Energy Policy 39 (2011) 7622–7636

Contents lists available at SciVerse ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Concentrating solar thermal power as a viable alternative in China's electricity supply

John Chung-Ling Chien [a], Noam Lior [b],*

[a] The Joseph H. Lauder Institute of Management & International Studies, The Wharton School of Business, University of Pennsylvania, Philadelphia, PA 19104-6330, USA
[b] Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, Philadelphia, PA 19104-6315, USA

ARTICLE INFO

Article history:
Received 10 January 2011
Accepted 16 August 2011
Available online 11 October 2011

Keywords:
Concentrating solar thermal power
Solar power
China energy

ABSTRACT

Study of low-carbon and pollution renewable alternatives for China revealed that concentrating solar thermal (CST) electric power generation was underemphasized in China's renewable energy plan. The analysis shows the competitive viability of CST: (1) China has the key prerequisites to make CST power generation economical including high-quality insolation and appropriate land, (2) CST's proven history, scale, and dispatchability makes it a good utility-scale power option, especially in the economically underdeveloped Western regions, (3) while CST power is currently more expensive than coal-fired electricity on a nominal basis, when costs of externalities are accounted for, CST, at 11.4 US cents/kWh, can become 57% cheaper than scrubbed coal and 29% cheaper than nuclear power, (4) CST power continues dropping in cost due to economies of scale and technological improvements and can potentially realize a levelized electricity cost of around 4 cents/kWh within ten years, (5) it would significantly rise in competitiveness if and when China completes the extensive smart grid for connecting its solar-abundant western regions with the high-demand eastern regions, (6) CST has the potential to positively impact Western China's economy, but proper policy and deal structure must be in place to ensure that the local community shares the benefit.

1. Introduction

1.1. *China's 2020 goal—"quadrupling GDP while only doubling energy consumption"*

China's stated plan for the next 11 years is to continue its economic growth with the stated goal of quadrupling its GDP by 2020 versus the year 2000 while only doubling energy consumption (CCCIN, 2005). Though this GDP target may be reduced in view of the current financial crisis, this economic policy target signifies the importance of economic growth in China's vision of realizing the building of a "well-off society in an all-round way" as set forth in the 17th CCP National Congress (Xinhua, 2007a). Having experienced traditional development issues and faced with increasing international pressure on environmental pollution, Chinese leaders appear to recognize the need for sustainable development – balancing economic, social, and environmental factors – in reaching the country's objective. A comprehensive review of sustainable energy development in China can be found in a recent special issue of Energy—The International Journal edited and prefaced by Jin et al. (2010a).

The seriousness of the global environmental consequence from China's continued pursuit of economic growth has not been lost on the global stage. At the World Economic Forum of 2007 at Davos, climate change and China's CO_2 emission trends were key issues of the international leaders. At COP 15 (2009), where 120 heads of states and government attended the conference to negotiate a new binding agreement on emissions control to replace the soon to expire Kyoto Protocol, the contentious issue of emissions control as a debilitating factor on economic growth for emerging economies such as China was partly responsible for the summit's failure in reaching a binding agreement. President Obama and Secretary Clinton have made climate change a key item on the foreign policy agenda for China. On Hillary Clinton's inaugural visit to China as Secretary of State in 2009, she cited that the key areas of collaboration with China are clean energy and climate change, and to accelerate the transformation to low-carbon economies while acknowledging China's right to grow and attain a good standard of living (DOS, 2009a). Importantly, Clinton preempted the oft used argument that developed countries polluted their way to affluence by saying "when we [USA] were industrializing and growing, we did not know any better; neither did Europe. Now we are smart enough to figure out how to have the right kind of growth… we hope you would not make the same

---

* Corresponding author. Tel.: +1 2158984803; fax: +1 2155736334.
E-mail addresses: john.chien.wg09@wharton.upenn.edu (J. Chien), lior@seas.upenn.edu (N. Lior).

0301-4215/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2011.08.034

mistake we made" (DOS, 2009b). The recognition of the importance of restraining the CO_2 emissions in China's development is recognized by China's government and other experts (see Jiang et al., 2010; He et al., 2010). Since 70% of China's energy comes from coal, of even more immediate importance than the CO_2 emissions are the health and life threatening consequences of coal mining, transportation, and combustion emissions, described thoroughly by Wang (2010a), Yao et al. (2009), and You and Xu (2010), which also have an important detrimental effect on China's net GDP.

