected.
1975–present	CAFÉ standards	Federal, State (1)	Transport	Command-and-control (with trading)	CAFE fuel efficiency standards do not fully apply to alternative fuels, thereby encouraging adoption of alternative fuels, including renewable fuels.
Many states in 1996	Net metering	States (39 as of 2004)	Electricity	Protocol setting	Allows end-users with installed power sources to sell excess power to the grid. Particularly useful to renewable power sources because of near-zero marginal cost of generation and inability to switch off. Other sources can be used as well.
1970s to present	R&D funding	Primarily federal	All	Research	Wide variety of research funding, such as $2.5 billion for research in the stimulus package to energy efficiency and renewable energy.
Varies	State goals	States (5)	All	Goal setting	Five states that do not have renewable portfolio standards have renewable portfolio goals.

Source: North Carolina Solar Center and U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, Database of State Incentives for Renewables & Efficiency (accessed June 2009 at *http://dsireusa.org/*).

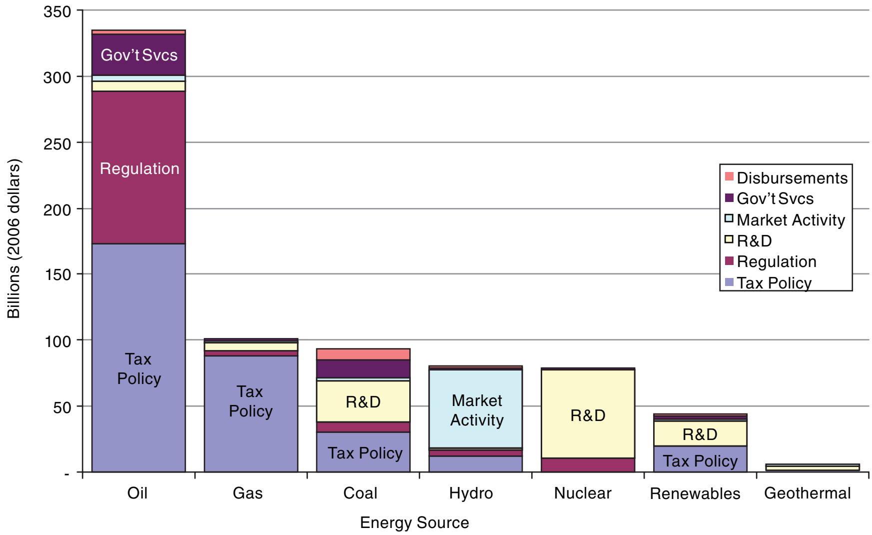


FIGURE 5-1 Comparison of federal incentives for energy development 1950–2006. Source: Bezdek and Wendling, 2007.

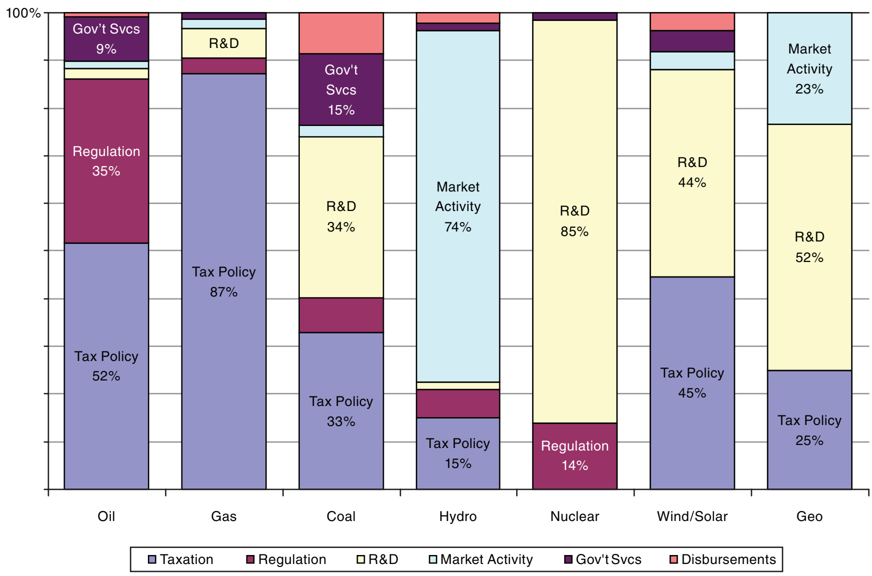


FIGURE 5-2 Mix of federal incentives for each energy source. Source: Bezdek and Wendling, 2007.

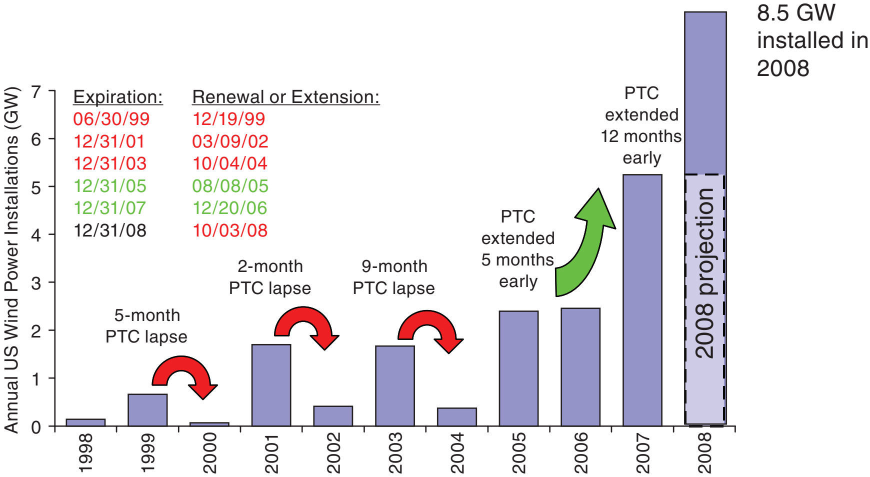


FIGURE 5-3 Fluctuations in wind power deployment and correlation with PTC. Adapted from Wiser, 2008.

The price of renewable energy depends on a variety of factors, such as resource strength, transmission costs, grid-integration costs, and policy (Brown and Busche, 2008). Historically, public policy and incentives have not been sufficient to support widespread deployment. Some project developers have tried "subsidy stacking"—pooling multiple sources of public funding to finance projects to overcome the high cost of infrastructure for renewables. Unless new policies are enacted, EIA (2010a) projects that renewable energy will remain a relatively small share of overall energy capacity in 2035. However, even with short-term price increases in recent years due to high demand and some material shortages of renewables, prices have declined overall and have met overall price projections from previous analyses.

COMPARISON OF ENERGY POLICIES

Although both China and the United States have implemented policies to promote the expansion of renewable energy in their respective markets, their general approaches to policy making differ dramatically. Table 5-5 presents a side-by-side timeline of major renewable energy policy events in each country.

If the United States has developed a "carrot on a stick" approach to ease the entry of renewables into its energy market, China has opted for simply "using the stick" by mandating both the production and consumption of renewable energy. The central government also uses feed-in tariffs (similar to those in Germany) and dictates prices to electric grid operators, who are required, by law, to connect renewable energy sites to the provincial and national electricity grids. In contrast,

TABLE 5-5 Timeline of Events in U.S. and Chinese Renewable Energy Policy

Year	Developments in the U.S. Renewables Policy	Developments in China's Renewables Policy
1978	Public Utilities Regulatory Policy Act enacted, which requires public utilities to purchase power from qualifying renewable facilities. Energy Tax Act provides personal income tax credits and business tax credits for renewables.	
1980	Federal R&D for renewable energy peaks at $1.3 billion ($3 billion in 2004 dollars). Windfall Profits Tax Act gives tax credits for alternative fuels production and alcohol fuel blending.	
1983		Suggestions to Reinforce the Development of Rural Energy.
1992	California delays property tax credits for solar thermal (also known as concentrating solar) power, which causes investment to stop.	China Agenda 21 Release of 10 Strategies on China's Environment and Development
1994	Federal production tax credit (PTC) for renewable electricity takes effect as part of the Energy Policy Act of 1992.	Brightness Program and Ride the Wind Program, formulated by the State Planning Commission, now the National Development and Reform Commission.
1995		State Science and Technology Commission (now the National Development and Reform Commission) Blue Paper No. 4: China Energy Technology Policy Outline on New and Renewable Energy Development in China, State Planning Commission, State Economic and Trade Commission (SETC) (Now incorporated by Ministry of Commerce) Electric Power Law New and Renewable Energy Development Projects in Priority (1996-2010) China, by SSTC, State Power Corporation, and SETC

Continued

TABLE 5-5 (continued)

Year	Developments in the U.S. Renewables Policy	Developments in China's Renewables Policy
1996	Net metering laws started to take effect in many states.	Guidelines for the Ninth Five-Year Plan and 2010: Long-Term Objectives on Economic and Social Development of China State Energy Technology Policy Ninth Five-Year Plan and 2010 Plan of Energy Conservation and New Energy Development by the State Power Corporation Ninth Five-Year Plan of Industrialization of New and Renewable Energy by SETC
1997	States begin to establish policies for renewable portfolio standards (RPS) and public benefits funds (PBF) as part of state electricity restructuring.	Circular of the Communication and Energy Department of SPC on Issuing the Provisional Regulations on the Management of New Energy Capital Construction Project Energy Saving Law
1998		Incentive Policies for Renewable Energy Technology Localization by State Development and Planning Commission (Now the National Development and Reform Commission (NDRC) and Ministry of Science & Technology (MOST)
1999		Circular of MOST and SDPC on Further Supporting the Development of Renewable Energy
2000	Federal production tax credit (PTC) expired in 1999 is not renewed until later this year, causing the wind industry to suffer a major downturn in 2000. Note that the PTC also expired in 2002 and 2004, both times causing a major slowdown in capacity additions.	10th Five-Year Plan for Energy Conservation and Resources Comprehensive Utilization
2001	Some states begin to mandate that utilities offer green power products to their customers.	10th Five-Year Plan for New and Renewable Energy Commercialization Development by SETC Adjustment of Value-Added Tax for Some Resource Comprehensive Utilization Products by Ministry of Finance (MOF) and State Tax Administration Electricity Facility Construction in Non-Electrification Townships in Western Provinces of China or Township Electrification Program by SDPC and MOF

TABLE 5-5 (continued)

Year	Developments in the U.S. Renewables Policy	Developments in China's Renewables Policy
		Renewable Energy Promotion Law Rural Energy Development Plan to 2020 for Western Areas
2004	Five new states enact RPSs in a single year, bringing the total to 18 states plus Washington, DC; PBFs were operating in 15 states	
2005	Energy Policy Act extends the PTC for wind and biomass for 2 years and provides additional tax credits for other renewable including solar, geothermal, and ocean energy.	
2006		Management Rules of Renewable Energy Power Generation Interim Measures for Renewable Energy Power Price and Cost-Sharing Interim Measures for Management of Special Fund for Development of Renewable Energy National 11th Five-Year Plan for Environmental Protection 10th Five-Year Plan for the Development of the Environmental Protection Industry
2007	Energy Independence and Security Act of 2007 provided support for accelerating research and development on solar, geothermal, advanced hydropower, and electricity storage.	Medium and Long-Term Development Plan for Renewable Energy in China
2008	27 states and the District of Columbia have enacted RPSs and another 6 states have adopted goals for renewable electricity. Emergency Economic Stabilization Act extends the PTC for one year and the investment tax credit for residential and commercial solar through 2016.	The Renewable Energy Development Planning during 11th Five Year Planning Period.
2009	American Recovery and Reinvestment Act extends the PTC for wind through 2012 and the PTC for municipal solid waste, biopower, geothermal, hydrokinetic, and some hydropower through 2013. It also provides funding for research and updating the electricity grid.	Mandates power grid operators to buy all the electricity produced by renewable energy generators under their region. Feed-in-tariff established for onshore wind power projects, replacing public bidding process.

the United States tends to favor market-based policies (e.g., PTC) to provide incentives for renewable energy use. Even U.S. quotas, like the RFS and state RPS, rely increasingly on market mechanisms to reduce the cost of compliance.

In the United States, job creation is a recurrent theme in the rationale for legislation in the United States (e.g., H.R. 6049, The Renewable Energy and Job Creation Act of 2008). China also considers renewable energy production a means of creating jobs, which numbered 1.12 million in the renewable energy sector in 2008 (CREIA, 2009). However, China also considers renewables development a means of economic and technological development. This sounds like a subtle distinction, but because of the nature of China's centralized planning approach to growing its economy, this means that the renewables sector is featured prominently in discussions of national investments in R&D, manufacturing capabilities, and overseas markets.

Both countries express concerns about the environmental impact of fossil-fuel combustion. China has focused its efforts on reducing emissions of particulates, sodium oxide, and nitrogen oxide. According to the Mid-Term and Long-Term Renewable Energy Development Plan, "The "2020 goal [of renewable energy production] is equivalent to an annual emissions reduction of 8 million tons of sulfur dioxide, 3 million tons of nitrogen oxide, 4 million tons of smoke and dust, 1.2 billion tons of carbon dioxide." The United States is also concerned about nitrous and sulfur oxides emissions, as well as GHG emissions. In November 2009, the White House proposed a goal to reduce GHG emissions by 83 percent by 2050.

Renewable energy has given China an opportunity to provide much needed electrical generating capacity in rural areas that are not connected to the grid. This situation mirrors the historical experience in rural communities of the United States. Since 1936, the U.S. Department of Agriculture has made direct loans and provided loan guarantees for electrification of rural areas, including guaranteed loans for renewable energy projects. In addition, biomass-based renewables can boost agriculture-based economies in the impoverished central and western provinces of China. In the United States, there is growing interest in using biomass to co-fire coal power plants, or in some cases, convert coal combustion facilities to biomass-based combustion facilities.

China and the United States have different attitudes toward the place of biofuels in their energy policies. The United States considers the development of biofuels relatively more important than China does because of concerns about energy security and transportation fuels. Ethanol, which constitutes more than 90 percent of the biofuel produced in the United States, is also a primary additive used to reformulate gasoline in order to meet oxygenate requirements under the Clean Air Act. China shares some of these concerns, particularly in light of the rapid increase in personal vehicle use, and has implemented pilot projects mandating ethanol blends in certain regions of the country. However, China's energy policy does not place nearly as much emphasis on biofuels as U.S. policy. One of the main drivers for biofuel production in China is the development of the rural economy.

POTENTIAL CONSTRAINTS ON DEPLOYMENT

Materials

A scarcity of key raw materials necessary to renewable energy technologies can keep manufacturing prices high. The wind energy sector, for example, is experiencing competition-driven shortages for some key materials. Table 5-6 lists the projected material requirements for the United States to meet a goal of producing 20 percent of its electricity from wind energy by 2030, which will require installing at least 7,000 turbines per year for 13 years beginning in 2017 (DOE, 2008a). Thus, trade issues and export/import controls can be a factor in accelerating or hindering the rapid deployment of wind power electricity and other renewables.

Rare-earth elements, one type of material in short supply, are used in the permanent magnets of wind turbines. These same materials are in great demand for an array of electronic devices. China currently accounts for almost 97 percent of the world's production of rare-earth elements. Although the United States also has some, mining operations for these compounds ceased a decade ago because of high production costs. With recent increases in market prices, however, the United States may soon re-initiate operations.

China could satisfy its requirements for steel and copper for wind turbine production but will have to improve its smelting processes to improve the quality of those materials. The composite materials necessary for manufacturing wind turbine blades include epoxy resin, glass fiber, adhesives, and foam core. Epoxy resin and glass fiber can be produced in China, but adhesives and foam core must be imported.

As PV production scales up, shortages of semiconductor materials can become an impediment. A shortage of silicon for PV production can also be a problem but is relatively easy to solve. Silicon in raw form is widespread throughout the world. The bottleneck is created by the shortage of purification plants, rather than the shortage of silicon itself. In fact, China's rapid investment (since 2005) in silicon purification contributed partly to recent decreases in the price of silicon-based PV panels, though the country now faces a problem of overcapacity, relative to global demand. Feedstocks for thin-film PV, particularly tellurium for cadmium telluride panels and indium for copper, indium, gallium, and selenide cells, could potentially be limiting factors if production of thin films scales up quickly. Obtaining sufficient quantities of these metals, although relatively abundant in nature, may require additional investments in extraction, refining, and recovery (i.e., recycling products containing the metals) (Fthenakis, 2009).

Workforce

The lack of skilled workers can limit the large-scale manufacturing and deployment of renewable electricity systems. For example, the wind power sector needs workers with a variety of particular skills and expertise (Tables 5-7 and 5-8). The

TABLE 5-6 Projected Material Requirements for 20 Percent Wind Energy Scenario.

Year	kWh/kg	Perm. Magnet	Concrete	Steel	Aluminum	Copper	GRP	CRP	Adhesive
2006	65	0.03	1,614	110	1.2	1.6	7.1	0.2	1.4
2010	70	0.07	6,798	464	4.6	7.4	29.8	2.2	5.6
2015	75	0.96	16,150	1,188	15.4	10.2	73.8	9.0	15.0
2020	80	2.20	37,468	2,644	29.6	20.2	162.2	20.4	33.6
2025	85	2.10	35,180	2,544	27.8	19.4	156.2	19.2	31.4
2030	90	2.00	33,800	2,308	26.4	18.4	152.4	18.4	30.2

Notes: kg = kilograms; GRP = glass fiber reinforced plastic; CRP = carbon fiber reinforced plastic.
Source: DOE, 2008a. Adapted from Sterzinger and Svrcek (2004).

TABLE 5-7 Types of Skills Required for Increased Deployment of Wind Energy.

Segment	Description	Details
Construction, repair, opereation, and maintenance	Building the wind farm, regular inspection and repair activities	Technical staff for O&M and repairing the wind turbines Electrical and civil engineers to coordinate the building work Health and safety experts Specialists in the transport of heavy goods Technical staff for activities in cranes, fitters, nacelles, etc. Other support staff
Independent power producers, utilities	Operation of the wind farm and sale of the electricity produced	Electrical, environmental, and civil engineers for the management of the plant Technical staff for the O&M of the plants Health and safety experts Financiers, salespersons, marketing people to sell the electricity
Consultancies, legal entities, engineering, R&D centers	Diverse specialized activities linked to the wind energy business	Programmers and meteorologists for analyzing wind regimes and output forecasts Engineers specialized in aerodynamics, computational fluid dynamics and other R&D areas Environmental engineers Energy policy experts Experts in social surveys, training, and communication Financiers and economists Lawyers in environmental matters Marketing staff, event organizers
Manufacturers	Wind turbine producers, including sub-component and assembly factories	Highly qualified chemical, electrical, mechanical, and material engineers dealing with R&D issues, product design, management and quality control of production process Semi-skilled and non-skilled workers for production chains Health and safety experts Technical staff for O&M and repairing turbines Other support staff (admin., sales managers, marketing, others)
Developers	Managing all the tasks related to the development of wind farms (planning, permits, construction, etc.)	Project managers (engineers, economists) to coordinate the process Environmental engineers and other specialists to analyze the environmental impacts of the wind farms Programmers and meteorologists for wind energy forecasts and prediction models Lawyers and economists to deal with the legal and financial aspects of project development Other support staff (admin., sales managers, marketing, others)

Source: EWEA, 2009.

TABLE 5-8 Direct Employment by Type for the Wind Energy Sector

Direct Employment by Type	
Manufacturers	37%
Component manufacturers	22%
IPP/Utility	9%
Developers	16%
Installation/Repair/Operations	11%
Consultancy	3%
R&D/University	1%
Financial/Insurance	0.3%
Others	1%

Source: EWEA, 2009.

number of jobs directly or indirectly related to the wind energy sector in the United States increased from 50,000 in 2007 to 85,000 in 2008 and remained steady in 2009. About a quarter of these jobs are in manufacturing and 12 percent are in construction; the rest (the vast majority) are in others jobs that support the industry, such as accountants, engineers, computer analysts, clerks, factory workers, truck drivers, mechanics, and so on (AWEA, 2009). Some of these workers may not even realize that they owe their livelihoods to renewable energy.

Table 5-9 shows a breakdown of private employment and revenues related to renewable energy industries in the United States in 2007. More than 95 percent of jobs and 90 percent of revenues in that year were in private industry and more than half of the jobs in government were in research and development (R&D) at national laboratories. Table 5-10 shows the number and types of jobs created by the renewable energy sector in 2007.

TABLE 5-9 The Renewable Energy Industry[a] in the United States, 2007

Industry Segment	Revenue/Budget (billions U.S. $)	Industry Jobs	Total Jobs Created
Wind	3.3	17,300	39,600
Photovoltaics	1.3	8,700	19,800
Solar thermal	0.14	1,300	3,100
Hydroelectric power	3.5	7,500	18,000
Geothermal	2.1	10,100	23,200
Biomass			
Ethanol	8.4	83,800	195,700
Biodiesel	0.4	3,200	7,300
Biomass power	17.4	67,100	154,500
Fuel cells	1.1	5,600	12,800
Hydrogen	0.81	4,100	9,400
Total Private Industry	**38.45**	**208,700**	**483,400**

[a] Does not include federal employees, laboratory employees, or direct support contractors.
Source: ASES, 2009.

TABLE 5-10 Renewable Energy Jobs Generated in the United States in 2007, by Selected Occupations

Industry Type	Jobs	Industry Type	Jobs
Agricultural Equipment Operators	4,260	Industrial Production Managers	760
Biochemists and Biophysicists	1,580	Inspectors, Testers, and Sorters	2,400
Bookkeeping and Accounting Clerks	8,228	Janitors and Cleaners	3,610
Business Operations Specialists	3,390	Machinists	1,820
Carpenters	780	Mechanical Engineers	1,950
Chemical Technicians	1,880	Payroll and Timekeeping Clerks	1,160
Civil Engineers	3,080	Plumbers, Pipefitters, and Steamfitters	4,670
Computer and IT Managers	1,210	Purchasing Agents	1,280
Computer Programmers	2,660	Sales Representatives	4,140
Computer Software Engineers	3,260	Security Guards	1,310
Database Administrators	560	Sheet Metal Workers	1,600
Electrical and Electronic Equipment Assemblers	840	Shipping and Receiving Clerks	2,210
Electricians	6,330	Surveyors	690
Engineering Managers	1,350	Tax Preparers	580
Environmental Engineers	630	Tool and Die Makers	620
Environmental Science Technicians	1,690	Training and Development Specialists	650
Employment, Recruitment, and Placement Specialists	600	Truck Drivers	9,500
Forest and Conservation Workers	1,440		
HVAC Mechanics and Installers	2,130		
Industrial Engineers	1,340		

Source: ASES, 2009.

The European Wind Energy Association (EWEA) estimates that approximately 15.1 construction jobs are needed for every MW of wind capacity, and 0.4 jobs per MW are needed for maintenance (EWEA, 2009). Ensuring the availability of a skilled workforce of that size will require a training infrastructure that targets every component of the industry's value chain (Weissman, 2009). Establishing certification and accreditation levels might help in creating a framework for training. Certification indicates that an individual meets competency standards for a predefined task; existing certification programs for the solar PV industry could serve as a template for certification programs in the wind energy industry. Accreditation denotes that an institution is capable of teaching students at a level that meets predetermined standards. As part of the 2009 American Recovery and Reinvestment Act, the U.S. Department of Labor provided training grants totaling $100 million to several states, to train workers in energy efficiency and renewable energy industries.

As the renewable energy industry scales up, it will be increasingly dependent upon a network of support services that are not necessarily compatible with the existing energy services sector. In the United States, firms offering these support services have proliferated rapidly, whereas in China they have been much slower to develop. For both countries, a mature renewables industry will rely on these ancillary services, which include energy audits, project design, and risk management.

Market and Financial Risks

Market risks reflect the uncertainty of finding a sufficiently large market for a new product and the difficulty of acquiring market share because of lower priced competition. Misplaced incentives or unfavorable fiscal policies, statutes, or regulations can cause long-term demand to fall short of expectations. Financial risks are a measure of the likelihood that an investment will not yield sufficient returns. A higher risk translates into more expensive access to capital and higher expected rates of return. These risks vary depending on how an industry is structured and may be particularly high under certain structures. Fragmented industries (e.g., much of the renewable energy industry) are characterized by a lack of standardization, and a high dependence on specialized markets. Industries characterized by monopolies (e.g., utilities in the electricity sector) tend to aggressively defend incumbent technologies and are slow to innovate.

Widespread deployment of renewables will require significant capital, which cannot be provided by the public sector alone. However, governmental presence is still very important, particularly in the early stages of deployment, because it could reduce market and financing risk and effectively leverage investments from the private sector. Some financing may come from venture capital firms (firms that invest in start-up companies hoping for large future returns). However, most venture capital firms have three- to seven-year investment timeframes, which is a small window for large-scale deployment projects.

Besides industry-specific market and financing risks, the health of the overall economy is an important factor in the cost and availability of capital. The global financial crisis of 2007–2008 caused a drop in total investments in the clean energy sector, although the situation had improved by early 2009, partly as a result of stimulus plans (REN 21, 2009). The United States and China each committed roughly $67 billion in stimulus funds to support "sustainable"[2] energy (UNEP/SEFI/NEF, 2009), although China outpaced the United States nearly 2 to 1 in terms of actual investments made in 2009, $34.6 billion to $18.6 billion (Pew Charitable Trusts, 2010).

High Costs

The cost of some renewable technologies might go down as increased deployment leads to economies of scale and efficiencies from learning. Experience curves, which model the relationship between cumulative deployment and cost, can help in determining investment requirements. Figure 5-4 illustrates the historical decrease in cost of wind turbine systems as cumulative installed capacity increased. Figure 5-5 shows experience curves for a variety of renewable energy technologies as well as natural gas combined-cycle and pulverized-coal technologies. As the latter figure illustrates, prices do not fall uniformly with experience; in some cases they rise as a result of market forces.

Using experience curves to estimate future costs should be done with some caution. First, in the short-term at least, experience curves do not reflect the effects of increased costs for raw materials. Second, a change in policy can create a sharp rise in demand for certain materials, which can lead to an increase in production

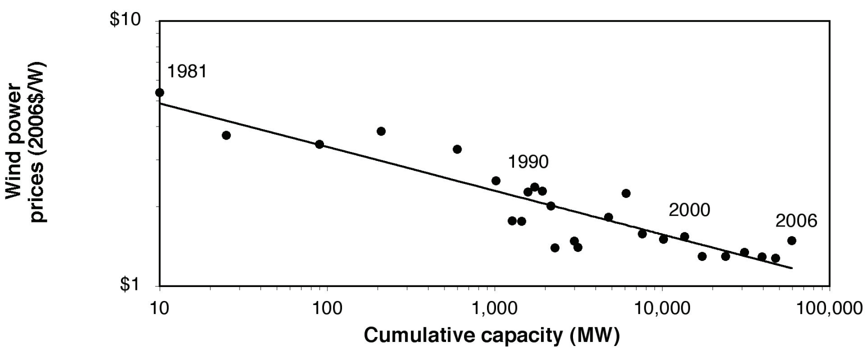


FIGURE 5-4 Experience curve for capital costs of wind turbines (1981–2006). Source: Nemet, 2009. Reprinted with permission from Elsevier.

[2] Primarily renewables and energy efficiency initiatives.

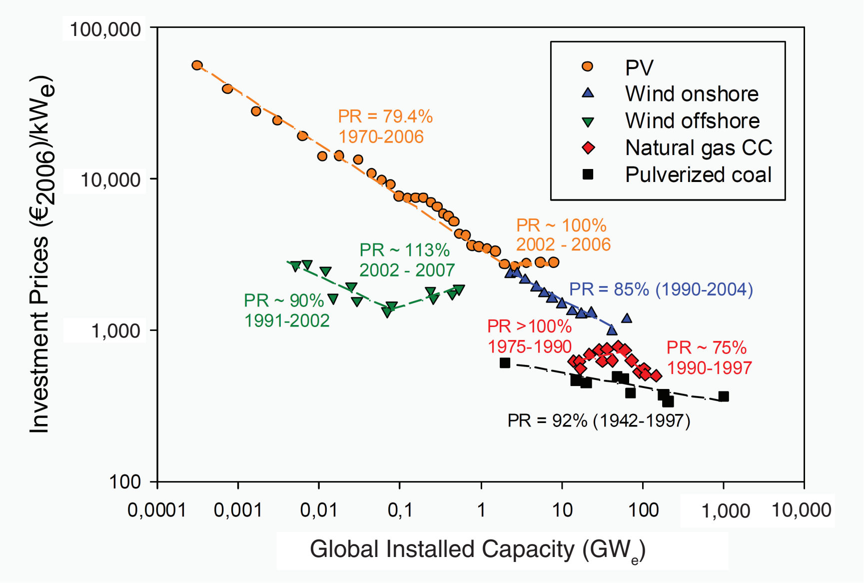


FIGURE 5-5 Comparison of experience curves for various energy supply technologies. Source: Junginger et al., 2008. Reprinted with permission.

costs. Finally, outsourcing to low-wage regions can translate into a decrease in production costs that does not signify improvements attributable to learning.

From a consumer's point of view, price can be a relative measure. Whether or not a renewable energy technology is considered expensive depends on the availability of a less costly alternative that can serve a similar function. Accurate predictions of the future cost of fossil-fueled electricity are therefore important considerations when forecasting the deployment of renewables. Although previous U.S. studies have done well predicting the cost of renewables, they consistently overestimated the retail price of fossil-fueled electricity, which led to inaccurate predictions for the penetration of renewable electricity (Bezdek and Wendling, 2003; McVeigh et al., 2000).

Other Constraints

Competition for construction management and equipment could delay deployment; these limitations could include a lack of tools for siting renewable energy technologies (e.g., meteorological equipment) and a lack of construction equipment (e.g., tall cranes). As renewable power installations increase in number, such competition will likely become more acute.

Incomplete and imperfect information about new renewable technologies and their performance can also be a barrier to deployment. Trustworthy information is limited today because stakeholders, constituents, supply chain providers, and user communities have not yet coalesced into a mature market, with standardized parts, tools, and performance metrics. This uncertainty engenders a technical risk (that an innovative technology will not perform to specifications), which can translate into an increase in financing costs.

FINANCING AN EXPANDED MARKET FOR RENEWABLES

Renewable technologies offer performance attributes that, at least at the outset, are not valued by a majority of existing customers. As disruptive technologies, renewables have largely been able to enter the electricity market because of direct and indirect subsidies driven by specific mandates (e.g., a state RPS), even though traditional electricity sources outperform non-hydropower renewables in terms of cost and availability. Figure 5-6 shows the growth of renewable energy sources in the United States and China from 1980 to 2009. Despite that growth, however, questions about long-term viability remain, particularly as both countries approach a material share of renewables in their power generation portfolios.