China's initiatives and actions thus far suggest that it is trying hard not to make those same mistakes that US and Europe did. It started promoting the development of renewable energy with the 8th Five Year Plan. Other notable legislations and regulations include the Energy Conservation Law of PRC (1997), the Air Pollution Prevention Law of PRC (2000), the 1996–2010 New Energy and Renewable Energy Development Principles, the 2000–2015 New Energy and Renewable Energy Development Principles, the Comprehensive Working Programs on Energy Saving and Emission Reduction, and many others. All of these policy actions are aimed at encouraging the use and development of energy conservation and efficiency, renewable energy use, the build-up of a renewable energy industry, and promoting greater renewable energy applications for emissions reduction. China has also passed the PRC Law of Renewable Energy in 2005 representing the Chinese government's priority on the issue of sustainable development, and setting the framework to enact supporting laws and policies to further renewable energy development (Zhang et al., 2009).

Against this backdrop, Hu Jintao, China's President and Chairman of the CCP, stressed the need for "energy resource conservation and environmental protection" and called for the implementation of a "system for the work of conserving energy and reducing emissions, develop and promote advanced practical technology that can save, replace, and recycle energy resources, and develop clean energy and renewable energy." (Xinhua, 2007a, 2007b) In short, China plans to achieve a sustainable policy in the energy sector by saving energy resources, increasing energy efficiency, and adding an increase of renewable energy resources into China's energy mix.

However, China's goal of quadrupling GDP while only doubling energy consumption by 2020 may be too optimistic. The recent study by Li and Oberheitmann (2009) shows that to achieve China's above-stated goal, the energy intensity would have to decrease 53% by 2020—a level of 30% below the year 2000 level of industrialized countries and represents an improvement of 2–5 times than what has been achieved during the past 20 years. Moreover, while China has made great progress in reducing energy intensity since the 1980s, as observed from the energy intensity reduction trend of developed countries such as US, Japan, and Germany, energy intensity reduction will become more difficult as China's economic development advances as shown in Table 1. Note that manufacturing nations typically have higher energy intensities than those focusing on trade, business, banking, software development and such, so as the world's factory China would have a higher intensity if it wishes to stay in that category.

Table 1
Energy intensity reduction trends.
Sources: Compiled by authors with data from World Bank (2009).

Selected developed countries vs. China	Energy intensity (KG OE/2005 PPP$)		Total reduction (%)	Avg. reduction/Yr (%)
	1995	2005	1995–2005	1995–2005
Japan	0.144	0.137	4.90	0.55
United States	0.232	0.188	19.00	2.31
Germany	0.155	0.137	11.60	1.36
China	0.469	0.321	31.60	4.13

Against the same backdrop of building a "well-off society in all-round way", Hu Jintao also reiterated the goal of "building a new socialist countryside" by promoting "coordinated urban and rural development", by "guiding reasonable cross-regional movements of production factors", by "breaking through administrative regional boundaries, form a few economic spheres and economic belts that are strong in leading and close in links", and by "grooming a new type of peasants who are educated, understand technology, and know management." (Xinhua, 2007a). In short, Chinese leaders seem to be keen on planning to improve the problem of regional income disparity.

A key ingredient in bridging regional disparity is economic and infrastructure integration. This integration involves not just roads and railways, but also the electrification of rural regions (Western and Central) which translates also to an increase in electricity demands. Additionally, the realization of a new socialist countryside with educated and technologically savvy peasants will almost certainly mean a drastic rise in China's growing middle class. As the standard of living in the underdeveloped regions improves, the "new peasants" may increase the demand for modern appliances leading to greater electric power consumption. Thus, while a necessary goal for China's social and political stability, the success in "building a new socialist countryside" will tend to frustrate China's energy consumption diet plans as well as reduction objectives for CO_2 emission.

Some studies suggest that China may already be off-target in meeting the stated 2020 energy consumptions goals. According to a 2007 Center for Strategic International Studies report, China is not only off track, but is at a point where it will be "nearly impossible to reach its stated energy consumptions goals" (Shealy and Dorian, 2007). The report also urges the Chinese government and major energy statistics agencies such as the IEA (IEA, 2003) and DOE to wake up from their optimistic forecasts as they no longer have a realistic basis with the observed current trend. The current trend shows a bleak future where the pursuit of quadrupling GDP will lead to quadrupling the use of coal and thereby lead to the quadrupling of CO_2 emission.

To address this concern, one area China should focus on is the energy supply side by aggressively incorporating large-scale renewable energy supplies into China's energy mix. According to the study by Chien and Hu (2007), increasing the share of renewable energy into a nation's energy mix has significant positive effects on the macroeconomic technical efficiency (TE) index (which incorporates energy along with traditional key inputs such as labor, and capital stock to produce GDP) and thereby the economic efficiency of producing GDP. Conversely, increasing the input of traditional energy sources decreases technical efficiency. This is a powerful result in that it suggests the use of renewables fundamentally changes the relationship between GDP and energy consumption, allowing a country to produce more output for a given amount of energy consumed.

Using OECD and non-OECD economies as a proxy for developed and non-developed economies, respectively, Chien and Hu's (2007) research also showed that OECD economies have higher TE and a greater share of geothermal, solar, tide, and wind fuel in renewable energy than in non-OECD countries. This implies that while all renewable energy sources have positive impact on TE, geothermal, solar, tide, and wind renewables may produce higher TE than biomass. Thus, by adding renewable energy alternatives into its current energy portfolio, China not only expands its energy supply, but may also be able to increase economic efficiency in producing GDP.

1.2. *China's renewable energy focus—not enough on solar*

While China's renewable energy production currently represents only 2.8% of total energy consumed in 2005, (World Bank, 2009) it is setting aggressive targets with priority focus on hydro, wind, and biomass. Table 2 shows that hydro power, currently the largest contributor to China's renewable energy supply, will continue to play the biggest role in 2020 in terms of total installed capacity. China is also planning a significant push on wind power and biomass with an expected 600% increase of total capacity from 2010 to 2020. Conspicuously, in China's plan for the future, solar for power generation will play a relatively minor role—contributing less than 1% of China's total renewable energy capacity by 2020. A very recent paper (Wang, 2010a, 2010b) reviews the status of solar thermal power development and its road map in China for the next 15 years (but does not forecast the overall generating capacity to be installed). It points out that significant cost reductions will be required to secure market acceptance, estimating that by 2025 the average 2006 solar power system cost should be lowered by 50% to reach a price that is 1.3 times the price of coal-fired power (0.030–0.042 $/kWh) at that time. Such cost reductions are stated to come from technical improvements, larger plant sizes, and large volume production.

We would argue that China's decision to marginalize solar energy in its renewable energy plan is a mistake and should be reconsidered.

First, from a resource perspective, solar energy is the most abundant, most widely distributed free energy resource on the planet, with its energy received on the earth's surface being more than three orders of magnitude higher than the world's total primary energy supply (TPES). Of course, a correct assessment of solar energy resource must also consider transmission and storage availability and efficiency, intermittency of solar energy supply due to climate and seasonality, and collector incidence angle effects. With these considerations, the available energy from the sun would be much smaller than the one given by current technology.

Table 2
Current and planned targets for renewable and nuclear energy.
Sources: NDRC (2007a, 2007b).

Installed capacity % of total energy structure	**2010** 10%	**2020** 16%	**2010–2020** % increase
Hydro	180 GW	300 GW	167%
Nuclear[a]	NA	40 GW	NA
Biomass	5.5 GW	30 GW	545%
Wind	5.0 GW	30 GW	600%
Solar	0.5 GW	1.8 GW	360%

[a] Nuclear power is not categorized as renewable energy, but it is included here for comparison purpose.

Some propose that tapping into the deserts alone may be enough to produce more energy than the world needs. A significant example is the DESERTEC concept created by Trans-Mediterranean Renewable Energy Cooperation (TREC) to use North African deserts' solar energy potential to provide electricity to Europe and to the Middle Eastern, and North African regions (Knies, 2008). With the potential to receive 2.2 TWh/yr/km^2 of desert surface, the sun can provide an amount of energy equivalent to that of all fossil fuel consumption in the world in less than six hours and an amount of energy equivalent to that of all fossil fuel proven and expected reserves in 274 days (Table 3). Based on the current solar technology with a 15% solar to electricity efficiency, DESERTEC estimates that using just 1% of the area of the world's deserts can provide enough energy to satisfy the world's primary energy consumption. It is noteworthy, however, that the solar potential in the African deserts is not the same as the deserts in China, having differences in solar radiation intensity, cloud cover, and ambient temperature. Still, with more than two-third of China receiving radiation of more than 5.02×10^6 kJ/m^2/yr (Zhang et al., 2009) and direct normal insolation values between 5 and 9 kWh/m^2/day in China's Western regions, the key message is that China is well-endowed with solar energy resources and should attempt to exploit it fully.