Public funds would be the most effective way to leverage private investment, but because of the nature of the electricity market, public funds will also

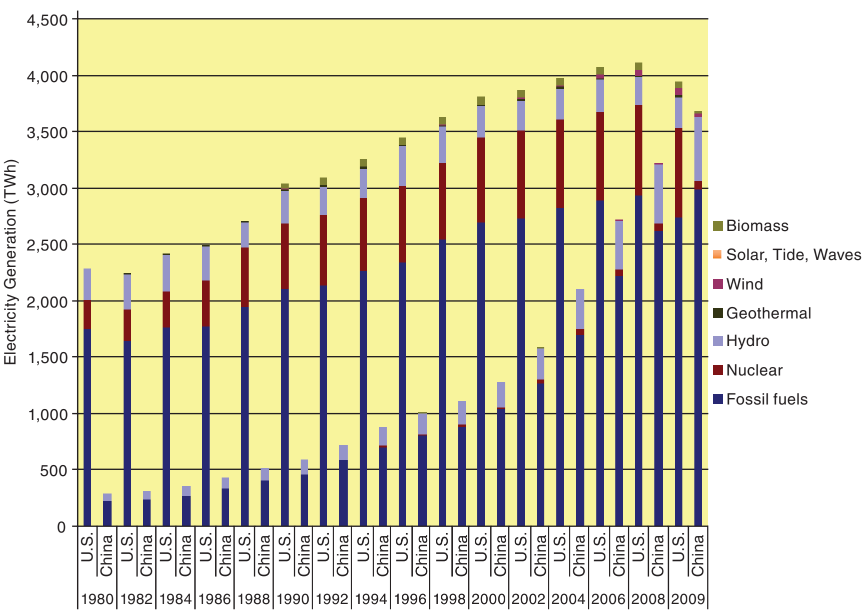


FIGURE 5-6 Power generation by source in the U.S. and China, 1980–2009. Sources: CEC, 2010; EIA, 2010b,d.

be needed to finance projects in the early stages of commercialization. Whereas consumer products can follow the traditional road map to commercialization, the homogeneity of electricity will make it difficult to market renewable energy to premium-paying early adopters. Electricity is the same whether it is generated from low-carbon renewable sources or coal-fired power plants. Renewable energy certificates (RECs) have been the preferred tool to overcome this limitation. RECs represent the "unbundled" attributes of electricity generated from renewable resources, and these attributes are then sold or traded independently of the electricity (Holt and Bird, 2005). RECs are now widely used to comply with a state's RPS, as part of a green power marketing strategy for retail consumers, and as a source of additional revenue to support renewable energy projects (Holt and Wiser, 2007).

Arguably, tax equity has been the most powerful recent driver in renewables development in the United States, through production and investment tax credits, which help project developers access financing. In addition, the renewable energy sector can benefit from the direct infusion of public funds for newly commercialized projects (Murphy and Edwards, 2003). Government support can be used to establish or expand existing public finance mechanisms (PFMs) (UNEP, 2008), which, although they vary in structure and focus, all attempt to mobilize commercial financing and build commercially sustainable markets for renewable energy projects. Table 5-11 lists some of the most common PFMs currently used in the renewable energy and energy efficiency sectors and summarizes the barriers and market segments they address. Most have been used in a variety of countries and some have track records that justify replication and scaling up.

NEAR-TERM PRIORITIES TO SUPPORT DEPLOYMENT

Beyond addressing environmental challenges, a sustainable market for renewable energy offers opportunities for economic development and job growth. In addition to a solid market infrastructure, widespread deployment of renewables will require (1) deploying adequate grid technology to optimize the operating characteristics and variable output of renewable sources, and (2) developing and adopting international standards to reduce market risks.

Grid Integration

An effective electrical distribution system must supply uninterrupted power to demand centers that vary in scale and location. This system must balance a portfolio of energy resources that have unique performance characteristics. As renewable energy assumes a larger share of the generation portfolio, the task of balancing resources will become increasingly complex. However, at present, non-hydro renewables account for less than 2 percent of electricity generation in China and the United States, and experience in the United States and Europe suggests that grid operators have been able to accommodate upwards of 20 percent of generation coming from non-hydro renewables without requiring storage (NAS/NAE/NRC, 2010a).

When evaluating the cost of integrating new technologies into the transmission and distribution infrastructure, the cost of expanding the current grid must be taken into account. In the case of the United States, if the transmission portion of the grid were simply expanded, the estimated cost would be $188 billion (2010 dollars). If the grid were modernized in a separate initiative, this would cost an estimated $112 billion. However, if expansion and modernization were done concurrently, the cost would still be $188 billion for expansion but would be only $54 billion for modernization (a savings of $58 billion). If, in addition, the distribution system were expanded and modernized concurrently, the estimated cost savings would be $209 billion (2010 dollars) (NAS/NAE/NRC, 2009a).

The deployment of renewable energy will create a need for more ancillary services, new storage technologies, and access to other dispatchable resources (e.g., natural gas) to maintain overall system reliability. These services, technologies, and resources are all components of a modernized grid (also discussed in Chapter 6). In general, a modern electrical grid has the following characteristics (NETL, 2007):

- It gives customers and utilities demand-management capability. The grid provides information to customers that enables them to participate in demand-response programs.
- It delivers high-quality power. The system provides power that meets industry standards. Hydropower and natural gas-fired generation, resources that ramp up fairly quickly, can compensate for the variability of wind and solar. It would be difficult to do this with nuclear or coal-fired generation.
- It has the capability of integrating distributed generation. The overall system integrates different types of distributed-generation and storage devices to complement large generating plants.

A number of insights have emerged from the increasing integration of wind power into existing power systems (VTT, 2008). These include:

- Larger balancing areas allow utilities to aggregate wind plants, decreasing the variability of output. On a short time scale, this translates into a smaller reserve requirement.
- Optimizing existing transmission capacity, which sometimes requires upgrading or extending existing transmission, brings benefits to large-scale wind farms and provides improved system balancing services.
- Integrating wind generation information (see Figure 5-7) with both real-time and updated forecasts (hourly and day ahead) will help reduce errors associated with forecasting and scheduling. Well-functioning hour-ahead and day-ahead markets can cost-effectively provide the balancing energy required of variable-output wind power plants.

TABLE 5-11 Common PFMs Used in the Renewable Energy and Energy Efficiency Sector

	Mechanism	Description	Barriers	Financial Markets	Sectors
Debt	Credit line for senior debt	Credit line provided to commercial fianncial institutions (CFIs) for on-lending to projects in the form of senior debt	CFIs lack funds and have high interest rates	Underdeveloped financial markets with lack of liquidity, and high costs for borrowing	Large-scale renewable energy (RE) and energy efficiency (EE); wholesale loans for energy access markets
	Credit line for subordinated debt	Credit line to CFIs for on-lending to projects with subordinated repayment obligations	Debt-Equity gap, whereby project sponsors lack sufficient equity to secure senior debt	Lack of liquidity in both equity and debt markets	Medium- and small-scale
	Guarantee	Shares project credit (i.e., loan) risks with CFIs	High credit risks, particularly perceived risks	Existence of guarantee institutions and experience with credit enhancing	Large-scale RE and EE and energy access markets
	Project loan facility	Debt providing by development finance institutions (DFIs) directly to projects	CFIs unable to address the sector	Strong political environment to enforce contracts and enable laws for special purpose entity	Large- and medium-scale EE and RE
Equity	Private equity fund	Equity investments in companies or projects	Lack of risk capital; restrictive debt-to-equity ratio	Highly developed capital markets to allow equity investors to exist from investee	Large-scale grid-connected RE; energy companies
	Venture capital fund	Equity investments in technology companies	Lack of risk capital for new technology development	Developed capital markets to allow eventual exits	Any new technology

	Mechanism	Description	Barriers	Financial Markets	Sectors
Carbon	Carbon finance	Monetization of future cash flows from the advanced sale of carbon credits to finance project	Lack of project development capital; lack of cash flow for additional security; uncertain delivery of carbon credits	Availability of underlying financing for projects. Adequate institutional capacity to host clean development mechanism/ joint implementation (CDM/JI) projects and to enforce contracts	Large-scale RE and EE; program of activities such as in energy access markets
	Carbon transaction in post-2012 credits	Contracting for the purchase of carbon credits to be delivered after 2012	Lack of regulatory framework and short-term compliance driver buyers	Availability of underlying financing. Adequate institutional capacity to host clean development mechanism/joint implementation project and enforce contracts	Any GHG emissions reduction project
Innovative Grants	Project development grants	Grants "loaned" without interest or repayment until projects are financially viable	Poorly capitalized developers; costly and time consuming development process	Can be needed in any financing market context	Any sector
	Loan softening programs	Grants to help CFIs begin lending their own capital to end-users initially on concessional terms	Lack of FI interest in lending to new sectors; limited knowledge of market demand	Competitive local lending markets	Medium- and small-scale EE and RE
	Inducement prizes	"Ex-ante prizes" to stimulate technology development. Unproven in climate sector	High and risky technology development costs and spill-over effects	Sufficient financing availability to deploy winning technologies	Any technology sector

Source: UNEP, 2008.

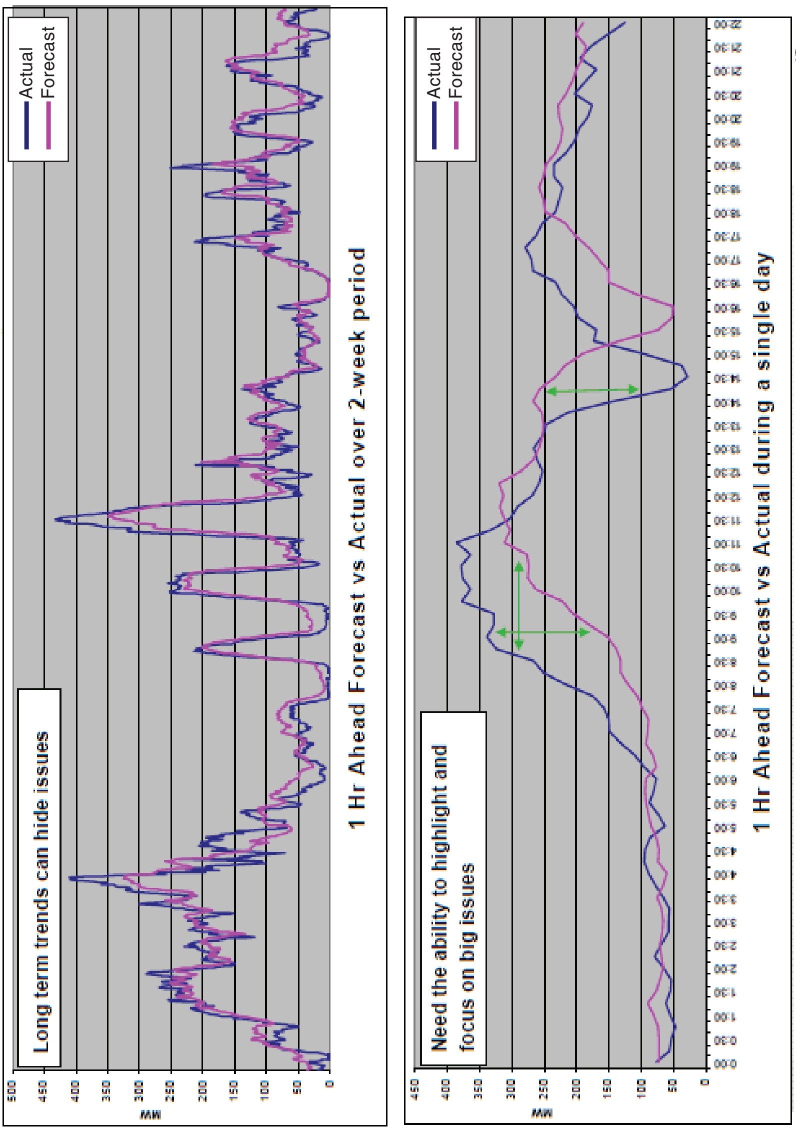


FIGURE 5-7 Requirements and expectations for a quality wind forecast. Source: Edelson, 2009. Reprinted with permission.

Finally, new transmission will be required to link remote areas rich in resources. Although this is recognized as an impediment to developing some renewable energy sources, progress is under way in parts of the United States (such as the Tehachapi region in southern California) to build transmission that will serve primarily renewables. China has favored high-voltage (750 kV and above) transmission for its new lines and has begun building transmission that would be primarily served by large renewable power bases in the west and northwest regions, e.g., Gansu province's construction of high-voltage lines for PV and wind. More efficient lines, cost sharing for interconnections, and advances in system flexibility, including storage, should help to mitigate concerns over new transmission costs.

The financing of new transmission facilities will also require large amounts of public and private capital. Which entity bears the responsibility for financing transmission facilities varies from region to region in the United States and is governed by tariffs filed at the Federal Energy Regulatory Commission (FERC). In some regions of the U.S., generation developers bear the full (or a large portion) of the financing responsibility for transmission network upgrades. In other regions generation developers are required to provide the upfront financing for network facilities and are refunded such costs after reaching commercial operation. In some cases, the load serving utilities have the discretion to upfront finance the cost of network facilities on behalf of the generation developers. Regardless of "who pays" upfront for the required transmission facilities, ultimately these network upgrade costs are capitalized into the utilities' rate bases and are reflected in transmission rates.

The EPAct of 2005 included the ability for FERC to grant certain incentives to promote the development and construction of new transmission infrastructure. These incentives, which can raise the rate of return on such investment to regulated utilities, and among other things, provide cost recovery to utilities if a transmission project must be abandoned for reasons outside of the control of the utility, have played an important role in the development and financing of high-profile transmission projects geared toward the interconnection of renewable resources, such as Southern California Edison's Tehachapi Renewable Transmission Project (a $2.1 billion investment to access 4500 MW of wind, solar, and other resources).

The allocation of financing responsibility can become even more complex in the case of long-distance transmission lines that cross state boundaries and control area boundaries. Thus, the "who benefits" from such facilities, in addition to the "who pays" concerns discussed previously, continue to cloud the outlook for such inter-state/inter-region transmission facilities. In 2010, FERC launched a Notice of Proposed Rulemaking to address regional Transmission Planning and Cost Allocation issues and seek solutions to these issues.

Industrial Research and International Standards

For both countries, the deployment of renewable energy technologies depends, at least partly, on the implementation of industry standards for manufacturing, installation, and operation. Investors may be reluctant to invest in renewable energy projects because of uncertainties about the performance of renewable energy sources. Deployment could, therefore, be easier if technical standards for product performance, manufacturing quality control, and standard grid interconnection have been developed and adopted (IEA, 2010e). Because of the absence of standards for transmission infrastructure, the electricity market remains fragmented. This has created significant barriers to the deployment of renewable electricity technologies.

In the Energy Independence and Security Act of 2007, the National Institute of Standards and Technology (NIST) was assigned to "coordinate development of a framework that includes protocols and model standards for information management to achieve interoperability of smart grid devices and systems." NIST has devised a two-pronged approach: (1) working groups to study various aspects of standards in grid integration, including transmission and distribution, building the grid, business, and policy; and (2) a cybersecurity coordination task group to examine issues related to data privacy.

FINDINGS

China's top-down, government-mandated approach to energy policy has led to aggressive development of the renewable energy industry. Although China will continue to use coal as its primary energy source for the foreseeable future, it is evident that its renewable energy policies have stimulated the creation of a strong manufacturing sector for renewable energy, and more recently, a domestic market for deployment.

Both the national and some provincial governments in China and some state governments in the United States have established goals and mandates for the share of electrical generation from renewables. However, the targets and implementation mechanisms differ. Chinese policy is characterized by "outcome-based goals" set at the national level, e.g., specific national targets for share of renewables in generation portfolio, or share of domestically manufactured equipment in renewable power systems. This approach, augmented by subsidies, has been successful in driving substantial new Chinese manufacturing capacity in recent years. U.S. renewable policy is characterized by a greater focus on advancing specific technologies at the national level with market outcomes encouraged at the state level. This approach has been successful in driving technology development but has been less successful in supporting the buildout of manufacturing capacity.

The most prominent national policy approach for renewable energy development in both China and the United States has been price support. In the United

States, the level of renewable energy investment has fallen when subsidies have been suspended, demonstrating the importance of price stability in an emerging renewable energy market, both for technology development and manufacturing capacity. U.S. subsidies, primarily tax breaks for producers and consumers, have been effective in driving specific technology development. China has been more effective at capturing a higher market share of renewable energy-associated manufacturing, particularly in the solar PV market and increasingly in the wind energy sector, at least partly because of general incentives for manufacturers (e.g., low-cost loans) and government-set pricing for renewable power generation.

Development of renewables has suffered in the United States and China because the costs of externalities, particularly the impact of GHG emissions, are not reflected in current energy prices. Both countries set subsidy values specific to particular resources (wind, solar, etc.). Subsidy values generally are driven more by specific policy goals and objectives and remain difficult to justify by real costs of production from competing supply resources. **Both countries might benefit from reorienting their policies and incentives to electricity markets (as opposed to individual technologies) and the utilities operating in these markets.** Examples include: promoting time-of-use rates to better match retail prices with generation costs, encouraging advanced metering to enable more demand response, and facilitating or streamlining transmission operation and expansion.

Government energy policies can have a critical impact on clean energy development, and legacy energy policy, regulations, and subsidies are key drivers in determining the success of clean energy initiatives and the achievement of green energy goals. **The historical legacy of U.S. energy subsidies—and the legacy in most developed and developing economies (a pattern that continues)—often places clean energy at an economic disadvantage in the marketplace.**

The design of outcome-based incentives will be critical for overcoming the barriers to renewable energy and promoting more rapid, sustainable clean energy development—in both the United States and China. To maximize the effectiveness of financial incentives, they should be designed to work with other policies to address market barriers. In addition, each jurisdiction should design financial incentives to complement national and regional incentives and mandates. Finally, incentives should be provided with enough time to support planning, capital formation, and construction.

In recent years, the United States and China have taken steps to include a larger share of renewable energy sources in their overall electricity generation portfolios. However, both countries face a number of challenges that warrant the attention of policy makers: the difficulty of introducing new technologies in a competitive market; finding adequate financing for long-term development; conducting market-enabling research that is understandable to various stakeholders; and developing government initiatives to share the risk of innovations in production and market transformation.

Other challenges include constraints on large-scale manufacturing and installation capacity, the lack of a trained workforce, the difficulty of integrating variable-output resources into the existing electricity infrastructure and market, stiff competition in price and performance with conventional power sources, and issues related to business risk and cost. China faces one very significant additional hurdle. It must create a robust supply channel for bringing renewable energy technologies to market.

The current focus in China, and to a lesser extent in the United States, appears to be on the installation of large blocks of power production plants. Widening the focus to include distributed generation, on both the community and customer levels, would have positive impacts on the electricity distribution system in both countries. With technological improvements and the rising costs of fossil fuels and nuclear power, renewables may soon be able to match the cost performance of traditional power generation sources, either in the wholesale power market or on the customer side of the meter.

Consistent and supportive policies would help the developing industry in both countries, but over the long-term renewable power developers will need to focus on becoming cost-competitive with fossil fuels. Innovative financing mechanisms for renewable projects could help them overcome the challenge of being capital-intensive (compared to conventional fossil-fuel generation). Project developers could begin placing value on the risk reduction attributes of renewable energy sources, notably the uncertainties of fossil-fuel prices and the threat of emissions regulation, when evaluating investments in new power generation. Both countries would benefit from implementing renewable-energy-based power pricing mechanisms so that costs and benefits of new technologies are shared by all market participants. They could explore market mechanisms, such as Renewable Energy Credits, that would enable consumers to participate in the renewable power market and develop market mechanisms to enable all market participants to share in the costs and benefits of grid interconnections.

Operating experience will become a valuable tool—utility and grid operators in both countries have much to gain from sharing their experiences in integrating and managing larger shares of renewable power generation. Costs can come down as market participants gain experience with a new technology. Feedback to other market participants such as the technology manufacturers, installers, and regulators can be critical for reducing costs. **Both countries could benefit from programs to capture performance data from renewable energy technologies operating in the field and the distribution of the data throughout the supply chain.** China's renewable power market could experience a more rapid evolution by establishing more formal and informal mechanisms to capture this organizational learning. Additionally, as the global industry grows, the United States and China can exhibit leadership by cooperating on establishing or supporting technical standards for the various generation technologies.

RECOMMENDATIONS

- The United States should consider conducting a multiagency strategic assessment of U.S. renewable energy manufacturing capabilities, in alignment with U.S. innovation activities, to determine where additional capacities should be promoted. Financial support should be considered to expand the manufacturing base for existing and near-term deployment needs through the research and demonstration of process improvements and efficiencies and the establishment of mechanisms to share the risk of private-sector investment in building new manufacturing capacity. In addition, targeted public/private risk-sharing programs should be considered to move technologies from concept through to manufacturing.
- Cognizant organizations in China and the United States, including government agencies, international standards organizations, and professional societies should collaborate on developing technical standards and certification mechanisms for renewable energy technologies for: (1) product performance and manufacturing quality control and (2) standard grid interconnection for both distributed, customer-sited resources and whole, central station resources.
- China should establish national facilities with capabilities to test performance and safety characteristics of complete renewable power systems and their subcomponents. Examples include testing PV systems to Underwriters Laboratories (UL) standards or evaluating the Power Curve from a small wind turbine.
- The United States and China should increase cooperation among researchers and grid operators to improve wind forecasting. Improved meteorological data and forecasting will provide more and better data on expected power output from existing wind power plants and assist with their integration into the grid.

6

Transitioning to a Sustainable Energy Economy

A sustainable energy economy is one that reliably meets demand at reasonable cost and accounts for externalities that are not reflected in the current cost of fossil-fuel energy (e.g., NRC, 2010a; Tester et al., 2005). No single technology, renewable or otherwise, will be sufficient to satisfy these conditions on its own, so we will need a portfolio of energy options. Moreover, new technologies must be incorporated into society, and so, beyond conversion efficiency and price per kWh, there are several factors to consider in attempting to increase the share of renewable power in both countries' generation portfolios.

In this chapter, we examine U.S.-Chinese cooperation in the context of integrating a variety of technologies into a cohesive energy system. We will also discuss some of the "enablers" of renewable power and identify barriers to the proliferation of renewables that will have to be overcome in the medium (2020 to 2035) and long term (to 2050).

MOVING TOWARD INTEGRATED SYSTEMS

Aligning Energy Efficiency and Renewable Energy Goals

For the next decade, deploying energy efficiency technologies will be the lowest-cost option for moderating energy demand (NAS/NAE/NRC, 2009a; 2010b), that is, reducing the amount of energy input required to deliver an expected level of service. Improvements in energy efficiency might even make it possible to delay, or eliminate, the need for new generation in some regions (NAS/NAE/NRC, 2010b). In the context of an integrated, sustainable energy economy, energy efficiency can offset the typically higher costs of energy from cleaner, mostly renewable, generation technologies.

Consider for example, the state of Hawaii, which intends to reduce electricity usage by 30 percent by 2030 while providing 40 percent of the remaining generation through renewable resources. If current energy use is 14,300 GWh, the 2030 goal would be met by reducing annual consumption by 4,300 GWh, and by serving 40 percent of the remaining load (4,000 GWh of 10,000 GWh total) through renewable power generation. Aligning energy efficiency strategies with longer term renewable energy goals effectively increases the share of renewables in the generation portfolio. Unless the rising demand for energy is addressed, increases in renewables and other clean energy options could be offset by even more rapid increases in primary energy demand, with the balance being met by fossil fuels.

China has put energy efficiency at the forefront of its policies to improve energy security, alleviate pressure on domestic resources (particularly coal and water for thermal power generation), and reduce environmental impacts as its economy expands. Energy efficiency and conservation are now a top priority in its energy planning and industrial development strategies, as reflected in its goals to reduce energy intensity (energy consumed per unit of GDP) by 20 percent from 2005 by the year 2020. Each province and major municipality has been assigned a reduction target ranging from 12 to 30 percent.

China has recognized that more efficient use of energy at the household and company levels translates into financial savings over time. Such savings could offer a significant offset to the higher cost of generating renewable energy (NAS/NAE/NRC, 2010a). In other words, if energy efficiency technologies can capture cost savings in the near term, they can act as a bridge to the deployment of more costly renewable energy technologies that could ultimately supplant conventional fossil-fuel generation.

Modernizing the Grid

A modernized grid is widely considered an essential component of a sustainable energy infrastructure (see Chapter 3 for a technical discussion of devices that comprise a modernized grid). The existing grids in both the United States and China are typically considered impediments to the accelerated deployment of renewables, because it is expensive to upgrade them in order to accept and balance large shares of electricity from variable-output sources like solar and wind energy. Both countries continue to make sizeable public investments (more than $7 billion each for 2010 [Zprýme, 2010]) in next-generation grid technologies, and China is spending nearly 10 times that amount ($70 billion from its economic recovery package) on new high-voltage transmission infrastructure (Robins et al., 2009). In addition, because a substantial portion of China's electricity grid has yet to be built, certain regions in China could potentially "leapfrog" to a modern grid system and effectively become experimental sites that would inform grid retrofitting efforts in the United States.

A modernized grid would have three distinct advantages for the integration of renewables. Most important, it would lead to more effective demand management by enabling load-shifting or dispatchable demand to smooth out peaks or take advantage of off-peak wind generation. Second, a modernized grid could facilitate the proliferation of distributed power generation, which would enable local and on-site generation (e.g., even for a single building) based on clean energy. As discussed below, distributed generation has the advantage of allowing for rapid deployment of renewables while minimizing the challenges associated with the zoning or new transmission lines required to integrate these sources directly into the existing distribution system. Third, a modern grid would make it easier to incorporate energy storage technologies and other integration services into the system itself to help optimize overall system performance. Utilities will not necessarily have to add storage for variable-output generation (e.g., backup for every wind turbine) as long as there are other options in the system to balance variability and maintain reliability. Cost-effective energy storage would also allow a utility to optimize available resources and dispatch electricity to correspond with demand, enhancing the value of installed wind turbines and other variable-output generators, as well as the value of the transmission lines.

The Tehachapi Wind Resource Area provides an example of how some of these elements would need to come together to support large-scale wind farms. Current estimates for wind power development in the Tehachapi region total 4,500 MW. Roughly 13.5 GW of storage capacity would be needed to capture three hours of generation if the region's wind resources are fully developed, and the wind farms are operating at full capacity. Alternatively, demand might be dispatched to use available wind. Finally, as a last resort, some of the turbines may need to be curtailed if alternate options are not in place to make use of the power when it is generated.

Distributed Generation

A major benefit of many renewable power generation technologies is that they are modular, which means they can be deployed at small scales (e.g., on individual buildings) and within existing distribution networks, provided that they include appropriate controls to maintain voltage. They are also appropriate for small, off-grid applications. Because most of China's early experience with the deployment of renewable energy systems has been to supply remote rural areas, the country has become a leader in small-scale hydropower, solar water heating, biogas digesters, and micro-turbines for wind energy conversion. Despite rapid urbanization in China, the population is still nearly 60 percent rural, and a substantial portion of that population has limited access to electricity. Thus, distributed generation will continue to be a priority in the countryside, and renewable power technologies will enable rural communities to harness locally available, clean energy resources.

Most current off-grid systems in China are powered by a single resource, such as wind, and many of these systems include energy storage. As China builds and maintains these systems, there will be opportunities to (1) build hybrid systems that draw on more than one resource to optimize electricity availability, (2) incorporate storage capabilities, and (3) develop appropriate controls to maintain reliability. Given the unique attributes of these off-grid systems (including sustained national and international investment), they might even be preferable to grid interconnections (which are constrained by prevailing electricity rates and possible disruptions to the grid) as proving grounds for hybrid systems and storage technologies.

Solar technologies are good candidates for distributed generation. China is the world leader in the manufacture and deployment of solar water heaters, which are now often more cost effective than gas water heaters—these technologies are not used for generation, but the lessons in terms of incentivizing deployment at a household- or individual consumer-level may transfer to rooftop PV. In the United States, utilities have offered programs (e.g., net metering) to encourage households to deploy rooftop PV systems. Recently, utilities have worked directly with commercial and industrial sites to lease rooftops and open areas to deploy PV systems; this helps utilities in warm climates to meet peak demand and can delay or eliminate the need to build new natural-gas peaking plants. China has been a leader in combined heat and power (CHP) technologies, although so far these have typically been coal- or gas-based systems. An area for future research will be to develop renewable-energy-powered systems that can provide heating, cooling, and electricity on a building or neighborhood scale. Fuel cells are already used in CHP applications and can use renewable fuel, and solar technologies are another suitable candidate for CHP.

Distributed generation can play an important part in the transition to a sustainable energy infrastructure. It offers advantages for utilities, which will be able to incorporate new renewable capacity without the challenges associated with zoning and permitting an entirely new site for development. In addition, the close proximity of electricity generators to electrical loads will reduce some of the costs associated with renewables, such as transportation costs and transmission line power losses. For example, in China today, electricity is relatively expensive along the coasts because of the high costs of transporting coal from distant locations. Finally, distributed generation could make the electrical system more resilient, which is a desirable quality for both utility operators and customers. This will depend on the specific technology and the local distribution grid characteristics. Distributed systems tend to be more costly, on a per watt basis, than central station or bulk renewable supplies, but this is highly dependent on the existing infrastructure, retail rates for electric power, and other factors. Ultimately, cost effectiveness and reliability concerns will dictate the deployment of renewable distributed generation and storage, vis-à-vis fossil-fueled alternatives or extensions to existing transmission and distribution networks.

Electricity-Powered Transportation

Both the United States and China have shown an interest in electricity-powered vehicles as a means of reducing harmful mobile source emissions, gaining a competitive edge in the growing market for manufacturing vehicles, and reducing dependence on petroleum. Electrifying transportation systems could also reduce some of the volatility associated with fuel prices. Although retail electricity prices would still fluctuate based on the time of day, aggregate demand, and other factors, producing a larger share of energy domestically could reduce some of the risks associated with dependency on a complex, global value chain for oil imports.

Electricity-powered transportation systems also have distinct advantages for an integrated, sustainable energy economy. Although vehicle-to-grid storage is not possible with today's electric vehicles, batteries, and grid infrastructure, a network of electric vehicles can (1) act as a network of distributed charging loads that can be turned on and off, and (2) through proper communications systems take advantage of wind resources, which tend to be more prevalent at night (when many vehicles should be more optimally recharging).

As many studies have shown, because disruptive technologies, such as renewable power generators, do not necessarily follow the standard evolutionary path (e.g., Christensen, 1997; NRC, 2009b) they may gain traction in new markets before they actually displace incumbent technologies. Electrifying the transportation system in the United States or China that includes personal vehicles (e.g., plug-in electric vehicles [PEVs]), public transit, and other transportation modes (e.g., electric-powered bicycles, which are already widely used in Chinese cities), would create a potentially enormous market for power generation. Whether this new electricity demand would cause reliability issues and significant cost increases depends on charge management. Therefore, it will be important to develop rates and programs that encourage vehicle charging when it is optimal for the system. Otherwise, PEVs could add additional peak load, increasing burdens on infrastructure and overall costs.

There are numerous economic and technical challenges to electrifying the existing transportation infrastructure in the United States (NRC, 2010c) and the large and rapidly expanding transportation infrastructure in China. There are also competing alternatives to electrified transportation, including improved internal combustion engines and hydrogen fuel cells. Thus a diversified portfolio of transportation technologies may be a more likely scenario (NRC, 2008, 2010c) than a wholly electrified system. An NRC (2010c) study estimates that, by 2030, 13 to 40 million PEVs could be part of the U.S. vehicle fleet of 300 million and that the costs and deployment of PEVs will depend largely on battery costs (although charging vehicles at night to reduce grid congestion and use off-peak power generation and other considerations would become increasingly important). Additional factors such as government incentives, oil prices, and environmental legislation will likely affect the deployment of PEVs.

According to Huo et al. (2010), widespread electric vehicle use in China, in the absence of corollary efforts to reduce air pollution from the power generation sector, could have unintended environmental impacts, even though electric vehicles would contribute to improvements in urban (i.e., local and regional) air quality where vehicle exhaust from internal combustion engines is now a major pollutant. Nevertheless, the authors suggest that China proceed with electrification programs in regions where clean, low-carbon energy sources are available. They also recommend that power-sector and transportation-sector policies be coordinated, even though power-sector reform tends to be slower than changes in the transportation sector because of the comparatively long lifespan of existing capital stock. Reforming these two sectors concurrently, they argue, would link the potential benefits to human health and the environment.

Urban Development

More than 80 percent of the U.S. population is urban, and U.S. cities consume approximately 75 percent of the nation's energy and are responsible for a similarly large share of greenhouse gas (GHG) emissions (Grimm et al., 2008). China now has more than 500 million urban residents, and that number is increasing rapidly. Cities are "concentrations of buildings and associated infrastructure, and the built environment, a key consumer of materials and energy, offers many opportunities for savings" (WRI, 2005). Thus efforts to build a sustainable energy economy can make considerable progress by addressing the needs of cities.

Although the effects of conventional energy use are felt on a regional and global scale, many opportunities to reduce the impact of energy consumption, in part by incorporating more renewable energy, will be on the local level (NAE/NRC/CAE/CAS, 2007). In addition to growing concerns about human contributions to climate change, cities must respond to concerns about air quality, rising energy costs, traffic congestion, and many other issues that can be addressed, at least in part, by pursuing a more sustainable energy strategy.

Technology-based solutions will be important for changing this scenario, but behavioral changes are also a major potential source of improvement, and cities can be catalysts for these changes. Cities are already making changes through policies for purchasing renewable power, the judicious use of incentives and regulations to engage the private sector in developing renewables, and land-use decisions that can impact a city's energy profile.

Rizhao, China, is an example of a city where some of these factors—local and provincial government financial support for solar R&D, local industries availing themselves of these incentives, and political leadership committed to deploying the new technologies—have converged. This northern Chinese city of 3 million inhabitants uses solar technologies for almost all of its heating (buildings and water) and much of the city's outdoor lighting (Bai, 2007). In the United States, Austin, Texas, Berkeley, California, and Madison, Wisconsin, also have very aggressive renewable energy programs, policies, and incentives that have greatly accelerated renewable energy development. The U.S. Department of Energy (DOE) Solar America Cities Program is working with many city governments to expand urban renewable energy development.

Cities are also well positioned to educate their communities on sustainable energy use. Public education can build support for local strategies and pressure state and national officials to adopt policies that promote sustainable energy use. Local projects to develop renewable energy can show what is possible, at what cost, and with what trade-offs (IEA, 2009). Studies have shown that cross-city learning is very important for spreading knowledge about developing cleaner energy systems (Campbell, 2009). Thus the systematic accumulation and generation of transferable knowledge from successful experiments can be extremely effective in moving toward a sustainable energy economy (Bai et al., 2010).

TRANSFORMING THE ENERGY SYSTEM

The relationship between technology and society, referred to as a sociotechnical system (Emery and Trist, 1965), has significant implications for increasing the presence of renewable energy technologies. Although substantial progress has been made in renewable-energy-related technologies, studies show that changes in the energy system as a whole are a "slow, painful and highly uncertain process" (Jacobsson and Johnson, 2000). Meaningful transformation will only be made when technologies that change current practices are actually adopted and accepted by society.

The high cost of renewables (e.g., capital requirements for generation technology, the need for new transmission lines, or the price per kWh) is often cited as an impediment to their growth and is often compared to the cost of coal-fired baseload generation. For both China and the United States, hydropower, and more recently, wind power and geothermal, are the most economic renewable power sources. In China, biopower is 20 percent more expensive than coal, and solar power can be up as much as 10 times as expensive. In this section we look into the interrelated roles of governments, public and private research, and society in transforming energy systems in the United States and China.

Shaping a Clean Energy Market

Market mechanisms alone cannot transform the existing energy system, and technological solutions are insufficient unless they are accepted or incorporated into society. Arguably, a fundamental challenge for both the United States and China is that, because of past subsidies and abundant domestic reserves of fossil fuels, the public continues to expect "cheap" energy, which puts almost every less-established technology at a disadvantage (IEA, 2010c; Weiss and Bonvillian, 2009). Chapter 5 described one approach to addressing this, by mandating a specific amount of renewables be included in the generation portfolio. The following section details some other, economy-wide reforms that would impact renewables.

Intervening in Energy Pricing

The rationale for government intervention in energy prices is that businesses make decisions based on the market price of energy, which may not include the costs associated with environmental damage, climate change, energy security, and other externalities (NRC, 2010a). As a result, most businesses opt not to implement technologies that are socially efficient because, they argue, the private return is too low. The primary mechanisms to adjust for this, or "to level the playing field" for clean energy options (including energy efficiency), are direct energy taxes, cap-and-trade or cap-and-dividend programs, and targeted subsidies (or reductions in subsidies for less desirable forms of energy). All of these mechanisms affect the proliferation of renewables in the marketplace, but to varying degrees.

Carbon Taxes. Taxes involve setting a price signal and letting industry choose the means of reducing energy consumption. A carbon tax affects the use of equipment and systems already in place and provides incentives for the adoption of new technology and operational efficiencies. Taxes send a clear, transparent, policy message that the purpose of the additional costs is to accomplish societal goals. The response to such a tax, however, is uncertain, and empirical estimates of elasticities (the ratio of change in price to change in demand) are not precise enough to predict the resultant energy savings.

A carbon tax may not provide sufficient incentives for technology development, particularly given the political difficulties associated with implementing a high enough tax to provide a significant incentive. In addition, although a carbon tax may lead to immediate savings if owners of existing plants and equipment reduce their energy consumption, it will nonetheless impose costs that were not anticipated when the investments in technology and vehicles were put in place, raising issues of equity. These issues could be addressed by phasing in the tax on a preannounced schedule.

Cap-and-Trade Systems. As of July 2010, Congress is considering enacting a "cap-and-trade" system to cap GHG emissions[1] at a predetermined level and

[1] HR 2454 was passed by the House of Representatives on June 26, 2009. The bill sets a cap on carbon dioxide emissions that covers about 85 percent of total U.S. emissions, including emissions from domestic oil refineries.

issue a number of permits equal to that cap. Controlled entities, such as electric utilities and oil refineries, would have to surrender a permit for each ton of CO_2 emitted. Because the permits could be traded, an entity could choose to reduce its own emissions or buy permits from a permit holder willing to sell, depending on the average total cost. The market price of permits will be reflected in the cost of production and ultimately passed on to the consumer. In some sectors, the permit price would have the same effect as an energy tax.

Targeted Subsidies. Both China and the United States have a precedent—sulfur dioxide (SO_2) pollution—for correcting market failures in the energy sector (NAE/NRC/CAE/CAS, 2007). The United States used targeted technological solutions (mostly SO_2 scrubbers and fuel switching) to force dramatic reductions in emissions, a pattern China is now following.

Subsidies, either in the form of direct price supports for renewable energy, or indirect supports through reductions in subsidies for other forms of electrical generation, are another pricing tool. The U.S. federal government already uses subsidies to affect prices. Over the course of seven years, 2002 to 2009, there were $72 billion in subsidies for fossil fuels and $29 billion for renewables (ELI, 2009). The difference in magnitude is important, but as was pointed out in Chapter 5, another crucial aspect of subsidies is their consistency over the long term. In this case, that consistency, or lack of it, deepens the divide between the subsidies. Many of the largest subsidies for fossil fuels were written into the U.S. tax code, while subsidies for renewables were passed as temporary initiatives[2] (Bezdek and Wendling, 2006, 2007). It is also significant that about half of the subsidies for the renewable sector were for corn-based ethanol.

China has a similar history of subsidies for coal, electricity, and petroleum. The central government regulates all energy prices, and these subsidies have been upheld as indirect support for energy-intensive heavy industries in China as well as a way to moderate consumer inflation. In 2008, some price controls were relaxed, these subsidies continue to be a subject of debate and, to the extent that they keep fossil fuel-derived power prices artificially low, they will continue to put new renewable power generation at a disadvantage.

Bringing Clean Energy into the Mainstream

There are several contemporary examples of renewable energy technologies that struggle in the marketplace for non-technical reasons. For example, wind farm developments have been delayed because of aesthetic concerns, and waste-to-energy facilities have been opposed on the basis of environmental injustice.

[2] For example, federal tax subsidies for intangible drilling expenses for oil and natural gas have been a permanent fixture of the U.S. tax code for more than 60 years. Subsidies for renewables, such as the production and investment tax credits (see also Chapter 5 discussion) have lapsed and been reinstated several times in the past decade.

Historically, the siting and construction of transmission projects have aroused a great deal of public and political opposition, and the debate has been reopened in the context of new transmission primarily for renewable power projects.

For renewables to achieve a substantial share of overall electricity generation, the industry will have to penetrate the mainstream energy markets in both the United States and China. However, until very recently, renewable power was typically referred to as a niche industry. Renewables might achieve mainstream status by steadily increasing market share. In the meantime, advocacy groups, professional societies, and industry associations in the United States and China are working to accelerate this trend by convening groups, disseminating information, lobbying policy makers, and sometimes conducting R&D (e.g., the Electric Power Research Institute [EPRI] in the United States).

In the United States, every major source of renewable power has a trade organization with tens of thousands of members. In China, the two largest industry associations are the Chinese Wind Energy Association and its parent organization, the Chinese Renewable Energy Society. The American Council on Renewable Energy (ACORE), established in 2001, now has almost 1 million paying members and recently created a U.S.-Chinese program as its flagship international effort to promote direct links between industry leaders in both countries. The impact of these organizations is difficult to quantify, but their rapid growth is an indicator of the increasingly prominent role that renewable energy is playing in matters of economic development and energy policy.

Strengthening Innovation

United States

Innovation in renewable energy has generally been linked to energy prices (Weiss and Bonvillian, 2009). In the United States, energy R&D in general has been greatly influenced by the prevailing price of oil (and thus the perceived need for innovation in energy efficiency and alternative sources). The decline in U.S. federal spending on energy R&D has been well documented (e.g., Dooley, 2008; Kammen and Nemet, 2005; Margolis and Kammen, 1999). Dooley (2008) notes that since the mid-1990s, energy R&D has accounted for only 1 percent of federal R&D expenditures. Margolis and Kammen (1999) suggested that cutbacks, which began around 1980 following the energy crisis in the late 1970s, would undermine innovation capacity in the energy sector.

Various reviews of federal investments in clean energy R&D have advocated dramatic increases, on the order of $15 to $30 billion per year (Duderstadt et al., 2009; Kammen and Nemet, 2005; Nemet and Kammen, 2007). As a reference point, in 2009, even with the one-time infusion of funding from the American Recovery and Reinvestment Act, the Department of Energy's R&D budget totaled about $9.5 billion. Moreover, this budget is split among defense (~37 percent), basic science (~42 percent), and energy (~21 percent), with applied energy R&D totaling $2.27 billion for the fiscal year 2010 (AAAS, 2010). Overall, investment in renewable energy research has not been sufficient to support massive deployment at sufficiently low-cost (NRC, 2000; NSB, 2009). In some industries, such as chemicals and electronics, private companies fund most R&D—in the United States, federal R&D funding in these sectors represents ~1 percent and ~0.5 percent, respectively (NSB, 2010). Private companies in these and other industries have typically exhibited higher R&D spending/sales ratios (~8-10 percent) than energy utilities (~0.5 percent). Direct government funding cannot make up for this shortfall, but governments can provide leverage directly (through additional investment in pre-commercial R&D) and indirectly (e.g., tax credits for private R&D spending).

Public and private R&D has tended to emphasize incremental improvements in commercialized or ready-to-be-commercialized renewable energy technologies. Government support has also tended to be technology-specific, focusing on advancing wind turbines, for example, along a cost/watt curve. Because of the abundance of solar energy, it has typically been considered the most promising renewable resource for new disruptive technologies (Lewis and Nocera, 2006).

However, for every technology commercially available and ready for accelerated deployment, several others on the drawing board could potentially be "game changers" in the sense that they could point the way down a dramatically different path to cost-effective clean energy. Although existing technologies are expected to continue to improve and governments and private industry will continue to invest in applied research in support of this, it is also critical that R&D be oriented toward long-term goals for sustainable energy (NSB, 2009).

Innovation in the United States is increasingly being influenced by university-industry partnerships, which, in turn, tend to emerge from and be influenced by government actions (Feller, 2009). The rationale for public-private partnerships in R&D is to address the funding gap for entrepreneurs attempting to commercialize scientific inventions; the rationale for government support for this sort of R&D is that the social rate of return (the benefits to society) are greater than private rates of return (material benefits to a particular firm) (Shipp and Stanley, 2009). These have been the underlying principles of U.S. government investments in renewable energy technologies since the 1970s.

Government investments continue to be directed toward public-private partnerships in an effort to leverage additional resources (financial, intellectual, and in-kind) and accelerate innovation. In 2009, DOE provided support for 46 Energy Frontier Research Centers, disbursing $100 million (augmented by $277 million in stimulus funds) for collaborative research in basic energy sciences. DOE also administers a Technology Commercialization Fund, which supports collaborations by several national laboratories and private industry to advance prototypes. For these "post-research, pre-venture capital" projects, the national labs make matching funds available to any private-sector partner willing to support deployment.

The National Renewable Energy Laboratory (NREL), the primary laboratory for research, development, and demonstration (RD&D) in renewables and energy efficiency, has a strategic focus on accelerating the commercialization of clean energy technologies. To further this goal, NREL has established a Clean Energy Entrepreneur Center, primarily to educate its own staff on commercialization issues, and a Venture Capitalist Advisory Board to provide external advice to the lab, identify additional capital, and form startup companies (NREL, 2010a). NREL also participates in the Solar Technology Acceleration Center (SolarTAC), a collaborative venue for research, demonstration, testing, and validation of near-market solar products and services.

As part of the *Rising Above the Gathering Storm* (NAS/NAE/IOM, 2007) report, the study committee found a serious lack of either government or industry mechanisms for exploring long-term, high-risk, but potentially very high-payoff energy research, development, and innovation directed specifically toward deploying new energy technologies. The committee thus concluded that creation of an "ARPA-E" (Advanced Research Projects Agency-Energy, modeled after the successful DARPA, Defense Advanced Research Projects Agency) was important to develop a base of "transformational research that could lead to new ways of fueling the nation and its economy." ARPA-E's mission would, in the committee's view, complement but not replace other mechanisms in the nation's energy R&D portfolio.

ARPA-E was thus authorized in 2007 and became operational in 2009, receiving an initial budget of $400 million. The goal of ARPA-E is to reinforce U.S. economic security by identifying technologies with the potential to reduce energy imports from foreign sources; cut energy-related GHG emissions; and improve efficiency across the energy spectrum. Although ARPA-E will indirectly support conventional energy research, its focus will be exclusively on high (market) risk, high-payoff concepts with the goal of encouraging the United States to remain a technological and economic leader in the development and deployment of advanced energy technologies.

China

China has made great strides in recent years in increasing its innovation capacity in general, and in renewable and alternative energy technologies more specifically. Investments in clean energy R&D have increased year on year, particularly in strategic areas such as high-voltage transmission, and a suite of policies has been developed to make China a global leader in these technologies (Tan and Gang, 2009). Still, there is considerable room for improvement, particularly in establishing a comprehensive innovation system that joins basic research capabilities to enterprises focused on commercializing and deploying these technologies.

Research institutions in China have had comparatively little interaction with the private sector. But, as demonstrated by universities contracting with companies and research institutes establishing startups, this model is changing. China's Ministry of Finance has proposed several policies to encourage private-sector investment in innovation, via partnerships, and the Ministry of Education has provided incentives to universities to turn their research results into practical products (Tan and Gang, 2009). Some of China's state-run research institutes (such as GIEC and the CAS-BP Institute in Dalian) have also tried to focus their efforts on commercializing technologies, a departure from their previous focus exclusively on research. China will have to continue investing in all facets of its innovation system if it wants to rely on domestic or "indigenous" innovation in the future.

By some accounts, China's current innovation system is characterized by insufficient investment, an unbalanced allocation of resources, and too little R&D (Mu, 2007). Only a little more than 6 percent of gross expenditures in R&D are devoted to basic research, industrial R&D is weak (in terms of output), and there is a general lack of integration among research components, coordination among government agencies, and linkages between academia and enterprises (Fang, 2008). Although Chinese companies have successfully improved foreign-developed innovations in renewable energy technologies, particularly in manufacturing products at scale and reducing costs, they do not typically leverage domestic research capacity. Multinational companies are increasingly locating their R&D facilities in China, so over the longer term this may have an influence, but at present China has not demonstrated that it is prepared to be a leader in innovative, high-technology industries like renewables.

To address these concerns, the national government administers two programs intended to accelerate China's progress in becoming a high-technology leader—the 863 Program, which focuses on national high-technology development and demonstration, and the companion 973 Program, which supports basic research. Both programs are managed by the Ministry of Science and Technology (MOST), and both are directed toward China's evolving national priorities. Thus, in the 11th *Five Year Plan* (2006–2010), renewable energy technologies are one of four energy-related priorities. However, funding for renewables is modest, even in comparison to funding for the other energy areas: 29 million yuan (~$4.5 million) annually in renewable energy technologies under the 863 Program, compared to 75 million yuan (~$11.5 million) for hydrogen and fuel cell technologies (Tan and Gang, 2009).

The 973 Program currently targets certain areas relevant to the deployment of renewables, such as grid modernization and utility-scale renewable resource development. Funds are also being channeled to programs such as the Chinese Academy of Sciences Solar Energy Action Plan to research technology and equipment for utility-scale (50–100 MW) solar thermal power plants. Again, only modest resources (approximately $143 million over a 10-year period, 1998–2008) were designated for energy research.

The 2006 Medium- to Long-Term Science and Technology National Plan establishes the government's central role in determining the direction of China's R&D until 2020. Government intervention to spur innovation can be critical in a country like China, which does not have a long-established R&D infrastructure (Tan and Gang, 2009). MOST has adopted numerous policies to stimulate more private-sector investment in R&D, ranging from preferential taxes (e.g., increasing the deduction for R&D expenses) to protections of intellectual property rights (IPRs); the latter adopts a holistic approach that includes a legal system respecting IPR, the development of technology standards, and active participation in setting international standards.

Finally, in late 2007 MOST and National Development and Reform Commission (NDRC) jointly established the International Science and Technology Cooperation Program on New and Renewable Energy, a program that identifies priorities for international cooperation on solar power integration, biofuels, biopower, and wind power generation. The approach is in line with recommendations by the U.S. National Science Board to the National Science Foundation to promote collaboration with developing countries to encourage the adoption of sustainable energy technologies (NSB, 2009). As a next logical step, the United States and China have agreed to establish the U.S.-China Clean Energy Research Center, which is expected to become operational in 2010 and will provide funding of up to $150 million from both countries over a period of five years for joint R&D on clean coal, building efficiency, and clean vehicles.

FUTURE SCENARIOS

Forecasts of the energy futures of the United States and China are necessarily filled with uncertainty. Both countries use energy-economic models to analyze different scenarios—government forecasts are provided by the DOE Energy Information Administration (EIA) in the United States and by the NDRC Energy Research Institute (ERI) in China. Although these scenarios are not prognostications of the future, they can be useful for exploring possible effects of different policy options as both countries develop energy R&D portfolios and as industries plan investments (Holmes et al., 2009; NRC, 2009a). The following section focuses on economy-wide reference cases provided by EIA (to 2035) and, where available, by ERI (to 2050). In this section we also consider some ambitious technology-specific forecasts. These forecasts may not offer a clear path forward, but taken together they measure the distance to be traveled.

Government Forecasts

The latest forecasts by EIA (Figures 6-1 and 6-2) predict that the share of renewable energy in the U.S. energy supply will double in the next two decades, reaching nearly 14 percent by 2030 (EIA, 2009a). EIA forecasts that biofuels will show the greatest absolute growth through 2030 and that solar/PV energy will grow the fastest. China's official forecasts (often interpreted as goals, but not mandates) are even more ambitious. China predicts renewables will be able to fulfill more than 30 percent of energy demand by 2050 and that hydro and other renewables together should meet 10 percent of China's energy demand for 2010, increasing to 15 to 20 percent by 2020; as non-hydro renewables become dominant, they are projected

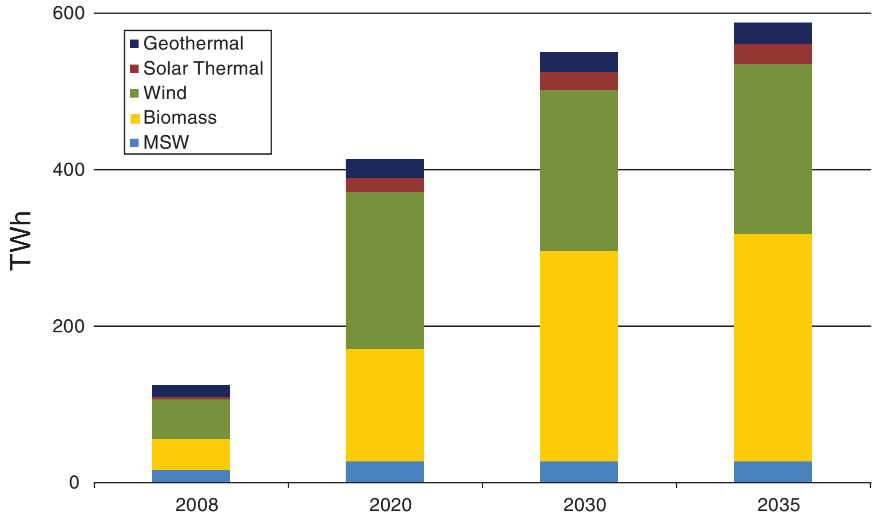


FIGURE 6-1 U.S. non-hydroelectric renewable electricity generation by energy source, 2008–2035 (billion kWh). Source: EIA, 2010a.

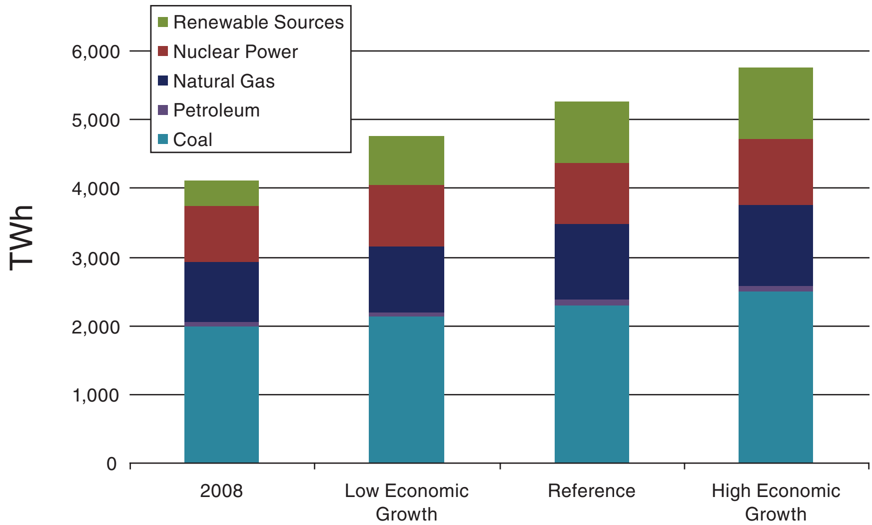


FIGURE 6-2 U.S. electricity generation forecasts for 2035, by fuel, in three cases. Source: EIA, 2010a.

to provide 26 to 43 percent by 2050 (NDRC, ERI 2009). EIA projections extend to 2035 but not beyond, at least not officially. However, the current administration has a stated goal of reducing GHG emissions by 83 percent by 2050.

Recent EIA analyses present an interesting perspective on U.S. electricity sources over the past 40 years and projected through 2030 (Table 6-1):

- Coal remains the dominant fuel for U.S. electricity generation. In terms of kW, coal-fueled electricity production is projected to increase more than three-fold from 1970 to 2030, from 704 billion kW to 2.3 trillion kW. However, its share of electricity generation is forecast to be nearly the same in 2030 as it was in 1970—slightly less than 46 percent.
- The share of petroleum will decrease the most, from 12 percent of total electricity generation in 1970 to about 1 percent in 2030.
- Nuclear power will increase the most, from a little more than 1 percent in 1970 to slightly less than 18 percent in 2030.
- Natural gas will drop from 24 percent in 1970 to 19 percent in 2030.
- Renewables will contribute the same percentage—slightly more than 16 percent—in 1970 and 2030. However, the distribution among types of renewables will change significantly. In 1970, virtually all renewable energy was from conventional (large) hydroelectric facilities, whereas in 2030 these facilities will contribute only about one-third of the renewables total.

ERI scenarios for China, which are based on goals set by the government, are slightly different. Because China has a central-planning approach, ERI sce-

TABLE 6-1 Total U.S. Electrical Production by Major Energy Source: History and Forecast

Million Kilowatts	1970	1990	2007	2020	2030
Coal	704.4	1,594.0	2,020.6	2,197.6	2,310.8
Petroleum	184.2	126.6	65.7	49.0	50.2
Natural gas	372.9	372.8	893.2	714.3	976.4
Nuclear electric power	21.8	576.9	806.5	876.3	890.1
Conventional hydroelectric power	251.0	292.9	248.3	298.7	299.9
Other (including other renewable)	0.9	78.4	132.2	437.2	527.1
TOTAL	**1,535.2**	**3,041.6**	**4,166.5**	**4,573.1**	**5,054.5**
Share of Total			Percent Share		
Coal	45.9	52.4	48.5	48.1	45.7
Petroleum	12.0	4.2	1.6	1.1	1.0
Natural gas	24.3	12.3	21.4	15.6	19.3
Nuclear electric power	1.4	19.0	19.4	19.2	17.6
Conventional hydroelectric power	16.3	9.6	6.0	6.5	5.9
Other (including other renewable)	0.1	2.6	3.2	9.6	10.4

Source: EIA, 2007a, 2009a.

TABLE 6-2 Summary of China's Renewable Energy Resource Potential for Power Production in 2050

Type	Theoretical Potential (100 GW)	Technically Available Potential (100GW)	Energy Production (100 Mtce/a)
Wind	43	7~12	5~8
Solar energy	$4.5*10^7$	22	11~14
Biomass	—	—	9.8
Hydro	6	5	8.6
Geothermal	462.6 Btce	0.2	0.5
Ocean	142	14.4	5.5
TOTAL	**—**	**55.7**	**40–46**

Source: CREDSRG, 2008.

narios also function as road maps, or at least guideposts, for the development of specific renewable energy industries. By contrast, EIA provides independent, impartial analyses based on energy information and statistics. DOE and its affiliate laboratories conduct separate analyses, including aggressive scenarios for specific technologies (e.g., DOE, 2008a). NREL also facilitates renewable power technology roadmaps for industry, which identify targets for costs, timeframes for commercialization, and policy needs to achieve these goals. But the United States does not currently have official roadmaps, which would authorize the requisite funding and policies to help realize specific goals. The Solar Technology Roadmap Act of 2009 was pending approval by Congress as of June 2010.

ERI scenarios focus on the near term (by 2010), medium term (by 2020), long term (by 2030), and a "future perspective" (to 2050—see Table 6-2). Figure 6-3 illustrates the goals for renewables to 2050. Figures 6-4 and 6-5 show technology road maps for wind and solar PV, complete with interim goals and targets. The Chinese Academy of Sciences (CAS) produced a report in 2007 assessing how the country could transition from its dependence on fossil-fuel, energy-intensive infrastructure to a cleaner, more sustainable energy system. This report posited that, even if nuclear, conventional hydro, and renewables development were accelerated, coal would still provide about 42 percent of the country's primary energy supply in 2050. However, the market could be shaped so that low-emissions and domestically produced energy would be favored (CAS, 2007). Under this scenario, with enough investments to bring down the costs of solar energy conversion, cellulose conversion for bio-derived fuels, and energy storage, renewables could meet approximately 25 percent of primary energy demand.

Industry Assessments

Some assessments attempt to forecast the size of all or parts of the renewable energy industry. Studies of this kind have been conducted for the United States (e.g., ASES, 2009; NCI, 2010; Pew Charitable Trusts, 2010), but the committee is not aware of any comprehensive forecasts for the renewable energy industry

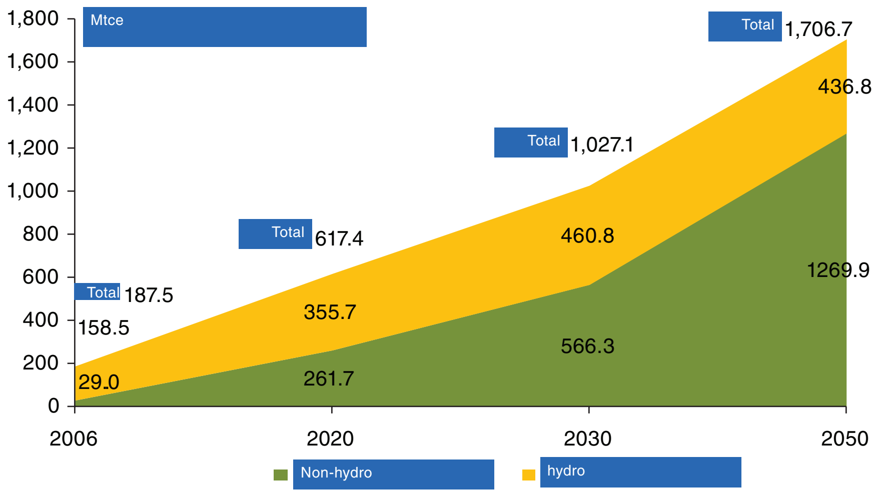


FIGURE 6-3 Renewable energy targets for China, in tons of coal equivalent. Source: CREDSRG, 2008.