Second, its large deployment would significantly reduce the harmful effects of all coal related emissions.

Third, in contrast to nuclear power development, solar energy as an alternative does not pose the risks associated with radioactive waste storage, safety and proliferation and has the potential to provide China with more than just the benefit of electricity. For example, China's nuclear power development plans call for new nuclear power facilities to be located in the relatively prosperous coastal areas (NDRC, 2007b). The solar energy option, however, should be located in the sparsely populated sunny regions of China's deserts like Xinjiang and Tibet (and to some extent Gansu and Inner Mongolia) to access the abundant supply of solar radiation for electricity generation. This, in turn, will transform the desert lands into competitive advantages and boost the economic development of these underdeveloped Western regions. Clearly, investments in these regions will only help bridge regional disparity if the economic benefits associated with those investments can directly affect the local community. Thus, with CST and the right policy, the Chinese government has the opportunity to help bridge China's regional disparity, as also proposed recently by Jin et al. (2010a, 2010b).

Fourth, in contrast to hydroelectric power, solar power faces fewer problems and objections on the grounds of environmental and social intrusion. The prerequisite for hydroelectric power is the need to dam rivers; the larger the river flow, the larger the hydroelectric potential, the larger the dam. Unfortunately, large dams, which are often ill-planned, carry an enormous social and environmental price tag. The social impact includes large scale

Table 3
Solar energy potential in Global Deserts.
Source: Knies (2008).

Fossil energy source	Annual production/ consumption (1000 TWh)	Equivalent solar delivery time in deserts (h)	[A] Proven reserves (1000 TWh)	[B] Exp add'l resources (1000 TWh)	Equiv solar delivery time for [A] (days)	Equiv solar delivery time for [B] (days)
All fossil fuels	107	5.7	10,400	50,700	47.0	227.0
Oil (conventional)	45	2.4	1900	960	8.5	4.3
Oil (non-conv.)	–	–	780	2900	3.5	13.2
Natural gas (conv.)	24	1.3	1600	1900	7.2	8.4
Natural gas (non-conv.)	–	–	2	1687	0.1	6.2
Coal (hard and lignite)	33	1.8	5700	29,000	25.0	129.0
Uranium, Thorium	4	0.2	460	1740	2.0	7.8

resettlement of surrounding communities that are usually poor and need to subsist on the fertile lands near the river. The environmental impact includes reduced biodiversity, degradation of water quality, arguably, the release of GHG emissions (methane), a fragmented ecosystem, land erosion, and could possibly trigger earthquakes.

With more than 25,800 large dams (Rhinelander, 2008) and the Three Gorges Dam (the world's largest) partially operational, China is now feeling the social and environmental pains from hydroelectric projects. So far, the construction of the Three Gorges project has necessitated the inundation of 2 cities, 11 counties, 140 towns, 326 townships, and 1351 villages covering 23,800 ha and involved resettling over 1.2 million people (Tillou and Honda, 1997; Hvistendahl, 2008). Chinese government officials who have long dismissed warnings of environmental damage have now admitted that the Three Gorges Dam has caused an ecological catastrophe including frequent landslides and pollution (Xinhua, 2007b). Worst still, there are new reports produced by both Chinese and US scientists examining the possibility that the world's largest dam may have helped trigger the 7.9 scale Sichuan earthquakes that killed 80,000 people (Naik and Oster, 2009). While no one is claiming direct proof that the Three Gorges dam caused the Sichuan earthquake, the US experience with the Hoover dam, for example, dam reservoirs do increase seismic activity.

To be sure, hydroelectric power is currently cheaper than solar and has a higher availability factor. But, in light of the huge environmental and social costs (as illustrated by the Three Gorges project), the infrastructure required for solar electricity generation, with a simple and proven design, a proven record of reducing GHG emissions without environmental risk (Aringhoff et al., 2005), and an optimal location at desert areas, creates less environmental and social intrusion compared to hydroelectric power.

At the same time, a major shortcoming of solar energy use, even in deserts where the insolation is intense and the real estate inexpensive, is the relatively high cost. This is brought about by its low energy density, transience, relatively low conversion efficiency to electricity, and relatively high electricity transmission costs and energy losses since deserts are usually rather distant from major electricity use centers.