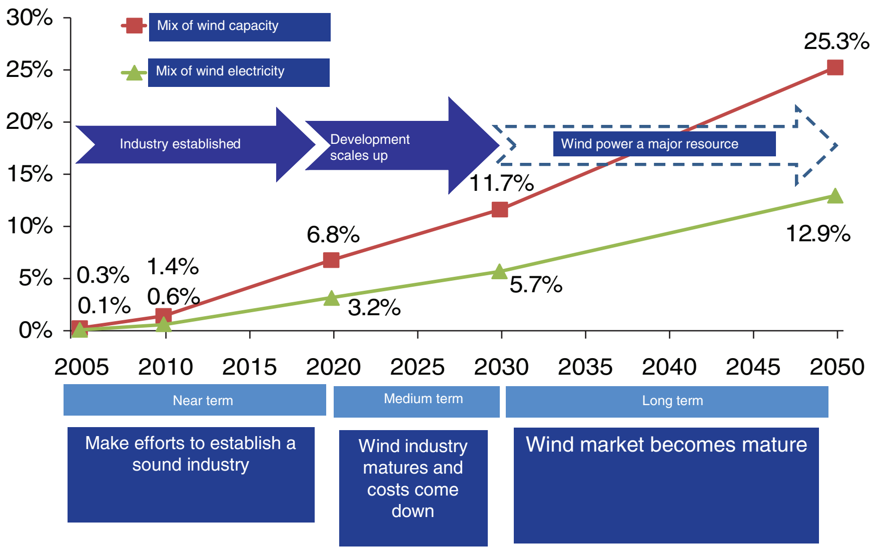


FIGURE 6-4 Wind technology roadmap for China. Source: CREDSRG, 2008.

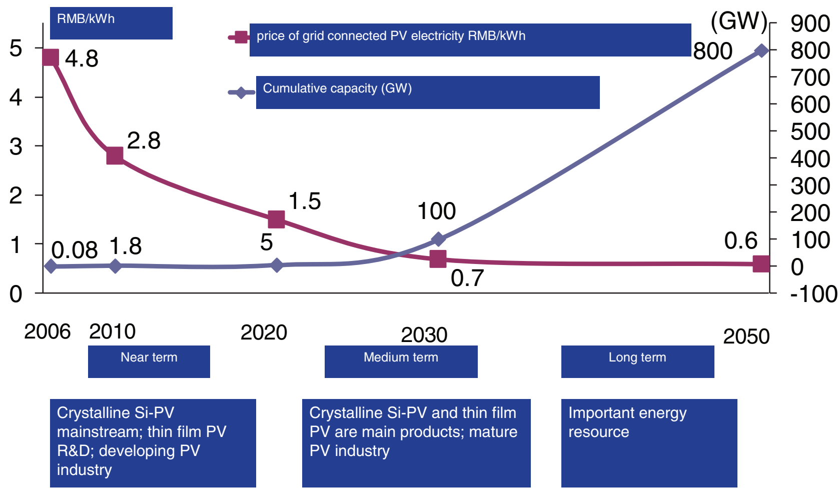


FIGURE 6-5 Solar PV technology roadmap for China. Source: CREDSRG, 2008.

in China. There are, however, recent analyses of some parts of China's energy market (e.g., Crachilov et al., 2009; McKinsey & Company, 2009).

Table 6-3 summarizes some of the results for the ASES (2009) scenario forecasts for 2030. The size of the industry in 2030 in the "Advanced Scenario" is nearly six times as large as in the "Base Case." More important, in the "Advanced Scenario," some renewable energy sectors grow much more than others: wind is 16 times larger; geothermal is 14 times larger; fuel cells is 9 times larger; biodiesel is 6 times larger; biomass power is 5 times larger; and PV and ethanol are more than 3 times larger.

Table 6-4 shows wide variations in jobs creation between the "Base Case" and "Advanced Scenario." The biggest differences in numbers are in the ethanol, biomass power, and wind sectors. The biggest differences in percentage increases are in the solar thermal, geothermal, and wind sectors.

The High Costs of Delay

In the aggressive scenario developed for the ASES (2009) report, the 2008 predictions for renewable energy/electrical energy industry in 2030 are significantly lower than the 2007 predictions:[3]

[3] The 2008 renewable energy and electrical energy forecast can be found in Management Information Services Inc., *Renewable Energy and Energy Efficiency: Economic Drivers for the 21st Century*, a report prepared for the American Solar Energy Association, November 2007; ASES (2009). The 2007 forecast can be found in Management Information Services Inc., *Green Collar Jobs in the U.S. and Colorado: Economic Drivers for the 21st Century*, American Solar Energy Society, Boulder, Colorado, January 2009 is from ASES (2007).

TABLE 6-3 The U.S. Renewable Energy Industry in 2030 (billions of 2007 dollars)

Industry Segment	Base Case	Moderate Scenario	Advanced Scenario
Wind	$5.6	$22	$89
Photovoltaics	13.5	27	45
Solar thermal	0.2	0.9	29
Hydroelectric power	4.8	5.1	6.8
Geothermal	2.9	8.2	40
Biomass			
Ethanol	22.6	45	82
Biodiesel	1.3	2.7	7.6
Biomass power	32.3	68	160
Fuel cells	5.2	14.1	45
Hydrogen	4.1	12.2	36
Total, Private Industry	**92.4**	**205.2**	**540.4**
Federal government	0.8	1	2.8
DOE laboratories	2.3	2.6	7.8
State and local government	1.5	2.2	5.7
Total Government	**4.6**	**5.8**	**16.3**
Trade & professional associations & nongovernmental ogranizations	0.8	1.5	3.6
TOTAL, ALL SECTORS	**$97.8**	**$212.5**	**$560.3**

Source: ASES, 2009.

- Projected real renewable energy revenues in 2030 are about 10 percent ($55 billion) smaller.
- The total number of jobs projected for the renewable energy industry in 2030 is about 8 percent (591,000 jobs) lower.
- Real electric energy revenues in 2030 are about 8 percent ($317 billion) lower.
- The total number of jobs generated by renewable energy in 2030 is about 7 percent (2.3 million jobs) lower.

All renewable energy/electrical energy initiatives take years to be implemented and then ramped up. Thus the largest gains in deployment are made in the years immediately preceding the target year, 2030. Therefore, a delay of just one year in the early years translates into a substantial loss in future deployment. The aggressive 2007 scenario was based on the assumption that the extremely ambitious, large-scale federal, state, and local government incentives, policies, and mandates would be implemented beginning in 2008. This did not occur, however, so the 2008 forecast moved the implementation date up to 2009. This one-year delay explains the significant differences between the 2007 and 2008

TABLE 6-4 U.S. Jobs Created by Renewable Energy in 2030

Industry Segment	Base Case	Moderate Scenario	Advanced Scenario
Wind	66,200	257,000	1,040,000
Photovoltaics	206,000	415,000	700,000
Solar thermal	3,800	17,000	540,000
Hydroelectric power	22,400	24,200	32,300
Geothermal	29,000	85,000	415,000
Biomass			
Ethanol	530,000	1,050,000	2,000,000
Biodiesel	25,100	56,900	160,000
Biomass power	282,000	603,000	1,420,000
Fuel cells	68,600	158,000	505,000
Hydrogen	47,200	143,000	420,000
Total, Private Industry	**1,280,300**	**2,809,000**	**7,232,300**
Federal government	3,000	3,100	8,550
DOE laboratories	11,000	12,300	36,100
State and local government	7,000	11,800	29,400
Total Government	**21,000**	**27,200**	**74,050**
Trade & professional associations & nongovernmental ogranizations	4,700	9,400	21,300
TOTAL, ALL SECTORS	**1,305,400**	**2,845,700**	**7,327,650**

Source: ASES, 2009.

scenarios. The lesson here is that the longer the United States (or China or any other nation) delays in implementing ambitious renewable programs and incentives, the more difficult it will be to achieve the goals for 2030—or any other target year.

The same is true for the ERI road maps, which are based on considerable acceleration from 2030 to 2050. These projections will have to be scaled back if early targets for 2020 and 2030 are not met. Every year of delay at the front end (e.g., 2009, 2010) has a highly disproportionate negative impact on the achievement of long-term goals. Thus, time is of the essence, and time lost in the next several years will be very difficult to make up.

FINDINGS

The scale and diversity of the energy system in terms of existing infrastructure and economic importance, in the United States and China, should not be underestimated. Transforming the existing model of fossil-fuel combustion into a low-carbon energy infrastructure will require the active involvement of a wide range of actors beyond the energy and technology sector. No single factor is motivating either country to push toward a more sustainable energy economy, and no single technology, renewable or otherwise, will wholly meet demand.

Meeting electricity demand sustainably is an important driver for the development of renewable power, but it is not the only one. The complex, systems challenge ahead will involve trade-offs and some missteps. **Manufacturing, deploying, and operating renewable power generators represent a potential new pillar of economic growth. So far, China has embraced this opportunity more rapidly than the United States.**

As both countries move forward to integrate renewable energy technologies, there will be many opportunities for U.S.-Chinese cooperation in areas with medium- to long-term impacts. **Collaboration may not focus directly on renewable power generation technologies but may instead focus on key "enablers" of a sustainable energy economy.** Successful projects might be considered experiments, and the United States and China could document and analyze them and then support similar projects in other cities. Assessments of local costs, benefits, and the impacts of energy use would also be valuable to local decision makers, as would an understanding of the main leverage points in implementing sustainable energy strategies.

China may have the benefit of hindsight, learning from earlier efforts in the United States and elsewhere, but its timetable continues to be compressed at the same time that international scrutiny is increasing. China is pursuing nearly 10 percent annual economic growth while rapidly reducing its GHG emissions profile. In any circumstances, progress on laying the groundwork for a future, sustainable energy economy will benefit both the United States and China over the longer term and could show other countries how to stimulate the development of their own sustainable energy infrastructure. **For both countries, delaying deployment will push back of some of the clean energy and emissions-reduction targets for 2030 and beyond.**

In the United States, research on clean energy is conducted at a variety of government and academic institutions, but NREL integrates these efforts into a coherent national overview. In China, the Energy Bureau has established a number of renewable energy research and development centers. Although both the United States and China have recently increased investments in energy R&D, both are still severely underinvesting, which will make it difficult to achieve goals for 2050 and beyond. Consistent, long-term public investments in clean energy RD&D would send private industry a clear signal of a commitment to change, which should leverage more industry investment in both applied research and commercialization.

RECOMMENDATIONS

- China should conduct a nationwide inventory of research centers and their capabilities in various aspects of renewable energy and related fields. Based on assessed capabilities, some facilities could be designated as technical centers of excellence in their major competencies. One option is to integrate some of the existing entities and to establish a research institute, under the National Energy Administration, that is responsible for the renewable energy sector. A new institution would not need to be the center of excellence for all technologies, but for the integration of technologies and understanding of the RD&D pipeline from resource base through to commercialization. It should also be a facility for investing in capital equipment that is otherwise too costly for individual research centers.

- China and the United States should cooperate on developing the standards and infrastructure for systems that optimize vehicle charging behavior, renewable power generation, and reduced emissions from the transportation sector. Developing and implementing these complex systems at scale will require substantial investments, and so joint pilot projects and demonstrations could be more efficient, in terms of expenditures and diffusion of technological learning.

7

U.S.-Chinese Cooperation

U.S.-Chinese renewable energy cooperation is beneficial for several reasons. It will increase the scale of utilization (which has direct benefits in terms of avoided emissions of greenhouse gases), and it will bring down costs by accelerating the learning rates at all stages of renewables development (R&D, manufacturing, deployment, operations, and maintenance). It can also promote trust and information sharing across stakeholders in the renewable energy sectors of both countries. To date, however, cooperation has been limited and inconsistent. In this chapter, the committee reviews the history of U.S.-Chinese cooperation on energy and climate change, describes the new era of cooperation ushered in by Presidents Hu and Obama and the participation of both countries in international discussions on energy and climate, and suggests how cooperation can be significantly expanded in the coming years.

THE BASIS FOR COLLABORATION ON RENEWABLE ENERGY

As identified throughout this report, there are several reasons for China and the United States to be harnessing their renewable resources. From an international perspective, climate change presents an additional driver. Both countries have three main options for reducing their greenhouse gas (GHG) emissions in the energy sector: (1) reducing emissions from coal-based power; (2) promoting energy efficiency and conservation; and (3) developing renewables and other low-carbon sources of energy. For decades, they have cooperated in these three areas, through governmental and nongovernmental channels. However, given the scale of the climate challenge, there is now an additional impetus for them to continue and even enhance collaboration.

Although other countries have led the way in the early development and deployment of renewable energy resources, the United States and China are poised to become the largest markets for the deployment of renewable energy in the coming years. In 2008, they became the two largest wind power markets in the world (with China outpacing the United States in capacity additions for 2009), and they are expected to remain so for years to come. Although the United States is ahead of China in solar deployment, China leads in solar PV production, and recent government signals in China have indicated a commitment to expanding the domestic use of solar technologies.

Working together, the United States and China can lead the world toward a sustainable energy future. The widespread global deployment of renewable technologies, which will be crucial to reducing human-induced climate change in the future, is unlikely to happen without leadership from the world's two largest energy economies. Both countries are working hard to expand the development and deployment of renewables, but better coordination and more collaboration could accelerate these trends.

OVERVIEW OF U.S.-CHINESE COOPERATION

The United States and China have a long history of bilateral cooperation on renewable energy technologies and policy, both through official government channels and among universities and nongovernmental organizations. Some examples of this historical and ongoing cooperation are described below. (A more comprehensive list of official collaborations on energy and climate change is provided in Appendix A.)

Official Bilateral Cooperation

In 1979, the Memorandum of Understanding (MOU) for Bilateral Energy Agreements was signed by the U.S. Department of Energy (DOE) and the Chinese State Development Planning Commission (SDPC); the MOU led to 19 cooperative agreements on energy, both conventional and renewable. Almost two decades later, in 1995, DOE signed bilateral agreements with: the Chinese Ministry of Agriculture on renewable energy, the State Science and Technology Commission (SSTC) on renewable energy technology development; and the State Planning Commission (SPC) to establish a plan for mapping China's renewable energy resources and develop strategies for financing U.S. renewable energy projects in China (this agreement also involved Chinese and U.S. export-import banks).

In 1995–1996, the Protocol for Cooperation in the Fields of Energy Efficiency and Renewable Energy Technology Development and Utilization was signed by DOE and various Chinese ministries. This Protocol has seven annexes: policy, rural energy (Ministry of Agriculture), large-scale wind systems (Ministry of Electric Power [MOEP]), hybrid power systems for villages, renewable energy business development (with the State Economic and Trade Commission [SETC]), geothermal energy, energy efficiency (with SPC), and hybrid-electric vehicle development.

In March 1997, Vice President Gore and then-Premier Li Peng co-chaired the first session of the U.S.-China Forum on Environment and Development in Beijing. The purpose of the forum was to increase cooperation and intensify dialogue between the United States and China on issues related to sustainable development, particularly the protection of the global environment. When President Jiang visited the United States during that same year, DOE and SPC signed the Energy and Environment Cooperation Initiative, an outgrowth of the forum, designed to focus cooperative efforts on the intersection of energy and environmental science, technology, and trade. Specific target areas included urban air quality, rural electrification, clean energy sources, and energy efficiency. The initiative, which involved many agencies and a number of business sectors, was perhaps the first U.S.-Chinese initiative to link energy development and environmental protection.

The second meeting of the forum, held in April 1999 in Washington, D.C., was co-chaired by Vice President Al Gore and then-Premier Zhu Rongji (OPS, 1999). Two key agreements came out of that meeting related to renewable energy: (1) an MOU for the establishment of a $100 Million Clean Energy Program to accelerate the deployment to China of clean U.S. technologies for energy efficiency, renewable energy, and pollution reduction (the deployment was facilitated by the U.S. Export-Import Bank, DOE, the China Development Bank, and SDPC); and (2) a Statement of Intent on Cleaner Air and Cleaner Energy Technology Cooperation focused on improving energy efficiency in industrial coal-fired boilers; clean-coal technology; high-efficiency electric motors; and grid-connected wind-generated electric power.

In 2006, the U.S. Department of State initiated the Asia-Pacific Partnership on Clean Development and Climate, which included the United States, China, India, Japan, Korea, Australia, and Canada and established public-private task forces for specific sectors, including renewable energy and distributed generation. Specific renewable energy projects have been announced that reportedly involve private- and public-sector participants from both the United States and China, including: a demonstration project using solar PV concentrators led by an Australian company; a technical exchange between the United States and China on PV module reliability and quality control, led by NREL and Sandia National Laboratories; a joint R&D project on fuel cells by U.S. and Chinese fuel-cell companies; a project on fuel-cell cars by China SAIC and General Motors; and an analysis of regulatory barriers to renewable energy uptake led by Australian and U.S. research organizations.[1]

[1] See *http://www.asiapacificpartnership.org/english/pr_renewable_energy.aspx*.

Also in 2006, the U.S.-China Strategic Economic Dialogue (SED) was founded by Vice Premier Wu Yi and U.S. Treasury Secretary Henry Paulson. Participants included several agencies, including DOE, the Environmental Protection Agency (EPA), and the National Development and Reform Commission (NDRC) and Ministry of Science and Technology (MOST) in China. SED was a two-track (energy and environment), semi-annual, cabinet-level dialogue. In April 2009, SED was renamed the U.S.-China Strategic and Economic Dialogue, with the U.S. Departments of State and Treasury as co-chairs. The strategic component of SED, which was transferred to the U.S. Department of State, includes discussions on U.S.-Chinese cooperation on energy and climate change. During the first meeting in July 2009, Treasury Secretary Timothy F. Geithner and Secretary of State Hillary Rodham Clinton were joined by their respective Chinese co-chairs, State Councilor Dai Bingguo (for the strategic track) and Vice Premier Wang Qishan (for the economic track).[2]

In 2007, the MOU on Cooperation on the Development of Biofuels was signed by the U.S. Department of Agriculture (USDA) and DOE, and by NDRC in China. This MOU encourages cooperation in biomass and feedstock production and sustainability; conversion technology and engineering; bio-based product development and standards; and rural and agricultural development strategies.

In 2008 the Ten-Year Energy and Environment Cooperation Framework was signed as part of the fourth SED. The signatories to the framework include DOE, the U.S. departments of the Treasury, State, and Commerce, EPA, and, from China, NDRC, State Forestry Administration, National Energy Administration, Ministry of Finance, Ministry of Environmental Protection, MOST, and Ministry of Foreign Affairs (MFA). The framework establishes five joint task forces on five functional areas: (1) clean efficiency and secure electricity production and transmission; (2) clean water; (3) clean air; (4) clean and efficient transportation; and (5) the conservation of forest and wetland ecosystems.

In July 2009, the Obama administration made its first announcement on U.S.-Chinese energy cooperation in conjunction with Secretary of Energy Steven Chu's first trip to China.[3] Chinese Minister of Science and Technology Wan Gang, Chinese National Energy Administrator Zhang GuoBao, and Chu signed a protocol announcing plans to develop a U.S.-China Clean Energy Research Center to facilitate joint R&D on clean energy by teams of scientists and engineers from the United States and China, and to serve as a clearinghouse for researchers in both countries. The center would have headquarters in both countries, and priority topics would include building energy efficiency, clean coal (including carbon capture and storage [CCS]), and clean vehicles. At the July meeting, the United States and China each pledged $15 million to support initial activities. Subsequently in September 2010, DOE announced that the U.S. component of the centers on clean

[2] See *http://www.ustreas.gov/initiatives/us-china/*.
[3] See *http://www.energy.gov/news2009/7640.htm*.

vehicle and clean coal technologies would be led by the University of Michigan and West Virginia University, respectively.[4]

The U.S.-Chinese Presidential Summit in Beijing in November 2009 resulted in significant new agreements on joint energy and climate cooperation.[5] First, details of the aforementioned U.S.-China Clean Energy Research Center were formally announced (OPS, 2009a). Second, the presidents of both countries announced the launch of the U.S.-China Electric Vehicles Initiative (OPS, 2009c), which will include the development of common standards, demonstration projects in more than a dozen cities, technical road mapping, and public education projects; this initiative builds on the U.S.-China Electric Vehicle Forum held in Beijing in September 2009.[6] Third, the presidents announced a new U.S.-China Energy Efficiency Action Plan that includes the development of energy efficient building codes and rating systems, energy efficiency benchmarking of industrial facilities, training for building inspectors and energy efficiency auditors for industrial facilities, the harmonizing of test procedures and performance metrics for energy efficient consumer products, the exchange of best practices in energy efficient labeling, and the convening of a new U.S.-China Energy Efficiency Forum to be held annually, alternating between the two countries (OPS, 2009d).

The presidential summit also produced a new U.S.-China Renewable Energy Partnership. According to DOE, "Both Presidents embraced a vision of wide-scale deployment of renewable energy including wind, solar and advanced bio-fuels, with a modern electric grid, and agreed to work together to make that vision possible." In addition, "The two Presidents recognized that, given the combined market size of the United States and China, accelerated deployment of renewable energy in the two countries can significantly reduce the cost of these technologies globally" (OPS, 2009e). Funding levels for the Renewable Energy Partnership were not specified by either country.

The Renewable Energy Partnership (OPS, 2009e) lists several projects, including:

- **Renewable energy road mapping:** The United States and China will develop a road map for widespread renewable energy deployment in both countries and identify the policy and financial tools, grid infrastructure, and technology solutions required to achieve that goal.
- **Regional deployment solutions:** As large and geographically diverse countries, renewable energy deployment requires region-specific solutions in both the United States and China. The Partnership will provide technical and analytical resources to states and regions in both countries to support wide-spread renewable energy deployment and facilitate state-to-state and region-to-region partnerships to share experience and best practices.

[4] See *http://www.energy.gov/9443.htm*.
[5] See *http://www.energy.gov/news2009/8292.htm*.
[6] See *http://www.pi.energy.gov/122.htm* and *http://www.energy.gov/news2009/8090.htm*.

- **Grid modernization:** Scaling up renewable energy production in both the United States and China will require modernizing the electrical grid with new transmission lines and smart grid technology. The Partnership will include an Advanced Grid Working Group bringing together policy-makers, regulators, industry leaders, and civil society from the United States and China to develop strategies for grid modernization in both countries.
- **Advanced renewable energy technology:** The United States and China will collaborate in the research and development of advanced biofuels, solar, wind, and grid technologies and work together to demonstrate pre-commercial renewable energy solutions.
- **Public-private engagement:** The Partnership will engage the private sector in promoting renewable energy and expanding bilateral trade and investment through a new U.S.-China Renewable Energy Forum that will be held annually, rotating between the two countries. The work of the Partnership will also be supported by the U.S.-China Energy Cooperation Program, a newly formed public-private partnership with leading U.S. clean energy companies.

Other announcements at the November 2009 summit included an agreement on "21st Century Coal" to promote cooperation on cleaner uses of coal, including large-scale CCS demonstration projects (OPS, 2009b), the Shale Gas Initiative (OPS, 2009f), and the U.S.-China Energy Cooperation Program to leverage private-sector resources for project development work in China on a broad array of clean energy projects. Founding members include more than 20 companies and will involve collaborative projects on renewable energy, smart grid, clean transportation, green building, clean coal, combined heat and power, and energy efficiency.

Nongovernmental Collaboration

In addition to official government-to-government collaborations on renewable energy, there are many other projects and programs among academic and research institutions, nongovernmental organizations (NGOs), foundations, and the private sector. For example, the U.S. Energy Foundation has a Renewable Energy Program based in its China Sustainable Energy Program (CSEP) in Beijing. CSEP supports China's renewable energy policy and has encouraged China's electric utilities and independent power producers to purchase renewable energy to drive down costs and accelerate the widespread introduction of renewable energy technologies. CSEP also encourages the development and implementation of new renewable energy policies that establish aggressive targets for national and provincial renewable energy deployment, including mandatory market-share programs, public-benefits wires charges, wind concession programs, and renewable energy pricing regulations (including recent feed-in tariffs for wind). CSEP as well as many other domestic and international NGOs and stakeholders were also closely involved both in providing input during the legislative development process of the 2005 renewable energy law, and in a recent review of the renewable energy law that led to the 2009 revisions.

Several nongovernmental partnerships have been established in the private sectors of both countries. These include the American Council on Renewable Energy's U.S.-China Program, which has a goal of helping the United States and China adopt renewable energy solutions by bringing together renewable energy technology companies from both countries. Other nongovernmental forums include cooperative programs between U.S. and Chinese universities, such as the Tsinghua–MIT Low Carbon Energy Research Center; public-private partnerships, such as the U.S.-China Clean Energy Forum; and regional and local partnerships, such as the mayoral training program run by the Joint U.S.-China Collaboration on Clean Energy.

The Chinese Academy of Sciences (CAS), China's lead national academic institution in natural sciences, is a major advisory body to the government on science- and technology-related issues and a national R&D center in the natural sciences and high-technology fields. In recent years, CAS has signed several MOUs with U.S. government research institutions on clean energy, including an MOU between the CAS Institute of Electrical Engineering and NREL on the measurement and standardization of solar PV and an MOU between the CAS Energy and Power Center and the U.S. National Energy Technology Laboratory and Pacific Northwest National Laboratory (PNNL) on fossil energy, focusing on advanced gasification, syngas conversion, carbon capture, energy storage, and energy utilization.

The Chinese Academy of Engineering signed an agreement on Cooperation in Engineering and Technical Sciences with the U.S. National Academy of Engineering in June 2008. This wide-ranging document covers several disciplines and industries and includes study visits for scientific exchanges, exploratory missions to facilitate joint research ventures, joint seminars and workshops, and the general exchange of information and research publications.

BARRIERS TO COOPERATION

As is apparent from the descriptions above, a good deal of cooperative activity has been initiated, or at least proposed, on all levels. Moving from governmental agreements into on-the-ground actions, backed by financial resources, has proven to be more challenging. The official governmental track, although not the only source of cooperation, is especially important, because it influences cooperation among nongovernmental actors, primarily by providing funding opportunities for cooperative activities.

Political and Financial Support

There is a long list of official bilateral agreements between the United States and China in the area of clean energy and climate change (see Appendix A). The agreements themselves and the officials who signed them have been well documented by both governments, but information about the results of these programs are much more difficult to find. With a few exceptions, official accounts of the achievements of these programs have not been made available.[7]

In addition, little is known about the level of funding for each initiative, often because the MOUs or the initiatives themselves were not backed by secure funding commitments or did not have sufficient political impetus to see them through. As a result, many people have become justifiably skeptical about government agreements for bilateral cooperation. In extreme cases, this has led to outright mistrust or, at least, reluctance to sign on to future agreements.

More U.S.-Chinese bilateral clean energy and climate change agreements were signed in 2009 than in any other year, and most of them were signed by the presidents of both countries, indicating that they had political support at the highest level. Nevertheless, the success of these agreements can only be measured by their results, which will depend on the resources provided to ensure that they are implemented successfully. As of early 2010 many details about the implementation of these agreements had yet to be worked out, but it was apparent that funding remains a serious limitation. For example, the agreements outlining the new China-U.S. Clean Energy Center and Renewable Energy Partnership refer to existing funding sources for implementing domestic actions in both countries, rather than to additional funding sources for collaborative projects. If no new resources are allocated for these agreements, it is unclear how the proposed new activities are a deviation from ongoing activities and thus able to have meaningful and transformational results.

The Multilateral Context for Bilateral Discussions

From a policy perspective, 2009 seems to have been a successful year for U.S.-Chinese cooperation on clean energy and climate change. The year began with the publication of many road maps by U.S. think tanks and NGOs calling for increased cooperation between the United States and China on these important issues, and[8] President Obama seems to have answered the call by signing a long list of bilateral agreements during his visit to Beijing in November.

---

[7] Examples include the "Protocol for Cooperation in the Fields of Energy Efficiency and Renewable Energy: Progress Report" conducted by DOE/MOST and published in December 1999, and follow-up assessments of DOE-supported projects for PV-wind hybrid household projects in Inner Mongolia.

[8] See, e.g., Asia Society/Pew Center Roadmap for US-China Cooperation, NRDC Roadmap, PNNL Roadmap, etc.

It was no coincidence that these agreements were signed in early December, just days before the start of the 15th Conference of the Parties to the United Nations Framework Convention on Climate Change and the 5th Meeting of the Parties to the Kyoto Protocol in Copenhagen, Denmark, where the United States and China, the two largest emitters of GHGs, took center stage, and the rest of the world watched to see if 194 countries could agree on an international treaty to address climate change.

Although direct bilateral engagement between the United States and China does not replace the participation of both countries in a multilateral agreement, a bilateral partnership may be crucial to facilitating international talks. Bilateral forums provide opportunities for concrete demonstrations of commitments through joint projects and initiatives outside the UN system, which necessarily involves all 192 UN member states.

Discussions on climate change, reframed as clean energy cooperation, can lead to fruitful technical discussions. But in Copenhagen, bilateral agreements appeared to have little bearing on discussions—even bilateral discussions—when many other countries were involved. Even issues that are technical in nature, such as the discussions over countries' measurement and reporting of national greenhouse gas emissions inventories, became politically charged.

The Challenge of Being Cooperative Competitors

The United States and China are often referred to as "cooperative competitors." Cooperation is increasingly common in many areas, from basic research to joint business ventures. At the same time, China and the United States increasingly find themselves competing for resources, talent, and economic markets. However, competition can also drive innovation and low-carbon growth. So, although cooperation will be vital for clean energy development, competition will lead to further innovation and accelerate deployment. If collaborations on clean energy are carefully designed, they can improve the economic prospects of both nations without conferring an unfair competitive advantage on either of them.

Recent events have shown how both countries can act cooperatively to expand access to clean energy markets. For example, announcements made in the fall of 2009 that a wind farm developer in west Texas had contracted with Shenyang Power Group, a Chinese wind turbine manufacturer, to supply its 2.5-MW turbines raised many concerns, particularly from members of Congress, that China was trying to compete with the United States in its own domestic market in an industry that the government had specifically been trying to promote with tax credits and other green jobs initiatives. The Texas wind farm development took place about the same time U.S. Commerce Secretary Locke had asked China to remove a long-standing policy requirement that wind turbines installed in China be locally manufactured, and China had agreed, thus potentially opening the Chinese market to U.S.-manufactured wind turbines. Likely in response to these concerns, Shenyang's parent company, A-Power Energy Generation Systems Ltd., later announced that it would partner with the U.S. Renewable Energy Group to build a wind turbine production factory in the United States (Burnham, 2009; Pasternak, 2009; Smith, 2009).[9] Goldwind, another leading Chinese wind turbine manufacturer, has also announced its intentions to manufacture wind turbines and source its components in the United States.[10] Several other Chinese wind turbine companies have benefited greatly from cooperation with U.S. wind technology companies, including American Superconductor's cooperation with leading Chinese firms, Sinovel and Dongfang Electric.

Although concessions have been made by both sides, tensions have increased with the Section 301[11] petition filed with the United States Trade Representative by the United Steelworkers (USW) in September 2010, claiming that "China's green technology practices violate WTO rules" (USW, 2010). These increasing tensions illustrate the growing importance for both the United States and China to look for ways to jointly address the concerns of both sides so that international trade conflicts can be avoided. Both countries should have access to the best, lowest cost, wind turbine technology available, and healthy competition in domestic and international markets should encourage both countries to produce it. Clearly, it will take time to build a foundation of trust, but in the long run, that trust will be crucial to scaling up the clean energy cooperation between the United States and China that will benefit the entire world.

OPPORTUNITIES FOR EXPANDING COOPERATION

The focus of expanded U.S.-Chinese renewable energy cooperation should be on a few general categories: (1) basic research; (2) joint strategic studies; (3) joint R&D; (4) joint technology demonstrations; and (5) sharing of best practices in policy implementation. These categories are elaborated in the sections that follow. Specific recommendations for cooperation that fall under the categories below are presented at the end of the preceding chapters.

---

[9] Burnham, Michael. (2009, November 17). "China's A-Power to Build U.S. Wind Turbine Factory. ***New York Times.*** [Online]. Available online at *http://www.nytimes.com/gwire/2009/11/17/17greenwire-chinas-a-power-to-build-us-wind-turbine-factor-22742.html*; Pasternack, Alex. (2009). "Chinese wind farm in Texas: Green jobs fail?" ***Treehugger***. [Online]. Available online at *http://www.treehugger.com/files/2009/11/chinese-wind-farm-texas-green-jobs-fail.php*; Smith, Rebecca. (2009, October 30). "Chinese-Made Turbines to Fill U.S. Wind Farm." ***Wall Street Journal***. [Online]. Available online at *http://online.wsj.com/article/SB125683832677216475.html*.

[10] See *http://www.prnewswire.com/news-releases/goldwind-debut-at-wind-power-2010-to-herald-global-expansion-94711839.html*.

[11] Section 301 of the U.S. Trade Act of 1974, commonly referred to as Super 301, describes itself as "the principal statutory authority under which the United States may impose trade sanctions against foreign countries that maintain acts, policies and practices that violate, or deny U.S. rights or benefits under, trade agreements, or are unjustifiable, unreasonable or discriminatory and burden or restrict U.S. commerce."

Basic Research

Basic research in fields that can contribute to future breakthroughs in renewable energy technologies can be an important area of cooperation. Although there are many opportunities for cooperation in applied research, the fundamentals of many renewable energy technologies would be greatly improved with basic scientific breakthroughs. Basic research is also important for the discovery of new technologies. Solar energy conversion is one such area where collaborative research could be beneficial, given the abundance of solar resources, and the opportunities for breakthroughs in new materials and processes.

Collaborative basic research can be particularly productive because there is usually less competition surrounding the sharing of intellectual property rights at this stage, because many research topics have no identified commercial value. Agreeing ahead of time to share intellectual property that results from joint research discoveries is one way to encourage innovation over competition. The U.S. national laboratories and Chinese national academies, as well as universities in both countries, are natural partners for collaborative basic research.

Joint Strategic Studies

Joint strategic studies can influence policy decisions in both countries. Scenario analyses and technology road maps in particular have been effective ways to articulate a vision and a rationale for promoting the use of renewable energy. For example, the *20 Percent by 2030* study, led by DOE (2008a), has helped policy makers envision the barriers and benefits of a scenario in which the United States greatly expands the share of wind power in its energy mix. China has also conducted similar exercises, which can be influential if timed to fit into the planning cycle of the country's five-year plans. NDRC's revisions to the 2020 target for wind power capacity (from 30 GW to 100–150 GW) provide one such example. Both countries could benefit from understanding all of the strategic studies being developed, because they are both facing similar technical and political challenges related to the increased deployment of renewable energy technologies.

Joint Research and Development

A good deal of discussion has been stimulated about joint R&D on advanced renewable energy technologies. Although huge benefits could accrue to both countries from participating in such a venture, the perceived costs could be huge as well. Potential benefits include access to state of the art knowledge about advanced, pre-commercial renewable energy technologies developed by some of the best scientists and engineers in the world, and accelerated learning (IEA, 2010b). Potential opportunity costs would be associated with the sharing of knowledge, information, or even intellectual property resulting from joint R&D.

The U.S.-China Clean Energy Research Center announced in November 2009 plans to sponsor joint R&D on clean energy technologies by teams of scientists and engineers from the United States and China and to serve as a clearinghouse to help researchers in both countries gain access to information. Costs will be shared equally, an arrangement that both countries have praised and that may become a precedent for future cooperation. In addition, equal cost sharing is likely to make sharing knowledge and product outputs easier.

Joint Technology Demonstrations

Joint demonstration projects, which are often very costly, can provide operational experience for pre-commercial technologies. Cost-sharing arrangements involving multiple countries can be beneficial to all concerned, both developers and the countries in which the products will be commercialized. One clean energy technology often considered appropriate for joint demonstration is CCS applied to coal-fired power plants—a technology that would be very costly for adopters but would benefit everyone by greatly reducing harmful emissions.

In the area of renewable energy, several pre-commercial solar technologies, including some concentrating solar-thermal electric and concentrating solar power (CSP), would also be appropriate for joint demonstrations. Both the United States and China could learn a great deal from further demonstrations of large-scale CSP plants. Energy storage technologies are similarly large-scale, capital-intensive projects and thus suitable candidates for joint demonstrations.

Joint technology demonstrations are not included in the U.S.-Chinese cooperation agreements announced in late 2009. Although a joint CCS project is alluded to, no specific commitments have been made or projects announced.

Sharing Best Practices in Policy Implementation

The sharing of best practices in renewable energy policy making can be a fruitful area for international cooperation. Both the United States and China can benefit from the experiences of successful (and unsuccessful) policies related to the deployment of renewable energy. Too often policy mistakes that could be prevented with the sharing of information across borders are instead repeated. For example, recent underperformance of wind farms in China was the result of incentives based on installed capacity rather than on kilowatt-hours generated. This experience was reminiscent of early challenges with wind farms in California when the capacity-based tax credits offered in the early 1980s resulted in the construction of many wind farms that were never connected to the grid. It is notable that over the past 10 years, Chinese government agencies such as NDRC and NEA have transitioned from a closed decision making process to one that it is more open to direct international input. Still, as the wind incentives experience demonstrates, sharing best practices (as was done through extensive consultations with U.S. and European Union practitioners, the World Bank, and various NGOs) is not always sufficient to prevent mistakes from being repeated.

There is a growing body of academic literature on renewable energy policy making. As a relatively late adopter, China has modeled its renewable energy support mechanisms almost exclusively on the successful mechanisms used by other countries. Although the United States was an early leader in government support for renewable energy, support at the federal level has waned recently, and states are now taking the lead. Thus, the United States and China face similar challenges in coordinating renewable energy policies and targets across states and provinces with differing renewable resource endowments and utility structures.

FINDINGS

In the coming years, renewable energy will be increasingly important to both the United States and China. As two of the largest renewable energy technology markets, the decisions made by these two countries will affect the use of these technologies around the world. Therefore, U.S.-Chinese cooperation on renewable energy will be crucial, both bilaterally and internationally.

Renewable energy cooperation between the United States and China should be coordinated under an overarching framework linked to a comprehensive program of U.S.-China energy and climate cooperation agreed to by the leaders of both countries. The 2009 U.S.-Chinese clean energy cooperation agreements may provide such a framework, but it is too early to assess their achievements. The effectiveness of these agreements will ultimately depend on the commitment of both governments in ensuring they are prioritized, funded, and sustained.

U.S.-Chinese renewable energy cooperation can help cultivate a more productive foundation for Sino-American relations, arguably the most important bilateral relationship in the world. Because the United States and China will be two of the largest markets globally for renewable energy deployment in the coming decades, they are natural partners for addressing common challenges to expanding the deployment of renewable energy technologies. **Failure to develop a sustained program of cooperation may open the door to increased tensions stemming from competition between the United States and China in these sectors, and possibly international trade disputes.**

The United States has as much to learn from China's experiences with renewable energy as China has to learn from the United States' experiences. China, which has the ability to quickly site and build projects to scale, may provide an important arena for initial deployments of renewable energy technologies that can yield lessons on policies and cost reductions that will make these technologies more accessible globally. In addition, the global climate change challenge cannot be met without a successful transition to low-carbon economies by both the United States and China. Thus, U.S.-Chinese renewable energy cooperation will be crucial to addressing global climate change.

Although international cooperation occurs commonly in basic research, sustaining collaboration in applied research, development, and demonstrations has been challenging. **The ongoing dialogue between the United States and China provides one framework for cooperation, but there is a pressing need for more interaction among governments, academia, and the private sector to create an environment that encourages breakthroughs and accelerates the commercialization of promising technologies.**

Although the mandate for cooperation should be framed at the highest levels of government, the people and organizations that will ultimately implement such agreements should be drawn from the best available participants in both countries, whether they be at the central, provincial/state or local levels, and from the governmental, nongovernmental, or private sectors. Many of the most productive bilateral cooperation programs to date have involved partnerships at regional and local levels, and such cooperation should be encouraged and nurtured by high-level mandates.

Currently, bilateral research is the result of ad hoc arrangements among research institutes. A better coordinated, bilateral agenda, with a platform for setting priorities and sharing research results, would benefit the energy research enterprise in both countries. The proposed U.S.-China Clean Energy Research Center **provides one such model for organizing consortia of participants from government, academia, business, and nongovernmental organizations in both countries around pressing research issues that were jointly identified by the governments of both sides.**

The U.S.-China Presidential Summit in Beijing in November 2009 resulted in a significant set of new agreements on joint energy and climate cooperation between the two countries, which if implemented effectively could serve as a platform for enhanced cooperation on renewable energy. **The proposed Renewable Energy Partnership includes several project activities that could integrate many of the recommendations detailed in this report, including technology road mapping, deployment solutions, subnational partnerships, grid modernization, R&D in advanced technologies, and public-private engagement.** Such engagement would be most effective if a sustained public-private forum were established with a multi-year commitment for ongoing communication. In addition, the forum could help facilitate new partnerships by coordinating participants from both sides and act as a clearinghouse for project information and funding or investment opportunities.

Important areas for cooperation that are not included in existing partnerships and should be the topic of future cooperation include joint technology development and demonstration efforts for advanced renewable energy technologies. Subnational cooperation should be further developed, based on resource profiles, allowing states/provinces in both countries to work together in advancing their renewable energy goals (examples include Colorado-Qinghai and Hawaii-Hainan). In addition, the development of a personnel exchange program, through government-sponsored fellowships that would involve short visits of U.S. and Chinese researchers and grid and power plant operators to each other's countries, would foster organizational learning in the fields of renewable power development and grid integration and help to promote understanding and trust in the years to come.

RECOMMENDATIONS

- To ensure that existing Chinese-U.S. partnerships are utilized most effectively, a stable stream of funding must be committed to their support. Activities should build upon existing cooperative activities between U.S. and Chinese experts and foster additional subnational cooperation on implementation issues.
- The United States and China should establish a comprehensive base for official bilateral energy cooperation, including (1) basic research in fields that can contribute to future breakthroughs in renewable energy technologies; (2) joint strategic studies advising policy makers; (3) joint research and development in advanced renewable energy technologies; (4) joint demonstrations of pre-commercial technologies, and (5) sharing of best practices in policy making, regional implementation, planning, operations, and management.

References

AAAS (American Association for the Advancement of Science). 2010. AAAS Report XXXV: Research and Development FY 2011. Washington, D.C.: American Association for the Advancement of Science.

Alsema, E.A. 2000. Energy pay-back time and CO_2 emissions of PV systems. Progress in Photovoltaics: Research and Applications 8: 17–25.

Alsema, E.A., and M.J. de Wild-Scholten. 2006. Environmental impacts of crystalline silicon photovoltaic module production. Presented at the 13th CIRP International Conference on Life Cycle Engineering, Leuven, May 31–June 2, 2006.

Asia Society and Pew Center on Global Climate Change. 2009. Common Challenge, Collaborative Response: A Roadmap for U.S.-China Cooperation on Energy and Climate Change. Produced by the Pew Center on Global Climate Change and Asia Society's Center on U.S.-China Relations. Arlington, Va.: Pew Center on Global Climate Change. Available online at *http://www.pewclimate.org/US-China*.

ASES (American Solar Energy Society). 2007. Tackling Climate Change in the United States: Potential Carbon Emission Reductions from Energy Efficiency and Renewable Energy by 2030. Boulder, Colo.: ASES.

ASES. 2009. Green Collar Jobs in the U.S. and Colorado: Economic Drivers for the 21st Century. Boulder, Colo.: ASES.

AWEA (American Wind Energy Association). 2009. Annual Wind Industry Report: Year Ending 2008. Washington, D.C.: AWEA. Available online at *http://bit.ly/bRnf5U*.

AWEA. 2010. Annual Wind Industry Report: Year Ending 2009. Washington, D.C.: AWEA.

AWS Wind LLC and NREL. 2010. Estimates of Windy Land Area and Wind Energy Potential by State for Areas 30 percent Capacity Factor at 80m. Available online at *http://www.windpoweringamerica.gov/wind_maps.asp*. Spreadsheet with data for individual states available online at *http://bit.ly/94oRm6*.

Bai, X. 2007. Rizhao: Solar-Powered City. In State of the World 2007: Our Urban Future. Washington, D.C.: Worldwatch Institute.

Bai, X., B. Roberts, and J. Chen. 2010. Urban sustainability experiments in Asia: patterns and pathways. Environmental Science and Policy 13(4):312–325.

Bain, R.L., W.A. Amos, M. Downing, and R.L. Perlack. 2003. Biopower Technical Assessment: State of the Industry and Technology. NREL/TP-510-33123. Golden, Colo.: NREL.

Baldinger, P., and J.L. Turner. 2002. Crouching Suspicions, Hidden Potential: United States Environmental and Energy Cooperation with China. Washington, D.C.: Woodrow Wilson International Center for Scholars.

Barrie, D.B., and D.B. Kirk-Davidoff. 2010. Weather response to a large wind turbine array. Atmospheric Chemistry and Physics 10: 769–775.

Bertani, R. 2005. World Geothermal Generation in the period 2001–2005. Geothermics 34(6): 651–690.

Bezdek, R.H., and R.M. Wendling. 2003. A half century of long-range energy forecasts: errors made, lessons learned, and implications for forecasting. Journal of Fusion Energy 21(3/4): 155–172.

Bezdek, R.H., and R.M. Wendling. 2006. The U.S. Energy Subsidy Scorecard. Issues in Science and Technology 22(3): 83–85.

Bezdek, R.H., and R.M. Wendling. 2007. A half century of federal energy incentives: value, distribution, and policy implications. International Journal of Global Energy Issues 27(1): 42–60.

Bird, L., C. Kreycik, and B. Friedman. 2009. Green Power Marketing in the United States: A Status Report (2008 data). NREL/TP-6A2-46581. Golden, Colo.: National Renewable Energy Laboratory.

BLM (Bureau of Land Management). 2005. Final Programmatic Environmental Impact Statement on Wind Energy Development on BLM-Administered Lands in the Western United States. Washington, D.C.: BLM. 2008. Final Programmatic Environmental Impact Statement for Geothermal Leasing in the Western United States. Available online at *http://bit.ly/bW6Cho*.

Boyd, T.L., D. Thomas, and A.T. Gill. 2002. Hawaii and geothermal: what has been happening? GHC Bulletin, 23(3): 11–21.

Brown, E., and S. Busche. 2008. State of the States 2008: Renewable Energy Development and the Role of Policy. Technical Report NREL/TP-670-43021. Golden, Colo.: NREL.

Burnham, M. 2009. China's A-Power to Build U.S. Wind Turbine Factory. *New York Times*, November 17, 2009. Available online at *http://nyti.ms/9pzt9o*.

CAE/NAE/NRC (Chinese Academy of Engineering/National Academy of Engineering/National Research Council). 2003. Personal Cars and China. Washington, D.C.: National Academies Press.

Campbell, R.J. 2010. China and the United States—A Comparison of Green Energy Programs and Policies. CRS Report for Congress R41287. Washington, D.C.: Congressional Research Service.

Campbell, T. 2009. Learning Cities: Knowledge, Capacity, and Competitiveness. Habitat International 33: 195–201.

Canfa, W. 2007. Chinese Environmental Law Enforcement: Current Deficiencies and Suggested Reforms. Vermont Journal of Environmental Law 8(2): 159–194.

Carmody, M., S. Mallick, J. Margetis, R. Kodama, T. Biegala, D. Xu, P. Bechmann, J.W. Garland, and S. Sivananthan. 2010. Single-crystal II-VI on Si single-junction and tandem solar cells. Applied Physics Letters 96: 153502.

Crachilov, C., R.S. Hancock, and G. Sharkey. 2009. The China Greentech Report 2009. Beijing: The China Greentech Initiative. September.

CAE (Chinese Academy of Engineering). 2008. Strategic Research on Renewable Energy Development in China. Beijing, China: China Electric Power Press.

CAS (Chinese Academy of Sciences). 2007. Addressing the Challenge: Developing a Sustainable Energy System. Beijing, China: CAS.

CEC (China Electricity Council). 2010. National Statistics for the Power Industry 2009. Beijing, China: CEC.

Cha, A.E. 2008. Solar energy firms leave waste behind in China. *Washington Post,* March 9, 2008.

Chaudhari, M., L. Frantzis, and T.E. Holff. 2004. PV Grid Connected Market Potential Under a Cost Breakthrough Scenario. San Francisco, Calif.: Energy Foundation and Navigant Consulting.

Christensen, C.M. 1997. The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail. Cambridge, Mass.: Harvard Business Press.

CMA (China Meteorological Administration). 2006. The Report of Wind Energy Resource Assessment in China. Beijing, China: CMA.

CMA. 2008. The Report on Solar Energy Resource Assessment in China. Beijing: China Meteorological Administration.

CNCIC (China National Chemical Information Center). 2009. CNCIC website, *http://www.cheminfo.gov.cn*, (last accessed April 23, 2009).

Council on Foreign Relations. 2007. U.S.-China Relations: An Affirmative Agenda, A Responsible Course. New York: Council on Foreign Relations.

CREDSRG (China Renewable Energy Development Strategy Research Group). 2008. China Renewable Eenrgy Development Strategy Research Series. Beijing, China: China Electric Power Press.

CREIA (Chinese Renewable Energy Industries Association). 2009. *http://www.creia.net.*

Cross, J., and J. Freeman. 2009. 2008 Geothermal Technologies Market Report. NREL Report No. TP-6A2-46022; DOE/GO-102009-2864. Golden, Colo.: NREL.

CWEA (Chinese Wind Energy Association). 2010. Wind Energy, Vols. 8–9. Beijing, China: CWEA.

CWERA/CMA (Center for Wind and Solar Energy Resources Assessment/China Meteorological Administration). 2010. Wind Energy Resource Assessment in China, 2009. Beijing, China: China Meteorological Press.

Denholm, P.L., and G. Kulcinski. 2003. Net Energy Balance and Greenhouse Gas Emissions from Renewable Energy Storage Systems. ECW Report Number 223-1. Madison, Wis.: Energy Center of Wisconsin. Available online at *http://www.cee1.org/eval/db_pdf/379.pdf*.

Dimroth, F., W. Guter, J. Schöne, E. Welser, M. Steiner, E. Oliva, A. Wekkeli, G. Siefer, S.P. Philipps, and A.W. Bett. 2009. Metamorphic GaInP/GaInAs/Ge Triple-Junction Solar Cells with > 41% Efficiency. In Proceedings of the 34th IEEE PV Specialists Conference, Philadelphia, Pa., June 7–12, 2009.

DiPippo, R. 2008. Geothermal Power Plants: Principles, Applications, Case Studies and Environmental Impact, 2nd Ed. Amsterdam: Elsevier.

DOE (U.S. Department of Energy). 2006a. Energy Demands on Water Resources: Report to Congress on the Interdependency of Energy and Water. December. Washington, D.C.: DOE.

DOE. 2006b. Fact Sheet: U.S. Department of Energy Cooperation with the People's Republic of China. Washington, D.C.: DOE.

DOE. 2007a. Enhanced Geothermal Systems Reservoir Creation Workshop. Summary Report, Enhanced Geothermal Systems Reservoir Creation Workshop, Houston, Tex. Washington, D.C.: DOE.

DOE. 2007b. National Solar Technology Roadmap: Thin Film-Silicon PV. Energy Efficiency and Renewable Energy. Washington, D.C.: DOE.

DOE. 2007c. National Solar Technology Roadmap: Wafer-Silicon PV. Energy Efficiency and Renewable Energy. Washington, D.C.: DOE.

DOE. 2008a. 20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply. Washington, D.C.: DOE. Available online at *http://bit.ly/a2U0nL*.

DOE. 2008b. Solar Energy Technologies Program: Multi Year Program Plan, 2008–2012. Washington, D.C.: DOE. Available online at *http://bit.ly/cBt7KS*.

DOE. 2008c. United States—Wind Resource Map. Washington, D.C.: DOE. Available online at *http://bit.ly/9wdy2j*.

DOE. 2009. Solar Energy Development Programmatic EIS Information Center. U.S. Department of Energy, Office of Energy Efficiency and Renewables and U.S. Department of Interior, Bureau of Land Management. Available online at *solareis.anl.gov/index.cfm*.

Dooley, J.J. 2008. U.S. Federal Investments in Energy R&D: 1961–2008. Report PNNL-17952. Richland, Wash.: Pacific Northwest National Laboratory.

Duderstadt, J.J., M. Muro, G. Was, A. Sarzynski, R. McGrath, M. Corradini, L. Katehi, and R. Shangraw. 2009. Energy Discovery-Innovation Institutes: A Step Towards America's Energy Sustainability. Washington, D.C.: The Brookings Institution.

Edelson, D. 2009. Requirements and Expectations for a Quality Wind Forecast. Wind Energy Production Forecasting Webinar. New York Independent System Operator, February 9.

EIA (Energy Information Agency). 2007a. Annual Energy Outlook 2007 with Projections to 2030. Report No. DOE/EIA-0383. Washington, D.C.: EIA. Available online at *http://tonto.eia.doe.gov/ftproot/forecasting/0383(2007).pdf*.

EIA. 2007b. Renewable Energy Annual, 2005. Washington, D.C.: EIA.

EIA. 2009a. Annual Energy Outlook. Table 7-1, Figures 7-1, 7-2. Washington, D.C.: EIA.

EIA. 2009b. Country Analysis Briefs: Electricity in China. Washington, D.C.: EIA. Available online at *http://bit.ly/b9YqiR.*

EIA. 2009c. Electric Power Annual: Electric Power Industry 2008: Year in Review. Washington, D.C.: EIA. Available online at *http://bit.ly/cOANrL*. Table available online at *http://bit.ly/bBZDGf*.

EIA. 2009d. International Energy Outlook 2009. Tables h15–h18. Available online at *http://www.eia.doe.gov/oiaf/ieo/*.

EIA. 2009e. Renewable Energy Annual, 2007 Edition. Washington, D.C.: EIA. Available online at *http://bit.ly/bmqdQp*.

EIA. 2010a. Annual Energy Outlook. Washington, D.C.: EIA. Available online at *http://www.eia.doe.gov/oiaf/aeo/*.

EIA. 2010b. Electric Power Monthly with Data for July 2010. Washington, D.C.: EIA.

EIA. 2010c. International Energy Statistics. Available online at *http://bit.ly/9GmNqp*.

EIA. 2010d. Renewable Energy Consumption and Electricity Preliminary Statistics, 2009. Washington, D.C.: EIA.

ELI (Environmental Law Institute). 2009. Estimating U.S. Government Subsidies to Energy Sources: 2002–2008. Washington, D.C.: Environmental Law Institute.

Elliott, D., M. Schwarz, S. Haymes, D. Heimiller, G. Scott, L. Flowers, M. Brower, E. Hale, and B. Phelps. 2010. 80 and 100 meter Wind Energy Resource Potential for the United States. Report NREL/PO-550-48036. Available online at *http://www.nrel.gov/wind/pdfs/48036.pdf*.

Elliott, D.L., L.L. Wendell, and G.L. Gower. 1991. An Assessment of the Available Windy Land Area and Wind Energy Potential in the Contiguous United States. Richland, Wash.: Pacific Northwest Laboratory.

Emery, F., and E. Trist. 1965. The causal texture of organizational environments. Human Relations 18: 21–32.

EPA (Environmental Protection Agency). 2010. Energy Projects and Candidate Landfills. Landfill Methane Outreach Program. Available online at *http://www.epa.gov/lmop/projects-candidates/index.html*.

EPA. 2009. National Emissions Inventory Air Pollutant Emissions Trends Data, updated June 2009. Available online at *http://www.epa.gov/ttn/chief/trends/*.

EPRI (Electric Power Research Institute). 2005. Final Summary Report: Project Definition Study: Offshore Wave Power Feasibility Demonstration Project. Palo Alto, Calif.: EPRI.

EPRI. 2007. Assessment of Waterpower Potential and Development Needs. Final Report. March. Palo Alto, Calif.: EPRI.

EWEA (European Wind Energy Association). 2009. Wind at Work: Wind Energy and Job Creation in the EU. Available online at *http://bit.ly/azvZ3v*.

Fang, X. 2008. From Imitation to Innovation: A Strategic Adjustment in China's S&T Development. Presentation at U.S.-China Symposium on Science and Technology Strategic Policy, April 15, 2008, National Academy of Sciences, Washington, D.C.

Feeley III, T.J., T.J. Skone, G.J. Stiegel, A. McNemar, M. Nemeth, B. Schimmoller, J.T. Murphy, and L. Manfredo. 2008. Water: a critical resource in the thermoelectric power industry. Energy 33(1): 1–11.

Feller, I. 2009. Industry-University R&D Partnerships in the United States. Pp. 169–185 in 21st Century Innovation Systems for Japan and the United States: Lessons from a Decade of Change, Report of a Symposium. Washington, D.C.: National Academies Press.

FERC (Federal Energy Regulatory Commission). 2010. Issued Hydrokinetic Preliminary Permits. October. Washington, D.C.: FERC.

Frandsen, S., R. Barthelmei, O. Rathmann, H.E. Jorgensen, J. Badger, K. Hansen, S. Ott, P.E. Rethore, S.E. Larsen, and L.E. Jensen. 2007. Summary Report: The Shadow Effect of Large Wind Farms: Measurements, Data Analysis and Modeling. Riso National Laboratory, Technical University of Denmark, Riskilde, Denmark.

Fredriksen, K.A. 2008. Acting Assistant Secretary, Office of Policy and International Affairs, U.S. DOE, Statement before the U.S.-China Economic and Security Review Commission, August 13, 2008. Available online at *http://www.pi.energy.gov/documents/FredriksenTestimony.pdf*.

Fthenakis, V. 2009. Sustainability of photovoltaics: the case for thin-film solar cells. Renewable and Sustainable Energy Reviews 13(9): 2746–2750.

Fthenakis, V.M., H.C. Kim, and E. Alsema. 2008. Emissions from photovoltaic life cycles. Environmental Science and Technology 42(6): 2168–2174.

FWS (U.S. Fish and Wildlife Service). 2003. Service Interim Guidance on Avoiding and Minimizing Wildlife Impacts from Wind Turbines. May 13. Available online at *http://www.fws.gov/habitatconservation/wind.pdf*.

Gagnon, L., and J.F. van de Vate. 1997. Greenhouse gas emissions from hydropower: the state of research in 1996. Energy Policy 25(1): 7–13.

GEA (Geothermal Energy Association). 2009. U.S. Geothermal Power Production and Development Update: March 2009. Washington, D.C.: GEA.

Gleick, P. 1994. Water and energy. Annual Review of Energy and the Environment 19: 267–299.

Green, M.A., K. Emery, Y. Hishikawa, and W. Warta. 2010. Solar cell efficiency tables (version 36). Progress in Photovoltaics: Research and Applications 18(5): 346–352.

Green, D., and R.G. Nix. 2006. Geothermal—The Energy Under Our Feet: Geothermal Resource Estimates for the United States. Technical Report NREL/TP-840-40665. Golden, Colo.: NREL. Available online at *http://www1.eere.energy.gov/geothermal/pdfs/40665.pdf*.

Grimm, N.B., S.H. Faeth, N.E. Golubiewski, C.L. Redman, J. Wu, X.M. Bai, and J.M. Briggs. 2008. Global change and the ecology of cities. Science 319: 756–760.

Gronowska, M., S. Joshi, and H.L. MacLean. 2009. A Review of U.S. and Canadian Biomass Supply Curves. BioResources 4(1): 341–369.

Gu, L. 2008. Pollution and energy consumption: soft spot of polysilicon. Guangdong Science & Technology 15: 91–93 (in Chinese).

Guter, W., J. Schoene, S.P. Philipps, M. Steiner, G. Siefer, A. Wekkeli, E. Welser, E. Oliva, A. W. Bett, and F. Dimroth. 2009. Current-matched triple-junction solar cell reaching 41.1% conversion efficiency under concentrated sunlight. Applied Physics Letters 94(22): 223504/1–3.

GWEC (Global Wind Energy Council). 2010. Global Wind 2009 Report. Brussels, Belgium: GWEC.

Hall, D.G., K.S. Reeves, J. Brizzee, R.D. Lee, G.R. Carroll, and G.L. Sommers. 2006. Feasibility Assessment of the Water Energy Resources of the United States for New Low Power and Small Hydro Classes of Hydroelectric Plants. Report DOE/ID 11263. Available online at *http://bit.ly/9buOxn*.

Haq, Z., and J. Easterly. 2006. Agricultural Residue Availability in the United States. Applied Biochemistry and Biotechnology 129(1-3): 3–21.

Holmes, K.J., J.A. Graham, T. McKone, and C. Whipple. 2009. Regulatory models and the environment: practice, pitfalls, and prospects. Risk Analysis 29(9): 159–170.

Holt, E., and L. Bird. 2005. Emerging Markets for Renewable Energy Certificates: Opportunities and Challenges. NREL/TP-620-37388. January. Golden, Colo.: NREL.

Holt, E., and R. Wiser. 2007. The Treatment of Renewable Energy Certificates, Emissions Allowances, and Green Power Programs in State Renewables Portfolio Standards. Report LBNL-62574. April. Berkeley, Calif.: Lawrence Berkeley National Laboratory.

Hondo, H. 2005. Life cycle GHG emission analysis of power generation systems: Japanese case. Energy 30(11-12): 2042–2056.

Hu, Y. The main problems in China's polysilicon industry. Solar Energy 8: 63–64 (in Chinese).

Huang, X. 2006. Environmental Impacts Report of Different Generation Electricity Technologies. China Huadian Engineering Co., Ltd. (CHEC).

Huo, H., Q. Zhang, M.Q. Wang, D.G. Streets, and K.B. He. 2010. Environmental Implication of Electric Vehicles in China. Environmental Science and Technology 44(13):4856–4861.