2. CST technology overview and assessment

2.1. Solar thermal electric systems—concentrating solar thermal

The main methods for using solar energy to generate electricity are photovoltaics (PV, "solar cells") where solid state devices (at present mostly based on silicon) convert solar radiation directly to electricity, and solar thermal collectors of different types that convert the solar radiation to heat, the heat is used to generate hot vapor or gas, which in turn is used to produce shaft power that is used to drive electricity generators. Currently, one of the most economical and robust solar power generation technologies is concentrating solar thermal (CST), in which typically parabolic line-focus single-axis sun-following concentrators are deployed to heat and evaporate a working fluid, which then uses a Rankine-type power generation cycle (other concentrating systems use point-focusing concentrators, either as individual "dishes" or a "solar tower" where many flat mirrors track the sun with all of them focusing their solar reflections onto a receiver positioned at a top of a tower in their midst).

With a thermal storage system and/or through hybridization with a secondary heat source using conventional fossil fuel, CST can be used effectively as a source of dispatchable power, as proven by 20 years of operating experience in successfully providing electric power on a commercial scale (Tester, 2005). The proven success of CST may be one of the reasons why some of the largest wind power companies are adding CST technology into their wind power portfolio to prepare for their next stage of growth and many utilities are also motivated to include CST into their electric power generation portfolio (Wolff, 2008; DOE, 2009).

Other benefits of the CST systems include: (1) ability to use conventional technologies and materials allowing for CST systems to scale with existing infrastructure; (2) flexibility and modularity to suit the needs of large utility-scale central power facilities in the 100 s of MW scale (e.g. SEGS in California) or to smaller, distributed power generation systems in 10 s of kW scale (Prabhu, 2006; Lior, 1977; Lior and Koai, 1982, 1984a, 1984b; Sherburne and Lior, 1986), and (3) relative simplicity in construction, operation, and maintenance because they are comparable in general with conventional thermal power generation systems. Like other solar energy technologies, they have significant potential for continued cost savings from both economies of scale and technological improvements.

To better match the inherently transient availability and quantity of solar radiation, and consequently transient generation of electricity, with the much more steady electricity demand by users, one of several methods can be used: (1) energy storage, where the solar system is made to have a higher generation capacity than the average demand, storing the excess generated energy and then using it when the generation rate falls below the demand (to be elaborated further in next paragraph), or (2) creating an auxiliary electricity generation back-up system using, say, fossil fuel, (3) as a minimum, typically not as the optimal solution, just using the solar-generated electricity in the quantities instantly available if the demand exists, and, probably the best, (4) providing "grid storage" by installing an adequate smart grid (cf, Jin et al., 2010a). Such a grid would transmit electricity in the real-time generated quantity to further regions of China if and when needed. The quality and extent of the electricity transmission grid is obviously of general major importance in providing and distributing electricity to this rapidly developing country, but is also of critical importance for increasing the role of solar and wind power that are intermittent by nature and where the grid can thus provide an effective and economical substitute to electricity storage. In that context, it can connect the solar- and wind-energy rich Western provinces, that have a relatively low power demand, to the southern and eastern regions of China where the demand is great. Such interconnection, mostly to make easier use of northwestern fossil fuel resources, is slowly under way anyway, via the "Power Transmission from the West to the East" plan that includes the development of new 1000 kV UHVAC and 800 kV UHVDC transmission systems (Zhou et al., 2010).

To elaborate on physical energy storage, this could be done by storing it (1) as the collector-generated heat, using sensible, latent or chemical reaction heat, or (2) as mechanical energy generated by the thermo-mechanical solar power plant, stored in potential energy of water pumped up to a dam and then released when needed by allowing it to flow back down through water turbines (pumped storage), or as compressed air in large caverns/tanks, retrieved when energy is needed by passing the compressed air through air turbines, or (3) as electricity in batteries. At this time, battery storage is too bulky and expensive, and the prevalently used storage method is (1), thermal storage, for which CST is also very synergetic.

While using the CST with a fuel back-up system, hybrid systems such as those described in Palgrave (2008) are more efficient and economical than parallel ones and has been suggested by the World Bank as being less risky for investors. Two examples of current hybrid plants: (1) the 150 MW Hassi R'mel plant (South of Algiers) with 25 MW of solar CSP parabolic trough

Table 4
Summary comparison of three different CST technologies.
Source: Aringhoff et al. (2005).