IEA (International Energy Agency). 2008. IEA WIND ENERGY, Annual Report 2008. Available online at *http://www.ieawind.org/AnnualReports_PDF/2008/2008%20AR_small.pdf*.

IEA. 2009. IEA Ocean Energy: Global Technology Development Status. IEA-OES Document No. T0104. Available online at *http://iea-oceans.org/_fich/6/ANNEX_1_Doc_T0104.pdf*.

IEA. 2010a. Energy Technology Perspectives 2010: Scenarios and Strategies to 2050. Paris: OECD/IEA.

IEA. 2010b. Global Gaps in Clean Energy RD&D. IEA Report for the Clean Energy Ministerial. Paris: OECD/IEA.

IEA. 2010c. Opportunities to Transform the Electricity Sector in Major Economies. IEA Report for the Clean Energy Ministerial. Paris: OECD/IEA.

IEA. 2010d. SolarPACES International Project Database. Available online at *http://www.solarpaces.org/News/Projects/projects.htm*. (See also IEA SolarPACES Annual Report 2008, published in May 2009, edited by C. Richter. Available online at *http://www.solarpaces.org/Library/AnnualReports/docs/ATR2008.pdf*.)

IEA. 2010e. Transforming Global Markets for Clean Energy Products: Energy Efficient Equipment, Vehicles and Solar Photovoltaics. IEA Report for the Clean Energy Ministerial. Paris: OECD/IEA.

Jacobsson, S., and A. Johnson. 2000. The diffusion of renewable energy technology: an analytical framework and key issues for research. Energy Policy 28(9): 625–640.

Jones, J.L. 2008. Open Letter on Securing America's Energy Future. July 16, 2008. Available online at *http://bit.ly/9gBAZq*.

JRC (Joint Research Center). 2009. PV Status Report 2009: Research, Solar Cell Production and Market Implementation of Photovoltaics. JRC Scientific and Technical Report EUR 24027 EN. Ispra, Italy: European Commission JRC, Institute for Energy.

JRC. 2010. PV Status Report 2010: Research, Solar Cell Production and Market Implementation of Photovoltaics. JRC Scientific and Technical Report EUR 24344 EN. Ispra, Italy: European Commission JRC, Institute for Energy.

Junginger, M., P. Lako, S. Lensink, W. van Sark, and M. Weiss. 2008. Climate Change Scientific Assessment and Policy Analysis: Technological Learning in the Energy Sector. Report 500102017. Bilthoven: Netherlands Environmental Assessment Agency.

Kammen, D.M., and G.F. Nemet. 2005. Reversing the incredible shrinking energy R&D budget. Issues in Science and Technology 22(1): 84–88.

Keith, D.W., J.F. DeCarolis, D.C. Denkenberger, D.H. Lenschow, S.L. Malyshev, S. Pacala, and P.J. Rasch. 2004. The influence of large scale wind power on global climate. Proceedings of the National Academy of Sciences 101(46): 16115–16120.

Kirk-Davidoff, D.B., and D. Keith. 2008. On the climate impact of surface roughness anomalies. Journal of Atmospheric Science 85: 2215–2234.

Kroposki, B. 2007. Renewable Energy Interconnection and Storage. Presentation at the First Meeting of the Panel on Electricity from Renewables, September, 18, 2008. Washington, D.C.

Kunz, T.H., E.B. Arnett, W.P. Erickson, A.R. Hoar, G.D. Johnson, R.P. Larkin, M.D. Strickland, W.R. Thresher, and M.D. Tuttle. 2007. Ecological impacts of wind energy development on bats: questions, research needs and hypotheses. Frontiers in Ecology and the Environment 5(6): 315–324.

Lechón, Y., C. de la Rúa, and R. Sáez. 2008. Life cycle environmental impacts of electricity production by solar thermal power plants in Spain. Journal of Solar Energy Engineering 130: 1–7.

Lewis, N.S., and D.G. Nocera. 2006. Powering the planet: chemical challenges in solar energy utilization. Proceedings of the National Academy of Sciences 103(43): 15729–15735.

Li, J., and L. Ma. 2009. Background Paper: Chinese Renewables Status Report. Paris, France: Renewable Energy Policy Network for the 21st Century. Available online at *http://bit.ly/9JVBT7*.

Long, G., B. Wu, S. Hai, and K. Qiu. 2008. Development status and prospect of solar grade silicon production technology. Chinese Journal of Nonferrous Metals 18 (E01): 386–392 (in Chinese).

Lu, X., M.B. McElroy, and J. Kiviluoma. 2009. Global potential for wind-generated electricity. Proceedings of the National Academy of Sciences 106: 10933–10938.

Macdonald, D.H., A. Cuevas, M.J. Kerr, C. Samundsett, D. Ruby, S. Winderbaum, and A. Leo. 2004. Texturing industrial multicrystalline silicon solar cells. Solar Energy 76(1-3): 277–283.

Mancini, T. 2009. Sandia National Laboratories, personal communication, February 2, 2009.

Mancini, T., P. Heller, B. Bulter, B. Osborn, S. Wolfgang, G. Vernon, R. Buck, R. Diver, C. Andraka, and J. Moreno. 2003. Dish Stirling Systems: an overview of development and status. Journal of Solar Energy Engineering 125(2): 135–151.

Margolis, R., and D. Kammen. 1999. Evidence of under-investment in energy R&D in the United States and the impact of federal policy. Energy Policy 27(10): 575–584.

McKinsey & Company. 2009. China's Green Revolution: Prioritizing Technologies to Achieve Energy and Environmental Sustainability. Shanghai, China: McKinsey & Company Greater China Office.

McVeigh, J., D. Burtraw, J. Darmstadter, and K. Palmer. 2000. Winner, loser, or innocent victim? Has renewable energy performed as expected? Solar Energy 68(3): 237–255.

Milbrandt, A. 2005. A Geographic Perspective on the Current Biomass Resource Availability in the United States. Golden, Colo.: NREL.

Miles, A.C. 2008. Hydropower at the Federal Energy Regulatory Commission. Presentation at the Third Meeting of the Panel on Electricity from Renewables, Washington, D.C., January 16, 2008.

Miller, R., and M. Winters. 2009. Opportunities in Pumped Storage Hydropower: Supporting Attainment of Our Renewable Energy Goals. National Hydropower Association White Paper. April.

Milly, P.C.D., K.A. Dunne, and A.V. Vecchia. 2005. Global pattern of trends in streamflow and water availability in a changing climate. Nature 438(7066): 347–350.

Minerals Management Service. 2006. Wave Energy Potential on the U.S. Outer Continental Shelf, Technology White Paper. Washington, D.C.: Renewable Energy and Alternate Use Program, U.S. Department of the Interior.

MIT (Massachusetts Institute of Technology). 2006. The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century. Cambridge, Mass.: MIT Press.

Mosey, G., D. Heimiller, D. Dahle, L. Vimmerstedt, and L. Brady-Sabeff. 2007. Converting Limbo Lands to Energy-Generating Stations: Renewable Energy Technologies on Underused, Formerly Contaminated Sites. Environmental Protection Agency Report No. 600/R/08/023, NREL Report No. TP-640-41522. Washington, D.C.: Environmental Protection Agency.

Mu, R.P. 2007. Research and Commercialization Infrastructure. In The Dragon and the Elephant: Understanding the Development of Innovation Capacity in China and India—Summary of a Conference. NRC, 2010. Washington, D.C.: National Academies Press.

Murphy, L.M., and P.L. Edwards. 2003. Bridging the Valley of Death: Transitioning from Public to Private Sector Financing. NREL/MP-720-34036. Golden, Colo.: NREL.

Musial, W., and S. Butterfield. 2004. Future for Offshore Wind Energy in the United States. Preprint. NREL/CP-500-36313. Golden, Colo.: NREL. Available online at *http://bit.ly/btRInE*.

NAE (National Academy of Engineering)/NRC (National Research Council)/CAE/CAS. 2007. Energy Futures and Urban Air Pollution: Challenges for China and the United States. Washington, D.C.: National Academies Press.

NAS (National Academy of Sciences)/NAE/NRC. 2009a. America's Energy Future: Technology and Transformation. Washington, D.C.: National Academies Press.

NAS/NAE/NRC. 2009b. Liquid Transportation Fuels from Coal and Biomass: Technological Status, Costs, and Environmental Impacts. Washington, D.C.: National Academies Press.

NAS/NAE/NRC. 2010a. Electricity from Renewable Resources: Status, Prospects, and Impediments. Washington, D.C.: National Academies Press.

NAS/NAE/NRC. 2010b. Real Prospects for Energy Efficiency in the United States. Washington, D.C.: National Academies Press.

NAS/NAE/IOM (Institute of Medicine). 2007. Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future. Washington, D.C.: National Academies Press.

NCI (Navigant Consulting, Inc.). 2010. Jobs Impact of a National Renewable Electricity Standard: Final Report. Prepared for the RES Alliance for Jobs, February 2. Washington, D.C.: NCI.

NDRC (National Development and Reform Commission). 2007. Medium and Long-Term Development Plan for Renewable Energy. Beijing: National Development and Reform Commission.

Nemet, G.F. 2006. Beyond the learning curve: factors influencing cost reductions in photovoltaics. Energy Policy 34(17): 3218–3232.

Nemet, G.F. 2009. Interim monitoring of cost dynamics for publicly supported energy technologies. Energy Policy 37(3): 825–835.

Nemet, G.F., and D.M. Kammen. 2007. U.S. energy R&D: declining investment, increasing need, and the feasibility of expansion. Energy Policy 35(1): 746–755.

NEA (National Energy Administration-China). 2010. China Energy Development Report 2010, edited by G.B. Zhang. Beijing, China: Economic Science Press.

NETL (National Energy Technology Laboratory). 2007. The NETL Modern Grid Initiative: A Vision for the Modern Grid. March. Pittsburgh, Pa.: NETL. Available online at *http://bit.ly/bqrMRO*.

NHA (National Hydropower Association). 2010. Converting America's Nonpowered Dams: Tapping Our Unrealized Energy Resources. Washington, D.C.: NHA.

North Carolina Solar Center and U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. 2009. Database of State Incentives for Renewables & Efficiency. Available online at *http://dsireusa.org/*. Accessed June 2009.

Norton, B., P.S. Eames, and N.G. Lo. 1998. Full-energy-chain analysis of greenhouse gas emissions for solar thermal electric power generation systems. Renewable Energy 15: 131–136.

NRC (National Research Council). 1990. Surface Coal Mining Effects on Ground Water Recharge. Washington, D.C.: National Academy Press.

NRC. 2000. Renewable Power Pathways: A Review of the U.S. Department of Energy's Renewable Energy Programs. Washington, D.C.: National Academy Press.

NRC. 2007. Environmental Impacts of Wind-Energy Projects. Washington, D.C.: National Academies Press.

NRC. 2008. Transitions to Alternative Transportation Technologies: A Focus on Hydrogen. Washington, D.C.: National Academies Press.

NRC. 2009a. Assessing Economic Impacts of Greenhouse Gas Mitigation: Summary of a Workshop. Washington, D.C.: National Academies Press.

NRC. 2009b. Persistent Forecasting of Disruptive Technologies. Washington, D.C.: National Academies Press.

NRC. 2010a. Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use. Washington, D.C.: National Academies Press.

NRC. 2010b. Toward Sustainable Agricultural Systems in the 21st Century. Washington, D.C.: National Academies Press.

NRC. 2010c. Transitions to Alternative Transportation Technologies: Plug-in Hybrid Electric Vehicles. Washington, D.C.: National Academies Press.

NRC/CAS/CAE (National Research Council/Chinese Academy of Sciences/Chinese Academy of Engineering). 2000. Cooperation in the Energy Futures of China and the United States. Washington, DC: National Academy Press.

NRC/NAE/CAS/CAE (National Research Council/National Academy of Engineering/Chinese Academy of Sciences/Chinese Academy of Engineering). 2004. Urbanization, Energy, and Air Pollution in China: The Challenges Ahead: Proceedings of a Symposium. Washington, D.C.: National Academies Press.

NREL (National Renewable Energy Laboratory). 2010a. FY 2009 National Renewable Energy Laboratory Annual Report: A Year of Energy Transformation. NREL/MP-6A4-45629. January. Golden, Colo.: NREL.

NREL. 2010b. The Open PV Mapping Project. Available online at *http://openpv.nrel.gov/*.

NSB (National Science Board). 2009. Building a Sustainable Energy Future: U.S. Actions for an Effective Energy Economy Transformation. NSB-09-55. August 3. Arlington, Va.: NSB.

NSB. 2010. Science and Engineering Indicators: 2010. NSB 10-01. Arlington, Va.: NSB.

O'Donnell, C., P. Baumstark, V. Nibler, K. Corfee, and K. Sullivan. 2009. Renewable Energy Cost of Generation Update. PIER Interim Project Report. CEC-500-2009-084. August. Sacramento, Calif.: California Energy Commission.

OHA (Office of Hawaiian Affairs). 2007. Protection of Wao Kele O Puna celebrated, Aug. 27, 2007. Available online at *http://www.oha.org/index.php?option=com_content&task=view&id=398&Itemid=1*.

OPS (Office of the Press Secretary). 1999. Fact Sheet: U.S.-China Forum on Environment and Development. Available online at *http://clinton6.nara.gov/1999/04/1999-04-08-fact-sheet-on-vice-president-and-premeir-zhrongji-forum.html*.

OPS. 2009a. Fact Sheet: U.S.-China Clean Energy Research Center. Available online at *http://www.energy.gov/news2009/documents2009/U.S.-China_Fact_Sheet_CERC.pdf*.

OPS. 2009b. Fact Sheet: U.S.-China Cooperation on 21st Century Coal. Available online at *http://www.energy.gov/news2009/documents2009/US-China_Fact_Sheet_Coal.pdf*.

OPS. 2009c. Fact Sheet: U.S.-China Electric Vehicles Initiative. Available online at *http://www.energy.gov/news2009/documents2009/US-China_Fact_Sheet_Electric_ Vehicles.pdf*.

OPS. 2009d. Fact Sheet: U.S.-China Energy Efficiency Action Plan. Available online at *http://www.energy.gov/news2009/documents2009/US-China_Fact_Sheet_Efficiency_ Action_Plan.pdf*.

OPS. 2009e. Fact Sheet: U.S.-China Renewable Energy Partnership. Available online at *http://www.energy.gov/news2009/documents2009/US-China_Fact_Sheet_Renewable_ Energy.pdf*.

OPS. 2009f. Fact Sheet: U.S.-China Shale Gas Resource Initiative. Available online at *http://www.energy.gov/news2009/documents2009/US-China_Fact_Sheet_Shale_Gas.pdf*.

Oregon Historical Quarterly. 2007. Significant events in the history of Celilo Falls. Oregon Historical Quarterly 108(4). Available online at *http://www.historycooperative.org/journals/ohq/108.4/editor.html*.

ORNL (Oak Ridge National Laboratory). 1993. Hydropower: Licensed to Protect the Environment. ORNL Review 26(3&4). Available online at *http://www.ornl.gov/info/ornlreview/rev26-34/text/hydmain.html*.

Palmer, K., and D. Burtraw. 2005. Cost-effectiveness of renewable electricity policies. Energy Economics 27(6): 873–894.

Pasternak, A. 2009. "Chinese" Wind Farm in Texas: Green Jobs Fail? Available online at *http://www.treehugger.com/files/2009/11/chinese-wind-farm-texas-green-jobs-fail.php*.

Pehnt, M. 2006. Dynamic life cycle assessment (LCA) of renewable energy technologies. Renewable Energy 31: 55–71.

Perlack, R.D., L.L. Wright, A.F. Turhollow, R.L. Graham, B.J. Stokes, and D.C. Erbach. 2005. Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply. Sponsored by the USDA and DOE. Available online at *http://bit.ly/bQSjUu*.

Pernick, R., and C. Wilder. 2008. Utility Solar Assessment (USA) Study: Reaching Ten Percent Solar by 2025. Washington, D.C.: Clean Edge Inc. and Co-op America Foundation.

Pew Charitable Trusts. 2010. Who's Winning the Clean Energy Race? Growth, Competition, and Opportunities in the World's Largest Economies. Philadelphia, Pa., and Washington, D.C.: The Pew Charitable Trusts.

Pletka, R., and Finn, J. 2009. Western Renewable Energy Zones, Phase 1: QRA Identification Technical Report. NREL/SR-6A2-46877. Golden, Colo.: NREL.

Price, R.S. 2008. A Chronology of U.S.-China Energy Cooperation. Washington, D.C.: Atlantic Council of the United States.

Pryor, S.C., R.J. Barthelmie, and E. Kjellström. 2005. Potential climate change impact on wind energy resources in northern Europe: analyses using a regional climate model. Climate Dynamics 25(7-8): 815–835.

Pryor, S.C., J.T. Schoof, and R.J. Barthelmie. 2006. Winds of change?: projections of near-surface winds under climate change scenarios. Geophysical Research Letters 33(L11702): 5 pp. doi:10.1029/2006GL026000.

Pryor, S.C., R.J. Barthelmie, D.T. Young, E.S. Takle, R.W. Arritt, D. Flory, W.J. Gutowski Jr., A. Nunes, and J. Roads. 2009. Wind speed trends over the contiguous United States. Journal of Geophysical Research 114(D14105): 18 pp. doi:10.1029/2008JD011416.

REN 21 (Renewable Energy Policy Network for the 21st Century). 2009. Renewables Global Status Report: 2009 Update. Paris, France: REN21 Secretariat. Available online at *http://www.ren21.net/pdf/RE_GSR_2009_Update.pdf*.

REN 21. 2010. Renewables 2010: Global Status Report. Paris, France: REN21 Secretariat. Available online at *http://www.ren21.net/REN21Activities/Publications/GlobalStatusReport/tabid/5434/Default.aspx*.

Robins, N., R. Clover, and C. Singh. 2009. A Climate for Recovery: The Colour of Stimulus Goes Green. HSBC Global Research.

Roy, B.S., S.W. Pacala, and R.L. Walko. 2004. Can large wind farms affect local meteorology? Journal of Geophysical Research 109(D19101): 6 pp. doi:10.1029/2004JD004763.

SEIA (Solar Energy Industries Association). 2004. Our Solar Power Future: The U.S Photovoltaic Industry Roadmap Through 2030 and Beyond. Washington, D.C.: SEIA.

Sherwood, L. 2010. U.S. Solar Market Trends 2009. July. Latham, N.Y.: Interstate Renewable Energy Council.

Shipp, S., and M. Stanley. 2009. Government's Evolving Role in Supporting Corporate R&D in the United States: Theory, Practice, and Results in the Advanced Technology Program. In 21st Century Innovation Systems for Japan and the United States: Lessons from a Decade of Change: Report of a Symposium. Washington, D.C.: National Academies Press.

Smith, R. 2009. Chinese-Made Turbines to Fill U.S. Wind Farm. *Wall Street Journal*, October 30, 2009.

Solarbuzz. 2009. Annual World Solar Photovoltaic Industry Report in 2008. Available online at *http://www.solarbuzz.com/Marketbuzz2009-intro.htm*.

Song, C. 2006. Global challenges and strategies for control, conversion and utilization of CO_2 for sustainable development involving energy, catalysis, adsorption and chemical processing. Catalysis Today 115(1-4): 2–32.

Spath, P., and M. Mann. 2004. Biomass Power and Conventional Fossil Systems with and without CO_2 Sequestration: Comparing the Energy Balance, Greenhouse Gas Emissions and Economics. NREL/TP-510-32575, Golden, Colo.: NREL. January.

Spitzley, D., and G.A. Keoleian. 2005. Life Cycle Environmental and Economic Assessment of Willo Biomass Electricity: A Comparison with Other Renewable and Non-Renewable Sources. Report # CSS04-05R (March 2004, revised February 10, 2005). Center for Sustainable Systems, University of Michigan, Ann Arbor.

Stefansson, B., B. Palsson, and G.O. Frioleifsson. 2008, Iceland Deep Drilling Project: exploration of supercritical geothermal resources. In IEEE Power and Energy Society 2008 General Meeting: Conversion and Delivery of Electrical Energy in the 21st Century, July 20–24, 2008, Pittsburgh, Pa.

Sterzinger, G., and M. Svrcek. 2004. Wind Turbine Development: Location of Manufacturing Activity. September. Washington, D.C.: Renewable Energy Policy Project.

Su, W. 2008. Measures for energy saving and reducing pollution in polysilicon production. Nonferrous Metals Processing 37(2): 57–59 (in Chinese).

Tan, X.M., and Z. Gang. 2009. An Emerging Revolution: Clean Technology, Research and Development in China. WRI Working Paper. Washington, D.C.: World Resources Institute.

Tester, J.W., E.M. Drake, M.J. Driscoll, M.W. Golay, and W.A. Peters. 2005. Sustainable Energy: Choosing Among Options. Cambridge, Mass.: MIT Press.

UNEP (United Nations Environment Program). 2008. Public Finance Mechanisms to Mobilize Public Investment in Climate Change Mitigation. Sustainable Energy Finance Initiative. Paris: United National Environment Programme.

UNEP SEFI (Sustainable Energy Finance Initiative)/New Energy Finance. 2009. Global Trends in Sustainable Energy Investment 2009 Report: Analysis of Trends and Issues in the Financing of Renewable Energy and Energy Efficiency. Geneva, Switzerland: UNEP. Available online at *http://www.unep.org/pdf/Global_trends_report_2009.pdf*.

USGS (U.S. Geological Survey). 1979. Assessment of Geothermal Resources of the United States—1978. Geological Survey Circular 790. Arlington, Va.: USGS. Available online at *http://pubs.er.usgs.gov/usgspubs/cir/cir790*.

USGS. 2005. Estimated Use of Water in the United States in 2000. USGS Circular 1268. Revised February 2005. Arlington, Va.: USGS.

USW (United Steel Workers). 2010. United Steelworkers' Section 301 Petition Demonstrates China's Green Technology Practices Violate WTO Rules. Available online at *http://assets. usw.org/releases/misc/section-301.pdf*.

Vant-Hull, L.L. 1991. Solar Thermal Electricity: An Environmental Benign and Viable Alternative. In Proceedings of the World Clean Energy Conference, Geneva, Switzerland, Nov. 4–7.

Viebahn, P. 2004. INDITEP, Integration of DSG Technology for Electricity Production, WP 4.3, Impact Assessment, Life Cycle Assessment of Construction Materials, Energy Demand and Emissions of DSG. Final Report. Available from *http://www.esa.int/*.

VTT (Technical Research Center of Finland). 2008. Design and Operation of Power Systems with Large Amounts of Wind Power: Final Report: IEA WIND Task 25: Phase one 2006–2008. Available online at *http://www.vtt.fi/inf/pdf/tiedotteet/2009/T2493.pdf*.

Walsh, M., R. Perlack, A. Turhollow, D. de la Torre Ugarte, D. Becker, R. Graham, S. Slinsky, and D. Ray. 2000. Biomass Feedstock Availability in the United States: 1999 State Level Analysis. Oak Ridge, Tenn.: Oak Ridge National Laboratory. Available online at *http://bioenergy.ornl.gov/resourcedata/index.html*.

Walsh, M.E. 2008. U.S. Cellulosic Biomass Feedstock Supplies and Distribution. M&E Biomass, University of Tennessee, Knoxville.

Wang, K.H., and D.Q. Zhao. 2007. Analysis and Comparison on Environment and Efficiency of the Trough and Tower Solar Thermal Power Generation. Energy Engineering 1: 25–28.

Wang, M., and Q. Guo. 2010. The Yangbajing Geothermal Field and the Yangyi Geothermal Field: Two Representative Fields in Tibet, China. In Proceedings of the World Geothermal Congress 2010, Bali, Indonesia, April 25–29.

Wang, Z.F. and Zhang M.M. 2008. Feed-in Tariff Research Report of Solar Thermal Power Plants, Institute of Electrical Engineering, Chinese Academy of Sciences (CAS).

Wang, Z.F. 2009. Prospectives for China's solar thermal power technology development. Energy 35(11): 4417–4420.

Weiss, C., and W.B. Bonvillian. 2009. Structuring an Energy Technology Revolution. Cambridge, Mass.: MIT Press.

Weissman, J. 2009. Credentialing: What's in a Name? A Lot. Solar Today (September/October): 44. Available online at *http://bit.ly/aPWN0V*.

WGA (Western Governors' Association). 2006a. Clean and Diversified Energy Initiative Solar Task Force Report. Washington, D.C.: WGA.

WGA. 2006b. Clean and Diversified Energy Initiative: Geothermal Task Force Report. Washington, D.C.: WGA.

WGA. 2009. Western Renewable Energy Zones Initiative: Phase 1 Report. June 2009. Available online at *http://bit.ly/d2igwv*. Comments online at *http://bit.ly/9oUKff*.

Williams, C.F., and B.S. Pierce. 2008. The U.S. Geothermal Resource Assessment. Available online at *http://energy.usgs.gov/flash/geothermal_slideshow.swf*.

Williams, C.F., M.J. Reed, and R.H. Mariner. 2008. A Review of Methods Applied by the U.S. Geological Survey in the Assessment of Identified Geothermal Resources. U.S. Geological Survey Open-File Report 2008-1296. Reston, Va.: USGS. Available online at *http://pubs.usgs.gov/of/2008/1296/*.

Wilkinson, C. 2007. Blood Struggle: The Rise of Modern Indian Nations. New York: Norton.

Wiser, R. 2008. The Development, Deployment, and Policy Context of Renewable Electricity: A Focus on Wind. Presentation at the 4th Meeting of the Panel on Electricity from Renewables, March 11, 2008, Washington, D.C.

Wiser, R. and M. Bolinger. 2010. 2009 Wind Technologies Market Report. DOE/GO-102010-3107. Washington, DC: National Renewable Energy Laboratory, Office of Energy Efficiency & Renewable Energy, U.S. Department of Energy.

WRI (World Resources Institute). 2005. Millennium Ecosystem Assessment: Ecosystems and Human Well-Being. Washington, D.C.: Island Press.

Wu, Y., D.G. Streets, S.X. Wang, and J.M. Hao. 2010. Uncertainties in estimating mercury emissions from coal-fired power plants in China. Atmospheric Chemistry and Physics 10:2937–2947.

Xu, Y. 2007. Treatment of acidic wastewater with fluoride in the cleaning process of polysilicon raw materials. Jiangsu Metallurgy 35(6): 52–53 (in Chinese).

Xu, D., T. Biegala, M. Carmody, J.W. Garland, C. Grein, and S. Sivananthan. 2010. Proposed monolithic triple-junction solar cell structures with the potential for ultrahigh efficiencies using II-VI alloys and silicon substrates. Applied Physics Letters 96(7): 073508.

Xue, H., R.Z. Zhu, Z.B. Yang, and C.H. Yuan. 2001. Assessment of wind energy reserves in China. Acta Energiae Solaris Sinica 22(4): 168–170.

Yan, L.G. 2009. Presentation to Committee, Xining, China, July 2009.

Yang, J.X., C. Xu, and R.S. Wang. 2002. Methods and Applications of LCA of Products. Weather Publishing Company.

Zeng, H. 2008. Analysis of harmful factors in in polysilicon production. Xinjiang Huagong (4): 41–46 (in Chinese).

Zhong, W. 2005. Discussion and application analysis of polysilicon solar cell production technology. Ceramics Science & Art (5): 36–40 (in Chinese).

Zhu, R., D. Zhang, and Y. Wang. 2009. Assessment of Wind Energy Potential in China. Engineering Sciences 7(2): 18–26.

Zprýme Research and Consulting. 2010. Smart Grid Snapshot: China Tops Stimulus Funding. Austin, Tex.: Zprýme Research and Consulting.

Appendixes

Appendix A

Timeline of U.S.-Chinese Cooperation on Clean Energy and Climate Change*

Year(s)	Name	Actors	Purpose
1979	Scientific and Technology Cooperative Agreement	Official bilateral governmental agreement established by President Carter and Vice Premier Deng Xiaoping	Started with focus on high-energy physics. Served as an umbrella for 30 subsequent bilateral environment and energy protocols. Extended for five years in 1991.
1979	MOU for Bilateral Energy Agreements	DOE and China's SDPC	Led to 19 cooperative agreements on energy, including fossil energy, climate change, fusion energy, energy efficiency, renewable energy, peaceful nuclear technologies, and energy information exchange.
1979	Atmosphere and Science and Technology Protocol	NOAA and Chinese Meteorological Administration	Bilateral climate and oceans data exchange, research, and joint projects.

*This timeline is based on a timeline prepared for Lewis, J. 2010. "The State of U.S.-China Relations on Climate Change: Examining the Bilateral and Multilateral Relationship," in China Environment Series 11, edited by J.L. Turner, Washington, DC: The Woodrow Wilson International Center for Scholars.

Year(s)	Name	Actors	Purpose
1983	Protocol on nuclear physics and magnetic fusion	DOE and SSTC	Long-term objective to use fusion as an energy source.
1985, 2000, 2005–2010	Protocol on Cooperation in the Field of Fossil Energy Research and Development (the Fossil Energy protocol)	DOE and Ministry of the Coal Industry (later MOST)	First major bilateral agreement on fossil energy. Now includes five annexes: power systems, clean fuels, oil and gas, energy and environment technologies, and climate science. Protocol is managed by the Permanent Coordinating Group including members of both countries.
1987	Annex III to the Fossil Energy Protocol Cooperation in the Field of Atmospheric Trace Gases	DOE and CAS	Cooperative research program on the possible effects of CO_2 on climate change.
1988	Sino-American Conference on energy demand, markets, and policy in Nanjing	LBNL/DOE and SPC/ERI	Informal bilateral conference on energy efficiency that led to an exchange program between ERI and LBNL, and the first assessment of China's energy conservation published by LBNL in 1989.
1992	U.S. Joint Commission on Commerce and Trade	U.S. Department of Commerce	Facilitate the development of commercial relations and related economic matters between the U.S. and China. The JCCT's Environment subgroup supports technology demonstrations, training workshops, trade missions, exhibitions, and conferences to foster environmental and commercial cooperation.
1993	U.S. Commercial Mission to China	U.S. DOE and Commerce	For U.S. companies to promote their electric power technology services in China. Industry representatives identified a potential for $13.5 billion in U.S. electric power exports between 1994–2003 (not including nuclear power), equating to 270,000 high-salary U.S. jobs and an opportunity for introducing cost-effective, environmental sound U.S. technologies into China's electric power industry.

Year(s)	Name	Actors	Purpose
1993	Establishment of the Beijing Energy Efficiency Center (BECon)	ERI, LBNL, PNNL, WWF, EPA, WWFN, SPC, SETC, SSTC	The first nongovernmental, nonprofit organization in China focusing on promoting energy efficiency by providing advice to central and local government agencies, supporting energy efficiency business development, creating and coordinating technical training programs, and providing information to energy professionals.
1994	Annexes to the fossil energy protocol	DOE and SSTC	(1) To make positive contributions toward improving process and equipment efficiency, reduce atmospheric pollution on a global scale, advance China's Clean Coal Technologies Development Program, and promote economic and trade cooperation beneficial to both parties (2) Cooperation in coal-fired magnetoydrodynamic (MHD) power generation
1994	China's Agenda 21 Document Released	SSTC and China's National Climate Committee	Lay out China's request for international assistance on environmental issues. The U.S. agreed to support China through DOE's Climate Change Country Studies and Support for National Actions Plans programs.
1995	Series of DOE bilateral agreements signed by Secretary of Energy O'Leary	Bilateral agreements on energy between DOE and Ministries: (1) MOU on bilateral energy consultations (with SPC) (2) Research on reactor fuel (with China Atomic Energy Authority) (3) Renewable energy (with Ministry of Agriculture) (4) Energy efficiency development (with SSTC) (5) Renewable energy technology development (with SSTC) (6) Coal bed methane recovery and use (with Ministry of the Coal Industry) (7) Regional climate research (with the China Meteorological Administration) Also established: -Plan for mapping China's renewable energy resources (DOE and SPC) -Strategies for facilitating financing of U.S. renewable energy projects in China (with DOE, SPC, Chinese and U.S. Ex-Im banks) -Discussions on reducing and phasing out lead in gasoline in China (DOE, EPA with China's EPA and SINOPEC)	

Year(s)	Name	Actors	Purpose
1995 (some annexes in 1996)	Protocol for Cooperation in the Fields of Energy Efficiency and Renewable Energy Technology Development and Utilization	DOE and various ministries	This Protocol has seven annexes: policy; rural energy (with Ministry of Agriculture); large-scale wind systems (with MOEP); hybrid village power; renewable energy business development (with SETC); geothermal energy; energy efficiency (with SPC); hybrid-electric vehicle development; and energy efficiency. Includes 10 teams of Chinese and U.S. government and industry representatives focusing on: energy policy, information exchange and business outreach, district heating, cogeneration, buildings, motor systems, industrial process controls, lighting, amorphous core transformers, finance.
1995-2000	Statement of Intent for statistical information exchange (later became a Protocol)	DOE and NBS	Five meetings to discuss energy supply and demand and exchange information on methods of data collection and processing of energy information.
1997	U.S.-China Forum on Environment and Development	Established by Vice President Al Gore and Premier Li Peng	Venue for high-level bilateral discussion on sustainable development. Established four working groups: energy policy, commercial cooperation, science for sustainable development, and environmental policy. Three priority areas for cooperative work: urban air quality, rural electrification, clean energy, and energy efficiency.
1998–ongoing	Agreement of Intent on Cooperation Concerning Peaceful Uses of Nuclear Technology (PUNT)	DOE and SPC	Paved the way for the exchange of information and personnel, training and participation in research and development in the field of nuclear and nuclear nonproliferation technologies.
1997	Energy and Environment Cooperation Initiative	DOE and SPC	Targeting urban air quality, rural electrification and energy sources, and clean energy sources and energy efficiency. Involved multiple agencies and participants from business sectors and linked energy development and environmental protection.
1997	U.S.-China Energy and Environmental Center	Tsinghua University and Tulane University, with DOE and SSTC/MOST	An initiative centered at Tsinghua and Tulane Universities co-funded by DOE and MOST to (1) provide training programs in environmental policies, legislation, and technology, (2) develop markets for U.S. clean coal technologies, and (3) help minimize the local, regional, and global environmental impact of China's energy consumption.

Year(s)	Name	Actors	Purpose
1998	Joint Statement on Military Environmental Protection	U.S. Secretary of defense and vice-chairman of Chinese Central Military Commission	MOU provides for the exchange of visits by high-level defense officials and the opening of a dialogue on how to address common environmental problems.
1999	U.S.-China Forum on Environment and Development	The U.S. Export-Import Bank, DOE, the China Development Bank, and the State Development Planning Commission	The second meeting of the Forum in Washington, co-chaired by Vice President Al Gore and Premier Zhu Rongji. Two key agreements that came out of the meeting related to renewable energy included a MOU for the establishment of a $100 Million Clean Energy Program to accelerate the deployment of clean U.S. technologies to China in the area of energy efficiency, renewable energy, and pollution reduction; and a Statement of Intent on Cleaner Air and Cleaner Energy Technology Cooperation, focused on energy efficiency improvements in industrial coal-fired boilers; clean coal technology; high-efficiency electric motors; and grid-connected wind electric power.
1999-2000	Fusion Program of Cooperation	DOE and CAS	Plasma physics, fusion technology, advanced design studies, and materials research.
2002-2003	U.S.-China Fusion Bilateral Program	DOE and CAS	Plasma physics, fusion technology, and power plant studies.
2003	FutureGEN	DOE with many international partners	Initially an IGCC plus CCS plant restructured in January 2008 as potential federal funding to support CCS on a privately funded IGCC or PC plant. Companies can bid for participation and funding.
2004	U.S.-China Energy Policy Dialogue	DOE and NDRC	Resumed the former Energy Policy Consultations under the 1995 DOE-SPC MOU. Led to an MOU between DOE and NDRC on Industrial Energy Efficiency Cooperation and includes energy audits of up to 12 of China's most energy-intensive enterprises, as well as training and site visits in the U.S. to train auditors.
2004	U.S.-China Green Olympic Cooperation Working Group	DOE, Beijing Government	Included opportunities for DOE to assist China with physical protection of nuclear and radiological materials and facilities for the Beijing Olympics as DOE had done in Athens.

Year(s)	Name	Actors	Purpose
2006	Asia-Pacific Partnership on Clean Development and Climate	U.S., China + India, Japan, Korea, Australia (later Canada)	Created public-private task forces around specific sectors; Aluminum, Buildings and Appliances, Cement, Cleaner Use of Fossil Energy, Coal Mining, Power Generation and Transmission, Renewable Energy and Distributed Generation, Steel.
2006	U.S.-China Strategic Economic Dialogue	Vice Premier Wu Yi and U.S. Treasury Secretary Henry Paulson. Includes DOE, EPA, NDRC, MOST	Bi-annual, cabinet-level dialogue that includes an energy and environment track.
2007	MOU on Cooperation on the Development of Biofuels	USDA and NDRC	Encourages cooperation in biomass and feedstock production and sustainability; conversion technology and engineering; bio-based product development and utilization standards; and rural and agricultural development strategies.
2007	U.S.-China Bilateral Civil Nuclear Energy Cooperative Action Plan	DOE and NDRC	To compliment discussions under the Global Nuclear Energy Partnership (GNDP) toward the expansion of peaceful, proliferation-resistant nuclear energy for greenhouse gas emissions-free, sustainable electricity production. Bilateral discussions include separations technology, fuels and materials development, fast reactor technology, and safeguards planning.
2007	U.S.-China Westinghouse nuclear reactor agreement	DOE, State Nuclear Power Technology Corporation (SNPTC)	DOE approved the sale of 4 x 1,100-megawatt AP-1000 nuclear power plants, which use a recently improved version of existing Westinghouse pressurized water reactor technology. The contract was valued at $8 billion and included technology transfer to China. The four reactors are to be built between 2009 and 2015.

Year(s)	Name	Actors	Purpose
2008	Ten-Year Energy and Environment Cooperation Framework (SED IV)	DOE, Treasury, State Commerce, EPA, NDRC, State Forestry Administration, National Energy administration, Ministry of Finance, Ministry of Environmental Protection, MOST, and MFA	Establishes five joint task forces on the five functional areas of the framework: (1) clean efficiency and secure electricity production and transmission, (2) clean water, (3) clean air, (4) clean and efficient transportation, and (5) conservation of forest and wetland ecosystems.
2009	U.S.-China Strategic and Economic Dialogue	U.S. Department of State and Department of Treasury, China Ministry of Foreign Affairs	In April 2009 the SED was re-branded as the Strategic and Economic Dialogue, with the U.S. State and Treasury Departments now co-chairing the dialogue for the United States. Treasury Secretary Timothy F. Geithner and Secretary of State Hillary Rodham Clinton were joined for the first July 2009 dialogue by their respective Chinese co-chairs, State Councilor Dai Bingguo and Vice Premier Wang Qishan, which covered a range of strategic and economic issues.

Year(s)	Name	Actors	Purpose
2009	Memorandum of Understanding to Enhance Cooperation on Climate Change, Energy and the Environment	U.S. Department of State and Department of Energy and the China National Development and Reform Commission	To strengthen and coordinate respective efforts to combat global climate change, promote clean and efficient energy, protect the environment and natural resources, and support environmentally sustainable and low-carbon economic growth. Both countries resolve to pursue areas of cooperation where joint expertise, resources, research capacity and combined market size can accelerate progress toward mutual goals. These include, but are not limited to: (1) Energy conservation and energy efficiency (2) Renewable energy (3) Cleaner uses of coal and carbon capture and storage (4) Sustainable transportation, including electric vehicles (5) Modernization of the electrical grid (6) Joint research and development of clean energy technologies (7) Clean air (8) Clean water (9) Natural resource conservation, e.g., protection of wetlands and nature reserves (10) Combating climate change and promoting low-carbon economic growth This MOU is to be implemented via the existing Ten Year Cooperation Framework on Energy and Environment Cooperation, and a newly established Climate Change Policy Dialogue, as well as new agreements forthcoming.
2009	Climate Change Policy Dialogue	Representatives of the two countries' leaders (TBD)	The United States and China will work together to further promote the full, effective, and sustained implementation of the United Nations Framework Convention on Climate Change. The dialogue will promote (1) discussion and exchange of views on domestic strategies and policies for addressing climate change; (2) practical solutions for promoting the transition to low-carbon economies; (3) successful international negotiations on climate change; (4) joint research, development, deployment, and transfer, as mutually agreed, of climate-friendly technologies; (5) cooperation on specific projects; (6) adaptation to climate change; (7) capacity building and the raising of public awareness; and (8) pragmatic cooperation on climate change between cities, universities, provinces, and states of the two countries.

Year(s)	Name	Actors	Purpose
2009	Memorandum of Cooperation to Build Capacity to Address Climate Change	NDRC and EPA	In support of the MOU to Enhance Cooperation on Climate Change, Energy and the Environment, this five-year agreement includes: (1) capacity building for developing greenhouse gas inventories; (2) education and public awareness of climate change; (3) impacts of climate change to economic development, human health, and ecological system, as well as research on corresponding countermeasures; and (4) other areas as determined by the participants.
2009	U.S.-China Joint Commission on Commerce and Trade	Co-chaired by U.S. Dept of Commerce Secretary Locke, U.S. Trade Representative Kirk, Chinese Vice Premier Wang Qishan, with participation from many Ministries/ Agencies from both countries	The Commission met in October 2009 in Hangzhou, China, and reached multiple agreements in many sectors, including, in the clean energy sector, for China to remove its local content requirements on wind turbines.
2009	U.S.-China Clean Energy Research Center	DOE, China MOST, Chinese National Energy Agency	First announced in July 2009 during Secretary Chu's visit to Beijing and finalized during the November 2009 Presidential Summit, the Center will facilitate joint research and development of clean energy technologies by teams of scientists and engineers from the United States and China, as well as serve as a clearinghouse to help researchers in each country. The Center will be supported by public and private funding of at least $150 million over five years, split evenly between the two countries. Initial research priorities will be building energy efficiency, clean coal including carbon capture and storage, and clean vehicles.
2009	U.S.-China Electric Vehicles Initiative	TBD	Announced during the November 2009 Presidential Summit and building on the first-ever U.S.-China Electric Vehicle Forum in September 2009, the initiative will include joint standards development, demonstration projects in more than a dozen cities, technical roadmapping, and public education projects.

Year(s)	Name	Actors	Purpose
2009	U.S.-China Energy Efficiency Action Plan	TBD	Announced during the November 2009 Presidential Summit, the plan calls for the two countries to work together to improve the energy efficiency of buildings, industrial facilities, and consumer appliances. U.S. and Chinese officials will work together and with the private sector to develop energy efficient building codes and rating systems, benchmark industrial energy efficiency, train building inspectors and energy efficiency auditors for industrial facilities, harmonize test procedures and performance metrics for energy efficient consumer products, exchange best practices in energy efficient labeling systems, and convene a new U.S.-China Energy Efficiency Forum to be held annually, rotating between the two countries.
2009	U.S.-China Renewable Energy Partnership	TBD	Announced during the November 2009 Presidential Summit, the Partnership calls for the two countries to develop roadmaps for wide-spread renewable energy deployment in both countries. The Partnership will also provide technical and analytical resources to states and regions in both countries to support renewable energy deployment and will facilitate state-to-state and region-to-region partnerships to share experience and best practices. A new Advanced Grid Working Group will bring together U.S. and Chinese policymakers, regulators, industry leaders, and civil society to develop strategies for grid modernization in both countries. A new U.S.-China Renewable Energy Forum will be held annually, rotating between the two countries.
2009	21st Century Coal	TBD	Announced during the November 2009 Presidential Summit, the two Presidents pledged to promote cooperation on cleaner uses of coal, including large-scale carbon capture and storage (CCS) demonstration projects. Through the new U.S.-China Clean Energy Research Center, the two countries are launching a program of technical cooperation to bring teams of U.S. and Chinese scientists and engineers together in developing clean coal and CCS technologies. The two governments are also actively engaging industry, academia, and civil society in advancing clean coal and CCS solutions.

Year(s)	Name	Actors	Purpose
2009	Shale Gas Initiative	TBD	Announced during the November 2009 Presidential Summit, the new U.S.-China Shale Gas Resource Initiative will use experience gained in the United States to assess China's shale gas potential, promote environmentally sustainable development of shale gas resources, conduct joint technical studies to accelerate development of shale gas resources in China, and promote shale gas investment in China through the U.S.-China Oil and Gas Industry Forum, study tours, and workshops.
2009	U.S.-China Energy Cooperation Program (ECP)	A public-private partnership, including 22 companies as founding members	Announced during the November 2009 Presidential Summit, the U.S.-China Energy Cooperation Program will leverage private-sector resources for project development work in China across a broad array of clean energy projects, to the benefit of both nations. More than 22 companies are founding members of the program. The ECP will include collaborative projects on renewable energy, smart grid, clean transportation, green building, clean coal, combined heat and power, and energy efficiency.

Sources: Baldinger and Turner, 2002; DOE, 2006; Fredriksen, 2008; Price, 2008. See also *http://www.energy.gov/news2009/documents2009/US-China_Fact_Sheet_Renewable_Energy.pdf*; *http://www.energy.gov/news2009/documents2009/U.S.-China_Fact_Sheet_CERC.pdf*; *http://fossil.energy.gov/international/International_Partners/China.html*, *http://www.energy.gov/news2009/8292.htm*, *http://www.state.gov/documents/organization/126802.pdf, http://clinton6.nara.gov/1999/04/1999-04-08-fact-sheet-on-vice-president-and-premeir-zhrongji-forum.html*, *http://www.ustreas.gov/initiatives/us-china/*, and *http://www.ustr.gov/about-us/press-office/fact-sheets/2009/october/us-china-joint-commission-commerce-and-trade*.

Appendix B

Life Cycle Assessment of Solar Thermal Power Technology in China

Description of the Assessment Model

This assessment model is based on a 300 MW solar tower power plant which will be built in Hami, Xinjiang Autonomic Region. The geographic reference of this assessment is Hami in China, and the data time reference is 2008. The functional unit used is 1 kWh produced at the power plant, and it is supposed that the exhaust pressure of the solar tower power plant is 0.06 bar. The characteristics of the 300MW solar tower power plant analyzed by Wang and Zhang (2008) are summarized below. Details can be seen in Table B-1.

Impacts Assessment Model and System Boundaries

The life cycle assessment (LCA) of the 300 MW solar tower power plant was performed using the software tool AGP (Assessment for Green-Product) developed by the Research Center for Eco-Environmental Sciences, Chinese Academy of Science (CAS), based on Chinese product and environmental data. LCA is conducted using APG modules for control interface, input of data listing, output of data listing, and environmental impact assessments. Five processes are divided and modeled in the life cycle of solar tower power plants:

1. The raw materials extraction and manufacturing of components of the power plant. This process includes the energy demand and emission of the facility materials in exploitation and manufacture.
2. The transport phase includes the transportation of raw materials, facilities, and construction materials.
3. The construction activities cover workshop, tower, and pipeline.

TABLE B-1 Characteristics of the Studied Solar Thermal Power

Technology type	Solar central tower power
Installed capacity	300 MW
Direct normal irradiation	1,875 KW h/m^2 yr
Number of heliostats	25,020
Aperture	2,502,000 m^2
Technical lifetime	25 years
Energy generated per year	657 GWh
Energy generated in the lifetime	16,425 GWh
Electricity consumption by self-produced electricity	1,150 GWh
Net efficiency	14.06%

4. In the operation stage the solar thermal power systems transform solar energy to electricity, and no other fossil energy is required except that a small amount of fossil fuel is required in the startup of the electricity generating set. Thereafter, electricity needs are met by the on-site solar generation. The energy demand and emissions can be neglected because so little fossil fuel is used.
5. The impacts of decommissioning of the power plant and the disposal of all the waste materials could not be quantified here due to the lack of reliable data, and so the energy and emissions produced in the disposal of all the waste materials of the power plant could not be accounted for in this study.

Processes modeled in the life cycle of the solar thermal power plants are depicted in Figure B-1.

Assessment Methods

The life cycle of the solar thermal power plant is completed using the following three environmental load profiles. First, the energy balance factor (EBF) is the ratio of energy output to input, which is used to confirm whether the system is feasible as an energy production system. Second, the energy payback time (EPT) is the index that accounts, by energy production, for the number of years required to recover the total energy input into the system over an entire life cycle. The third is the CO_2 emission factor (CEF), which is the CO_2 emission per unit of electricity generated. The CEF of the solar thermal power generation plant analyzed in this study are compared with that of a coal-fired power generation plant, which is reported to have the highest environmental impact among various power generation technologies.

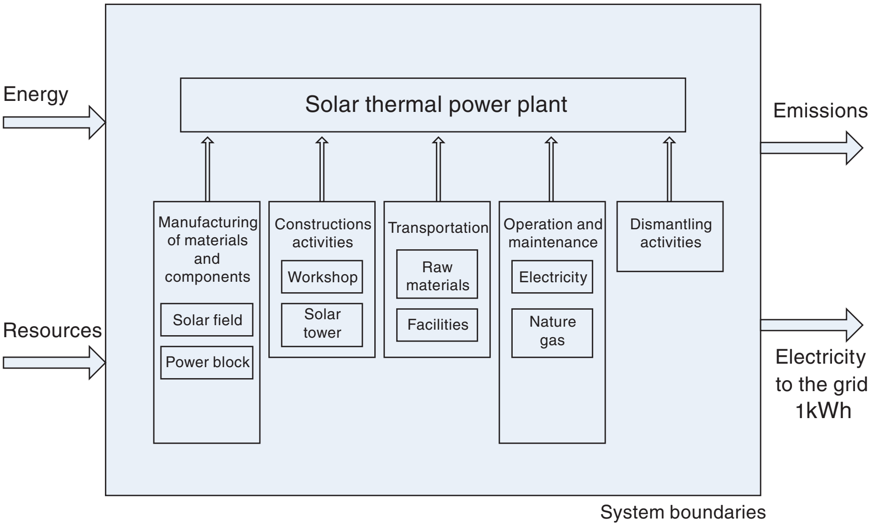


FIGURE B-1 Life cycle of a solar thermal power plant.

After defining the goal and scope, an inventory analysis was carried out based on the collected and processed data. The parameter that has the most impact on the life cycle inventory (LCI) results in this study, i.e., EBF, EPT, and CEF, was evaluated so that problems and improvements of the system could be revealed. The basic theoretical equations for the three environmental load profiles defined in this study (EBF, EPT, CEF, global warming protocol [GWP] and acidification potential [AP]) are expressed as:

$$\mathrm{EBF} = \frac{LCEO}{LCOE + \sum_i LCEE_i} \tag{B-1}$$

$$\mathrm{EPT} = \frac{\sum_i LCEE_i}{AEO - AOE} \tag{B-2}$$

$$\mathrm{CEF} = \frac{\sum_j \left[\left(LCOEE_j + \sum_i LCEEE_{ij} \right) \bullet CEE_j \right]}{LCEO} \tag{B-3}$$

where LCEO is the energy output from an energy conversion plant over its entire life cycle; $LCEE_i$ and LCOE are the "equipment" and "operation" energies over the life cycle of each process of the system, respectively (*i* represents each process, i.e., manufacturing material and equipment, transportation, and construction); AEO is the annual energy output; AOE is the annual operation energy of plant;

$LCEEE_{ij}$ and $LCOEE_j$ are the equipment and operation energies of each kind of energy resources, e.g., electricity, coal, and oil, over the life cycle of each process, respectively (*j* represents each kind of energy resources); and CEE_j is the CO_2 emission per unit energy of each energy resource.

In this study, the energy input consists of the equipment and operation energies. Consequently, the denominator of the right side of Eq. B-1 represents the energy input into the system over its entire life cycle. Equipment energy is defined as the energy necessary for manufacturing equipment, which constitutes a system, i.e., heliostats and power block in this study, and is composed of the "material," "production," "transportation," and "construction" energies. Material energy is the energy necessary for refining raw materials, e.g., steel, glass, and concrete. Production energy is the energy necessary for producing the parts of equipment, e.g., heliostats and a plant generator. Transportation energy is the energy necessary for transporting the equipments and construction material. Construction energy is the energy necessary for constructing equipment workshop.

With regard to the calculation of the energy input, a process analysis, in which the object is divided into several processes and the energies required for each process are integrated, is adopted in this study. The following equation is used to calculate the equipment energy over the entire life cycle of the system:

$$\sum_i LCEE_i = \sum_i \left(ME_i + PE_i + TE_i + CE_i \right) \tag{B-4}$$

Where ME_i, PE_i, TE_i, and CE_i are the material, production, transportation, and construction energies of each process, respectively.

On the other hand, operation energy is defined as the energy necessary for operating a system and is composed of the fuel consumption of warming turbines in startup and the electricity consumed in operating equipments. The operation energy over the entire life cycle of the system is calculated on the basis of the following equation:

$$LCOE = FC_{fuel} + FC_{electricity} \tag{B-5}$$

where FC_{fuel} is the fuel consumption for warming turbines in startup of electricity generation sets, and $FC_{electricity}$ is electricity demanded in operation, which is provided by self-produced electricity.

Global warming potential (GWP) and acid potential (AP) analysis were performed to identify the environmental impact characteristics of solar thermal power plant. Based on the environmental impact characteristics of solar thermal power plant, global warming emissions such as CO_2, NO_x, CO, and acidification emissions such as SO_2, and NO_x in the life cycle of the power plant are quantified and analyzed. The Equivalency Factor Approach is adopted for the GWP analysis in this report. Output data of listing are classified according to GWP and AP assessment, and all kinds of values of emissions are multiplied by the Equivalency

Factor. Finally, the sum of the equivalent values is achieved as the total impact potential. In this calculation, Equivalency Factors are adopted from research results of the IPCC (Yang et al., 2002).

Data Listing

Data needed to perform the LCA were provided by firms investing in solar thermal power plant and related technology research departments in China, complemented with data obtained from the most up-to-date databases in the National Bureau of Statistics of China or from existing academic literature.

At the time of performing this LCA, some data related to the weight of materials of some parts of the power plants could not be obtained, because the studied 300 MW solar tower power plant has not been built. Consequently, some assumptions were made by referring to similar materials used in coal-fired power plants of the same capacity.

Many material categories are involved in the life time of solar thermal power plants, and the material whose weight is 5 percent less than the total material can be neglected. Total material weights for the life time of the 300 MW solar tower power plant are depicted in Table B-2. Life cycle inventory (LCI) of 300 MW solar thermal power plant: (I) energy balance is depicted in Table B-3.

On all accounts by the software tool AGP, primary inputs and outputs in LCA of 300 MW solar thermal power plant are depicted in Table B-4.

RESULTS AND DISCUSSION

Energy Balance

From Tables B-1, B-3, and B-4, the equipment and operation energies are calculated using Eqs. B-1, B-2, B-4, and B-5, respectively, clarifying the energy

TABLE B-2 Total Material Weights of the Life Time of 300 MW Solar Tower Power Plant (t)

Technology	Steel	Glass	Concrete	Diesel	Gasoline
Solar tower power plant	203,815	37,530	42,067	262	1,127

TABLE B-3 Life Cycle Inventory (LCI) of Solar Thermal Power Plant: (I) energy balance (tce)

Stages	Materials extraction and production of equipment	Transport	Building construction	Operation	Total
Energy input	135,662.48	2,152.39	13,896	11,394	163,105

TABLE B-4 Life Cycle Inventory of Solar Thermal Power Plant: (II) emissions (g/kWh)

	Types	Materials extraction and production of equipment	Transport	Buildings construction	Operation	Total
Input	Steel	11.55	-----	0.86	----	12.41
	Glass	2.28	----	----	----	2.28
	Concrete	-----	-----	2.56	----	2.56
	Diesel	-----	0.0160	-----	----	0.0160
	Gasoline	-----	0.0686	-----	----	0.0686
Output	CO_2	24.93	0.65	3.78	2.21	31.6
	SO_2	0.0370	----	0.0032	0.0030	0.0432
	NO_X	0.0051	0.0050	0.0036	0.0011	0.0148
	HC	----	0.00166	----	$1.26*10^{-4}$	0.0018
	CO	----	0.0132	----	$9.91*10^{-4}$	0.0142
	Powder and Soot	0.0242	$6.29*10^{-4}$	0.0025	0.0021	0.0293

inputs and outputs in all processes of the system examined in this study. When calculations are conducted, the life cycle inventory of solar thermal power plant on the EBF is achieved as 12.38, and EPT is 1.89 years. That means the total energy input into the system that has a life time of 25 years can be recovered for a shorter period of 1.89 years with power generation. On the other hand, the EBF is 12.38, which means that 12.38 times more energy is required than for the total energy input that can be produced during the entire life cycle of the system. This result indicates that the system examined in this study is feasible as an energy production system.

Cumulative Energy Demand

The consumption of electricity required in the operation of solar thermal power systems is provided by self-produced electricity. No hybrid system has been built, and no other fossil energy is required in the operational stage except that little fossil fuel is required in the startup of the generating set. Without taking into account these energy expenses, from Tables B-1 and B-3, the fossil energy required in the power plant life cycle is calculated to be 0.29 MJ/kWh for central tower technology. Cumulative energy demand and the life cycle of solar thermal power plants are listed in Table B-5. Results from other LCAs yield 0.14–0.16 MJ/kWh for a trough-type plant (Pehnt, 2006; Viebahn, 2004). For the central tower technology, the cumulative energy demand was 0.17-0.41 MJ/kWh (Lechón et al., 2008; Wang and Zhao, 2007).

The energy input into the system can be analyzed by aggregating the equipment and operation energies of each process in Table B-5. Consequently, 92.6 percent of the total energy input is occupied by the equipment energy, and the operation energy corresponds to the remaining 7.4 percent, that means, the amount of energy required for equipment of the system is much larger than the energy required in operation, which is illustrated in Figure B-2. In order to reduce the total energy input, it is essential to first reduce the equipment energy by taking such measures as developing new techniques and improving the manufacture efficiency of raw material and production processes.

Greenhouse Gas Emissions

From Tables B-1 and B-4, the equipment and operation energies are calculated using Eqs. 3. Global warming emission CO_2 produced during the life cycle of the analyzed solar thermal power plants are calculated, and its CEF value is around 31.6 g/kW h. Cumulative CO_2 emissions in each process of the life cycle of solar thermal power plants are listed in Table B-6. Most of them come from the material and production stages (see Figure B-3). The Equivalency Factor Approach is adopted to make GWP analysis in LCA of 300 MW solar tower power plant. Emission sources such as CO_2, CO, and NO_x were studied, and the analysis result is depicted in Table B-7. Values are around 32.1 g CO_2 equiv/kWh. It is similar to the values reported in the literature (see Table B-8). Values of global warming emissions reported in the literature range from 11 g CO_2 equiv/kWh to 48 g CO_2 equiv/kWh for the central tower type and from 12 g CO_2 equiv/kWh to 80 g CO_2 equiv/kWh for the parabolic troughs type, with the exception of the values reported in bracket by Lechón et al. (2008) for a hybrid operation. The emissions are higher in hybrid operation for the obvious reason of natural gas consumption.

Acidification

From Table B-4, in this study SO_2 emission value is 43.2 mg/kWh. For acidification emissions such as SO_2 and NO_x, the Equivalency Factor Approach

TABLE B-5 Cumulative Energy Demand in the Life Cycle of Solar Thermal Power Plants

Phases	Energy demand values (MJ/KWh)
Solar field	0.2394
Power block	0.0037
Buildings construction	0.0248
Transports	0.0035
Operation	0.0203
Total	0.29

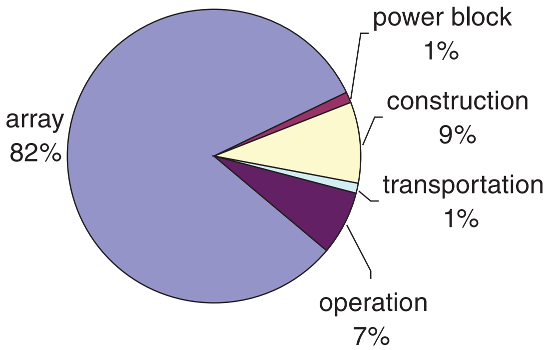


FIGURE B-2 The percentage breakdown of energy demand in the life cycle of solar thermal power plants.

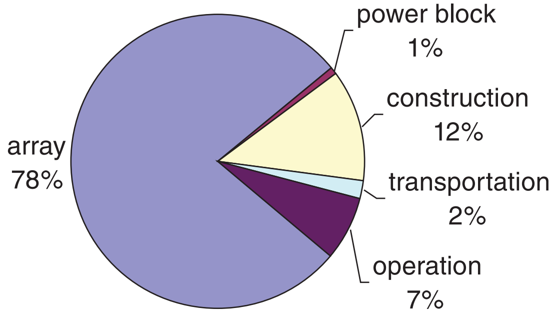


FIGURE B-3 The percentage breakdown of CO_2 emissions in the life cycle of solar thermal power plants.

TABLE B-6 CO_2 Emissions in Each Process of the Life Cycle of the Solar Thermal Power Plants

Phase	CO_2 emission (g/kWh)
Solar field	24.6777
Power block	0.2514
Buildings construction	3.7845
Transports	0.6475
Operation	2.2100
Total	31.5711

TABLE B-7 GWP Analysis in LCA of 300MW Solar Tower Power Plant

Impact types	Item	Mass quality (kg)	Equivalency factor ($kg.kg^{-1}$)	Impact potential value (kg)	Total (g CO_2 equiv./kWh)
GWP	CO_2	31.6	1	31.6	32.1
	NO_X	0.0148	320	0.4736	
	CO	0.0142	2	0.0284	

TABLE B-8 Global Warming Emissions for Solar Thermal Power Plants Reported in Literatures (g CO2 equiv./kW h)

	Central tower	Parabolic trough
Lechón et al. (2008)	17 (186)	24 (161)
Vant-Hull (1991)	11	
Norton et al. (1998)	21–48	30–80
Viehban (2004)		12

is adopted to make AP analysis in LCA of 300 MW solar tower power plant. The analysis result is depicted in Table B-9. Acidification value is 53.6 mg SO_2 equiv/kWh. Values reported in the literature are higher than the values obtained in this study. Acidification values reported are 69.28 mg SO_2 equiv/kWh (Pehnt, 2005) for a parabolic trough plant and 621 mg SO_2 equiv/kWh (Lechón et al., 2008) for hybrid operation in solar tower power plant. The emissions are higher in the hybrid operation for the obvious reason of natural gas consumption. In China, strict policy to control the discharge of sulfur oxides has been established in recent years. In response to this policy the enterprises utilize technologies to reduce the SO_2 and NO_x discharge; as a result the acidification emission is greatly reduced.

Comparison with Coal-Fired Plants

In China, the environmental factors for a coal-fired generation system include coal demand value 320 g ce/kWh, warming emission discharge (CO_2) value 738 g/kWh, and NO_x value 3.25 g/kWh, acidification emission (SO_2) value 9.38 g/kWh, and other emissions such as powder and soot discharge value 0.283 g/kWh from 1 kWh functional unit of 300 MW generation (Huang, 2006). Comparison of coal-fired plants and the solar thermal power plant in energy demand and emissions is depicted in Table B-10.

TABLE B-9 AP Analysis in LCA of 300 MW Solar Thermal Power Plants

Impact types	Item	Mass quality (g)	Equivalency factor ($kg.kg^{-1}$)	Impact potential value (kg)	Total (g SO_2 equiv./kWh)
AP	SO_2	0.0432	1	0.0432	0.0536
	NO_X	0.0148	0.70	0.0136	

TABLE B-10 Comparison of a Coal-Fired Power Plant and Solar Thermal Power Plant in Terms of Energy Demand and Emissions

technology	Energy demand MJ(kWh)	Powder and soot (g/kWh)	CO_2 (g/kWh)	SO_2 (g/kWh)	NO_X (g/kWh)
Coal-fired	> 9.37	0.283	738	9.38	3.25
Solar thermal power	0.29	0.0293	31.6	0.432	0.0148

Conclusions

From the LCA performed for the 300 MW solar tower power plant, some important conclusions can be drawn:

- First, this technology shows an environmental profile much better than the current mix of technologies used to produce electricity in China.
- The cumulative energy demand of the life cycle of solar thermal power plant is much lower than the energy produced.
- CO_2 value of global warming emissions is around 31.6 g/kWh, which is much lower than the value of 738 g/kWh for competing fossil technologies.
- Other impacts calculated are much lower than those produced by the current Chinese electricity generation system, and most of them are produced in the operation of the fossil-fired plant due to the consumption of natural gas or coal.

Appendix C

Life Cycle Assessment of Biomass Power in China

As a renewable energy, biomass is generally considered CO_2-neutral. This is particularly the case with regard to agricultural residues, which are periodically planted and harvested. During the growth, these plants have removed CO_2 from the atmosphere for photosynthesis, which is released again during combustion. Although the direct emissions of SO_2 and NO_x at generation stage are smaller than from fossil fuels because of the relatively low nitrogen and sulfur content of biomass, its environmental impact cannot be ignored from the perspective of life cycle assessment. The main reason is that cultivation, harvesting, transportation, and pre-treatment of biomass are energy-consuming processes that are accompanied by significant emissions.

At present, there are three mature technologies of biomass power generation: direct-combustion, gasification, and co-firing. The environmental capacity and energy consumption at all stages of generation process could be understood comprehensively using life cycle assessment methodology, thereby considering adopting measures to conserve resources and protect the environment. Figure C-1 presents a simplified process-flow diagram for power generation using biomass, beginning with plant cultivation and ending at the generation stage.

Throughout the life cycle assessment process, the energy consumption and pollutant emissions depend on a number of factors, which mainly include the biomass feedstock, type of technology used, and the boundary conditions chosen for the system. When it comes to the assessment of power generation from agricultural residues, whether the life cycle assessment includes the plant cultivation process may have a significant impact on the results. In the following assessment, the energy consumption and pollutant emissions from cultivation were included. Figures C-2 and C-3 show the assessment results for a 25 MW biomass power plant using direct-

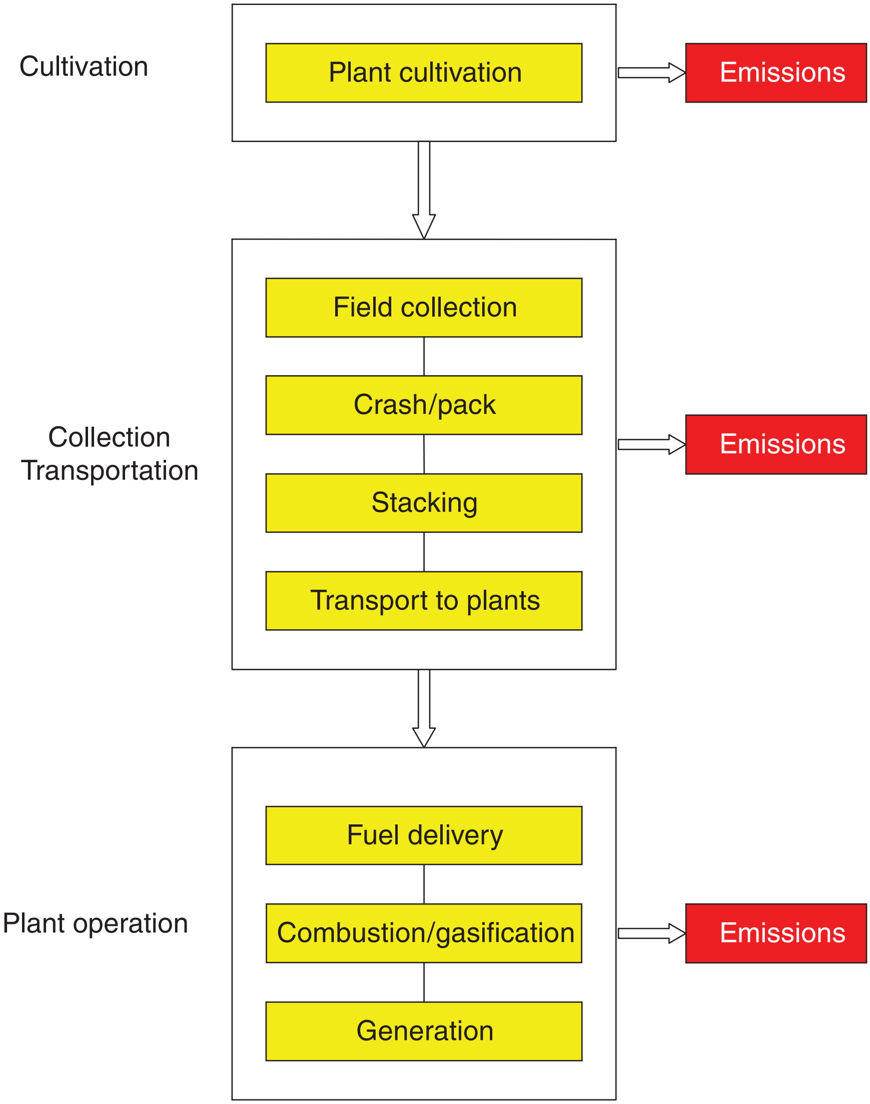


FIGURE C-1 Process flow-diagram of biomass combustion for electricity.

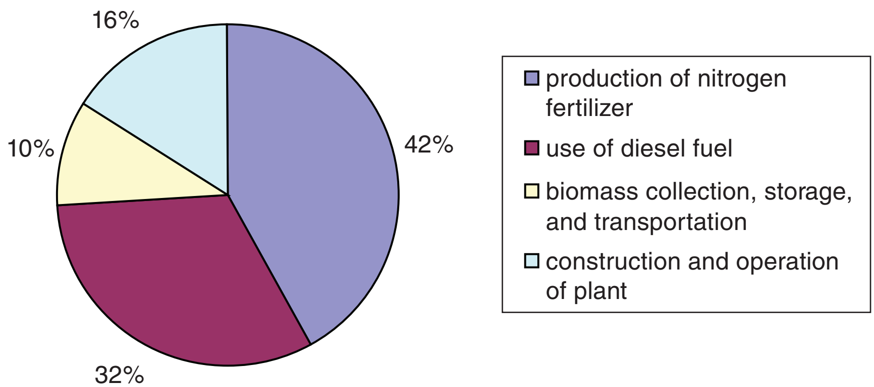


FIGURE C-2 Life cycle CO_2 emissions for biomass power generation in China.

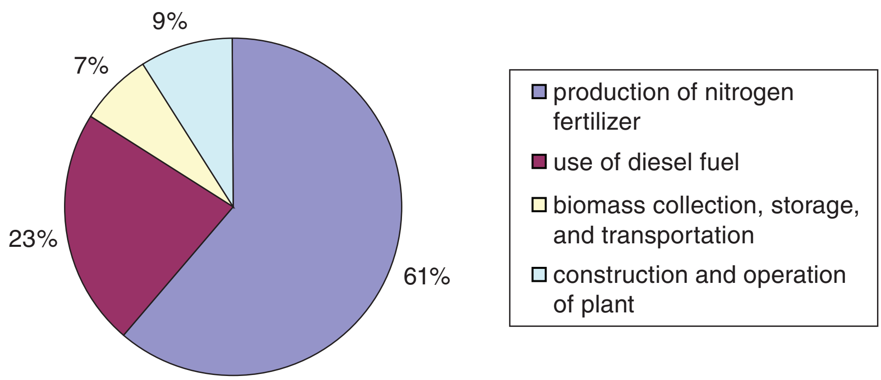


FIGURE C-3 Life cycle energy consumption for biomass power generation in China.

combustion. We can see that biomass cultivation is the main stage responsible for emissions, producing more than 70 percent of the CO_2, while the emissions in the collection, transportation, and pre-treatment stages are much lower. Considering the consumption of fossil fuel, the cultivation stage still dominates, due mainly to fuel used in the production of nitrogen fertilizer and the use of diesel.

As mentioned above, there are three technology routes for biomass power generation. In China, direct-combustion generation currently is the most developed technology. Due to lack of policy support, co-firing only accounts for a very small share. In addition, most gasification power generation projects are only in the demonstration phase. Different biomass generation systems were compared with respect to energy conversion efficiency and CO_2 emissions. As shown in Figure C-4,

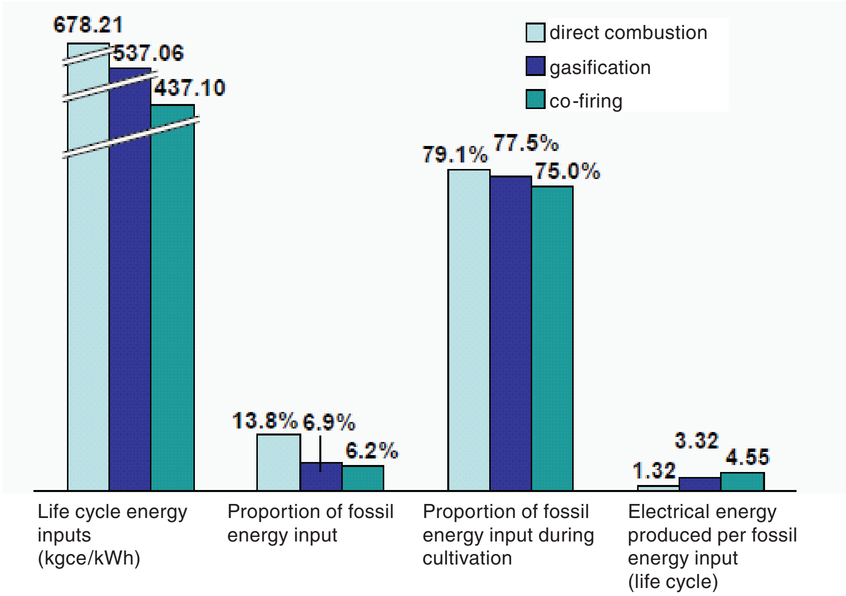


FIGURE C-4 Relative efficiencies for direct-combustion, gasification, and biomass co-firing power plants.

the co-firing has the highest energy efficiency, followed by gasification and direct-firing. The scale of power generation is a key factor for energy efficiency. For direct-combustion and gasification, the scale of power plant is limited because of low density of biomass. In China, the largest installed capacity is 25 MW for direct-combustion power plants and 6 MW for gasification. The generation efficiency of both is less than 30 percent. In contrast, the scale of co-firing plants is not significantly influenced by biomass resources because only part of the coal is substituted by biomass. Values shown in Figure C-4 reflect operating experience with a 140 MW co-firing power plant for which the generation efficiency reached 36.13 percent, which is much higher than the efficiency of direct-combustion and gasification. Because the 6 MW gasification power plant studied in Figure C-4 included a heat recovery and generation system, the system efficiency is a little higher than that of the 25 MW direct-combustion plant. The CO_2 reduction rates of all three systems (relative to the coal they displace) are more than 95 percent, suggesting that the CO_2 reduction effect of biomass power generation is considerable.

In comparison to fossil-fuel and nuclear power plants, renewable power sources also require a large amount of land for a given amount of generating capacity. Land-use requirements for large-scale hydropower and concentrating solar thermal power are especially high. On the other hand, some renewable technologies, such as photovoltaics, can be deployed in locations such as residential and warehouse roofs, where they create little interference with other land uses and are close to the point of use of the electricity. Although producing power from cultivated feedstock is very land intensive, land-use requirements are much lower if waste biomass is used. Land use can serve as a rough proxy for other impacts of new development, including impacts on ecosystems, cultural and historical resources, scenery, and loss of agricultural lands. Because of relatively high land-use intensity for most renewable electricity generating technologies, careful assessment of local environmental, cultural, and aesthetic impacts should be required before large projects are developed.

Appendix D

Environmental Considerations for Photovoltaics

Life Cyle of Photovoltaic Technology

In the past five years, solar photovoltaic industries have continuously increased manufacturing capacity, decreased costs, and achieved remarkable growth. Conventional flat plate silicon PV occupies greater than an 80 percent share of the global solar cell market. However, the industry presently suffers from high energy consumption and serious pollution, such as the treatment and recycling of large amounts of wastewater containing hydrofluoric acid (HF), nitric acid (HNO_3), and other metal ions. As such, the development of environment-friendly technologies is urgently needed (Gu, 2008; Hu, 2008).

Environmental Problems in the Preparation of Polysilicon

The factories under construction use a modified Siemens process to manufacture polysilicon. Currently, the process is the most advantageous process available, and it produces 70 to 80 percent of the total production in the world. Figure D-1 shows the modified Siemens process (Long et al., 2008).

However, some of the key technologies for the modified Siemens process are owned by several companies in the United States, Germany, and Japan. It is very difficult for Chinese companies to acquire these key technologies, which is a major reason for the high energy consumption and high pollution of existing polysilicon producers. Table D-1 shows the economic factors for an annual production of 1,000 tons of polysilicon in China (Long et al., 2008; Su, 2008; Zeng, 2008).

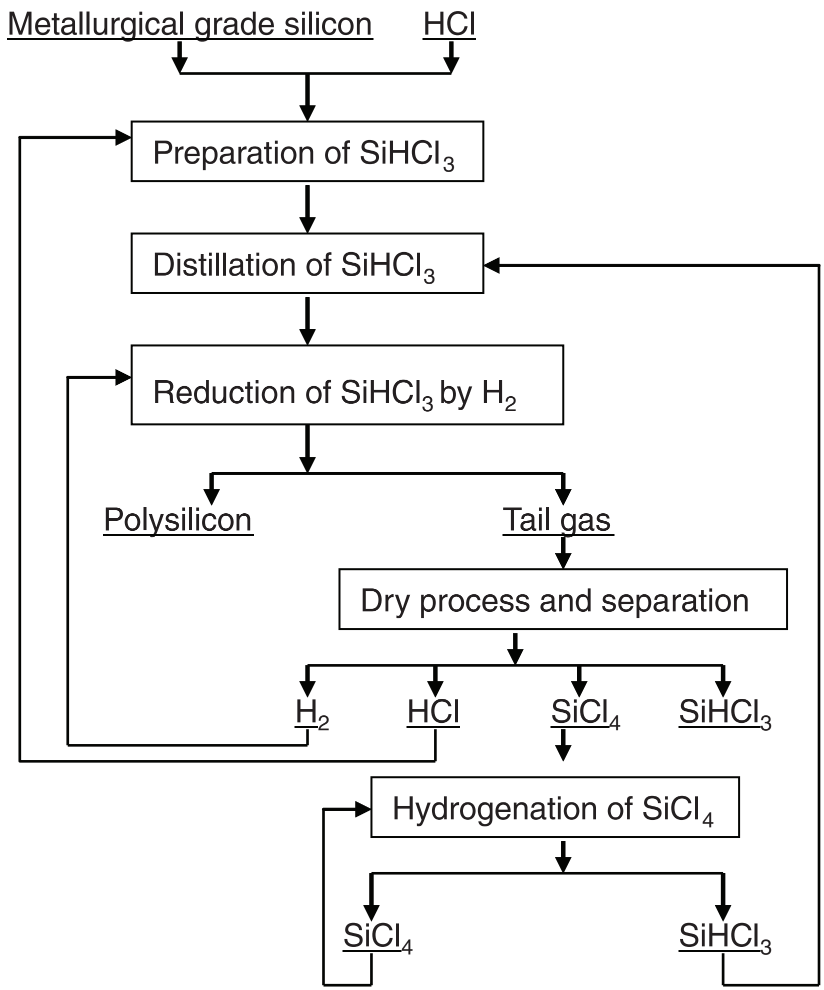


FIGURE D-1 Flow sheet of the modified Siemens process.

Preparation and Purification of Trichlorosilane ($SiHCl_3$)

High purity $SiHCl_3$ is prepared from quartz sand. The steps are as follows.

(1) Preparation of industrial silicon: $SiO_2 + C \rightarrow Si + CO_2\uparrow$.
(2) Preparation of $SiHCl_3$: $Si + HCl \rightarrow SiHCl_3 + H_2\uparrow$, which produces a gas mixture of H_2, HCl, $SiHCl_3$, $SiCl_4$, and Si.
(3) Purification of $SiHCl_3$ from the gas mixture.

TABLE D-1 Economic Factors for an Annual Production of 1,000 Tons of Polysilicon in China

Items	Economic costs/benefits
Yield of polysilicon	1,000 tons per annum
Total investment	U.S.$ 0.17 billion
Production cost	U.S.$ 70–80/kg (China) U.S.$ 25/kg (Europe and U.S.)
Power consumption	0.6 billion kWH per annum
Power produced by solar cells	200 MW per annum
Power regeneration ratio (over 20 years)	About 8
Power generation cost	7–12 times biomass power generation, 6–10 times wind power generation, 11–18 times traditional coal power generation.
By-product $SiCl_4$	8,000 tons per annum

In the above steps, there are two pollution problems that need to be solved: the capture of by-product CO_2 in the preparation of industrial silicon, and the recycling of the tail gas in the purification of $SiHCl_3$ from the gas mixture.

Reduction of $SiHCl_3$

High purity polysilicon is obtained from the reduction of $SiHCl_3$. The reactions are as follows.

(1) Main reaction: $SiHCl_3 + H_2 = Si + 3HCl\uparrow$,
(2) Secondary reaction: $4SiHCl_3 = Si + 3SiCl_4 + 2H_2\uparrow$.

Si obtained from reactions (1) and (2) is deposited to form high purity polysilicon. In this process, about 25 percent of trichlorosilane is converted into polysilicon, and the remainder into tail gas. A large amount of tail gas containing many useful materials such as H_2, HCl, $SiHCl_3$, and $SiCl_4$ is emitted from the reduction furnace. Moreover, the tail gas includes many erosive and toxic substances. The tail gas must be recycled, or else it will cause serious pollution and also increase costs.

Silicon tetrachloride ($SiCl_4$) is the main component in the tail gas. It is a highly corrosive and toxic liquid. About 8,000 tons of by-product $SiCl_4$ are produced in the production of 1,000 tons of polysilicon. Due to the expensive treatment cost of $SiCl_4$, most Chinese companies do not have such treatment equipments, which then makes tail gas treatment become the bottleneck in the manufacture of polysilicon.

Separation and Recycling of Tail Gas

The components of the tail gas are very complex. These often include H_2, HCl, $SiHCl_3$, and $SiCl_4$, whose separation and recycling are difficult. It is necessary to separate H_2, HCl, $SiHCl_3$, SiH_2Cl_2, and $SiCl_4$ individually from the tail gas before they can be recycled. A multistage separation technology that couples pressure condensation, absorption, and desorption is needed. Figure D-2 shows the process of separation and recycling of the tail gas.

Figure D-2 shows that the components of the tail gas can be well separated and recycled, which would reduce tail gas emission and environmental pollution. Silicon tetrachloride can also be used as the raw material for the preparation of white carbon black by the gas phase method. However, due to the backward technologies and equipments, the costs of separation and recycling of the tail gas are very expensive and cannot be borne by Chinese companies.

The environmental pollution from the preparation of polysilicon has attracted the attention of the Chinese government, especially the separation and recycling of tail gas. Research on key technologies for comprehensive utilization of by-products of the polysilicon production process has been supported by 863 program of China (CNCIC, 2009).

However, the effort has just begun. Further research on efficient and low cost technologies and equipments for the separation and recycling of the tail gas is urgently needed.

Wastewater from the Texturing of Polysilicon

The application flow sheet of chemicals used for the texture preparation of polysilicon wafers are shown in Figure D-3. The first trough uses most of the acid and alkali for the texture preparation (nitric acid, hydrofluoric acid, hydrochloric acid, and potassium hydroxide).

In 2008, Solarbuzz (2009) reported that the Chinese annual production of solar cells had a capacity for 3,000 MW. This consumed a lot of hydrofluoric acid and nitric acid. With the rapid growth of the solar industry, it is apparent that even more of these substances will be used in the future.

Currently, Chinese companies follow the principle of respective discharging and treating of acid wastewater and alkali wastewater. Too much fluoride in drinking water will lead to a variety of diseases, so the discharging and treating of wastewater with hydrofluoric acid is controlled, and the standard for the discharging of fluoride wastewater is very strict. Table D-2 shows the effects of excessive fluoride in drinking water on health, based on Shanxi Province's guidelines issued in 2006.

The treatment process in the discharging and treating of hydrofluoric acid wastewater couples chemical precipitation, flocculent precipitation, and filtration. The fluoride is changed into calcium fluoride and separated from the wastewater

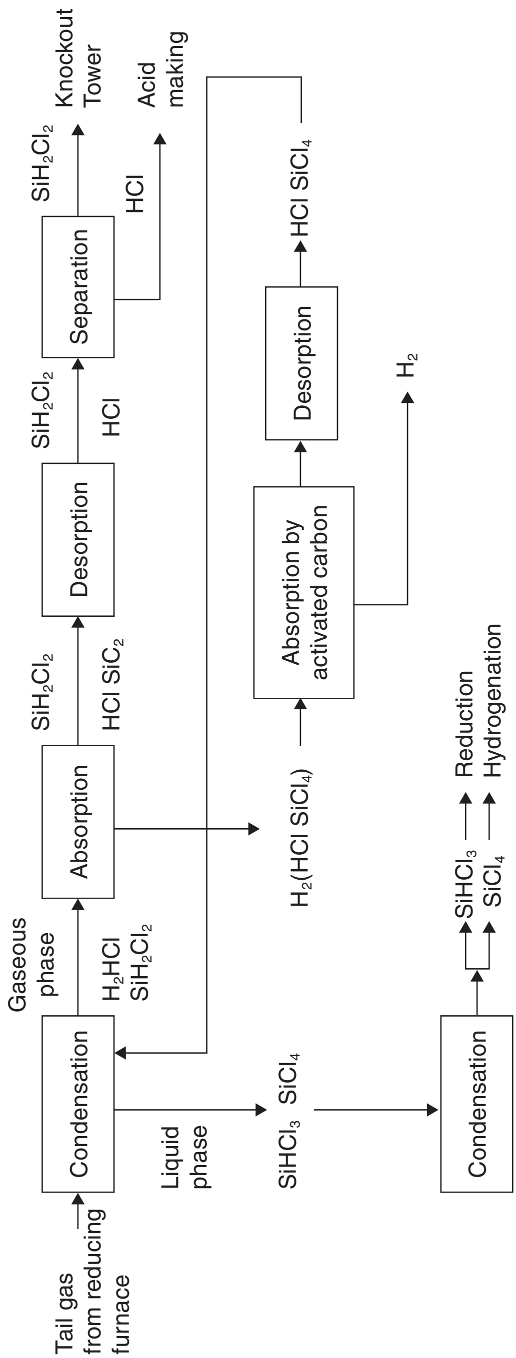


FIGURE D-2 Process of separation and recycling of tail gas.

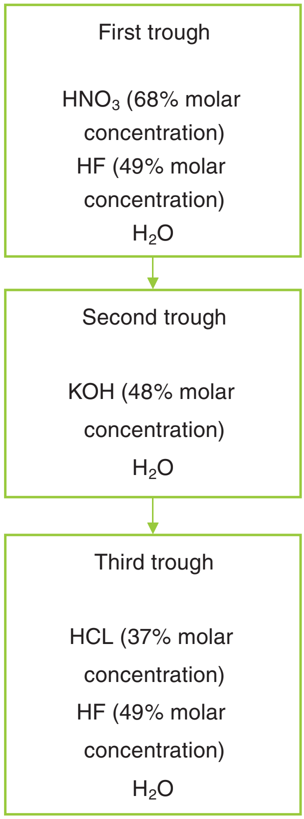


FIGURE D-3 Flow sheet of chemicals used for the texture preparation (based on discussions with polysilicon production plants in China).

by flocculent precipitation and filtration. The filtered mud is abandoned and buried. The process is shown in Figure D-4.

However, if the environment has acid rain or acidic soil, the fluoride ion of the calcium fluoride in the filtered mud will be displaced and will enter the groundwater with the rainwater and pollute the soil and water. This is a very serious problem. Thus, a better technology is urgently needed, such as the recycling of hydrofluoric acid, in order to reduce costs and solve the pollution problem.

It is currently difficult to separate hydrofluoric acid from nitric acid. Advanced membrane separation technologies, such as a modified polytetrafluoroethylene membrane and ceramic membrane, can be used for the purification of the acid wastewater by the removal of metal and nonmetal compounds in the acid wastewater. The purified acid wastewater would only have hydrofluoric acid and nitric acid, which can be easily recycled for reuse by adjusting the concentrations of the two acids.

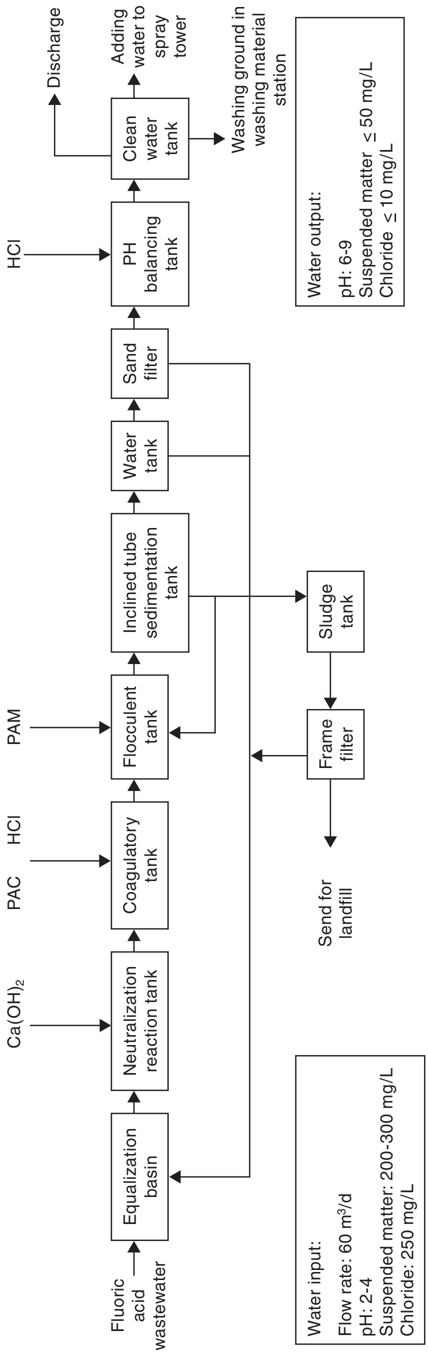


FIGURE D-4 Treatment process in the discharging and treating of hydrofluoric acid wastewater.

TABLE D-2 Effect of Excessive Fluoride in Drinking Water on Health

Fluoride content (mg/L)	Body parts	Effect on health
0.5–1.0	Tooth	There is an anti-caries effect, in which the tooth forms a protective surface layer with a hard mass density.
1.1–2.0	Tooth and skeleton	The incidence of dental fluorosis is 30 percent, with a small amount of skeletal fluorosis.
2.1–4.0	Tooth and skeleton	The incidence of dental fluorosis is 80 percent, with a certain amount of skeletal fluorosis.
> 4.1	Tooth and skeleton	The incidence of dental fluorosis is 90 percent, with much skeletal fluorosis.

Urgent Problems

In China, the production of high purity polysilicon and solar photovoltaic panels causes many serious environmental problems. These problems have become the bottleneck in the development of the solar energy industry. The following environment-friendly technologies with low energy consumption are urgently needed:

1. In the process of making polysilicon advanced capture technologies for the CO_2 by-product produced in making industrial silicon is urgently needed. Efficient technologies and low cost equipment for the separation and recycling of the tail gas are also urgently needed.
2. In the process of manufacturing solar cells from polysilicon, a treatment process for the acidic wastewater that contains hydrofluoric acid and nitric acid is urgently needed. Because it is difficult to separate hydrofluoric acid and nitric acid, the simultaneous recycling of hydrofluoric acid and nitric acid should be used.
3. Advanced membrane separation technologies, such as the modified polytetrafluoroethylene membrane and ceramic membrane, can be used for the purification of the acidic wastewater to remove metal and non-metal compounds in the acidic wastewater. The purified acid wastewater then only contains hydrofluoric acid and nitric acid, which can be easily recycled for reuse by adjusting the concentrations of the two acids.
4. Due to their low cost, material abundance, and material non-toxicity, thin-film silicon solar cells are also promising for producing electricity cleanly. And amorphous silicon solar cells have been much studied and have reached large-scale production. However, the low conversion efficiency and photo-induced attenuation effects of amorphous silicon solar cells also urgently need to be solved.