Dish engine	Power tower	Parabolic trough
Applications		
Stand-alone, small off-grid power systems	Grid-connected plants, high temperature process heat	Grid-connected plants, mid to high process heat
Can be clustered to form larger grid-connected dish parks.	Highest per unit solar capacity in 2005 is 10 MWe with another 10 MWe under construction	Highest per unit solar capacity in 2005 is 80 MWe
Highest per unit solar capacity in 2005 is 25 kWe		Total capacity as of 2005: 354 MW
Advantages		
Very high conversion efficiency	Good prospects for high conversion efficiencies with operating potential beyond 1000 °C (565 °C proven at 10 MW scale)	Commercially available—over 12 billion kWh of operational experience
Peak solar to electrical efficiency can achieve 30%	Storage at high temperatures	Operating temperature potential up to 500 °C (400 °C proven)
Modularity	Hybrid operation possible, but not proven	Commercially proven annual net plant solar to net electric efficiency of 14%
Hybrid operation possible, but not proven		Commercially proven investment and operating costs
Operational experience on demonstration projects		Modularity
		Best land-use factor of all solar technologies
		Lowest material demand
		Hybrid concept proven
		Storage capability
Disadvantages		
Needs improvement in reliability	Projected annual performance values, investment and operating costs still needs to be proven commercially	Use of oil-based heat transfer limits temperature to 400 °C yielding only moderate steam quality
Projected cost goals of mass production still need to be achieved		Long (70 km) continuous tubing through the parabolic trough collectors make it susceptible to breakdown interruptions

due to go into operation in 2009; (2) California Central Valley's 100 MW CSP hybrid with a co-fire using agricultural waste and manure.

In terms of comparative costs, Dersch et al. (2004) show that in most cases the levelized electricity cost for hybrid systems are lower than solar only systems at the same site and under the same operating scheme[1] constrained by the same economic assumptions.[2] The investment on a thermal storage for hybrid plants also lowers the LEC by about 10–15%.

With the above described advantages and the high likelihood of maintaining its economic advantage among solar power generation systems for at least the next couple of decades, we believe that CST is a good utility-scale clean energy power plant option for China.

2.2. *Comparison of CST systems*

With three different technologies, CST systems cover a diverse range of scale, capacity, applications, and costs with each combination having its own advantages and disadvantages. Table 4 shows the qualitative differences between the three main CST technologies. Table 5 provides a summary of operating characteristics. Table 6 provides a summary of estimated costs for the three CST technologies.

Though the dish engine may still have much to prove, its small capacity, modular design, and significant potential for decrease in capital costs (estimated at 57%) make the dish engine a potential future solution in building a decentralized power infrastructure in China. But in terms of utility-scale electricity generation, the two centralized systems, parabolic trough and power tower, with high power output potential (100 s of MWe) and thermal storage and hybridization capabilities (provide power around-the-clock), are best suited for China's large-scale power generation needs.

For China, the choice between power tower and parabolic trough may not be an easy one. While the parabolic trough offers commercially proven experience (operation, efficiency, investments, and returns), lowest material demand, and best land-use factor, the 400 °C operating temperature limitation and susceptibility to significant interruption from a single point of breakdown (over 70 km in continuous tubing through the U-shaped collectors) are disadvantages compared with the power tower. Unless technology innovation overcomes these limitations, some experts argue that the power tower will therefore be the future of CST as it will offer higher solar to electric efficiency at a lower levelized cost of electricity (Wolff, 2008).

From a holistic perspective, however, there are good reasons for China to start with parabolic troughs. The trough is at an advanced development stage with ongoing R&D efforts expected to advance it further. Taggart (2008) describes some areas of research to include: (1) higher efficiency mirrors and improved tracking of the sun to improve solar field conversion efficiency; (2) improvements in heat transfer techniques to overcome the current temperature limitations and improve overall solar to electric conversion efficiency; (3) improvements in mirror

---

[1] Two operating schemes are investigated in this study. (1) Scheduled load mode—the plant operation follows a fixed demand curve where the electricity demand is high during the day and the evening and lower at night hours. Therefore, the plants operate for 16 h at full load and 8 h at 80%. If no solar energy is available to fulfill the load curve, the fossil back-up is used. (2) Solar dispatching mode, no specific load profile is prescribed. The gas turbine operates at full load for 24 h and the output of the gas turbine then depends only on the ambient temperature and the site elevation. No back-up burner is used in this mode.

[2] Assumptions used for the study includes: 2002 as base year, constant real discount rate of 6.5%, plant lifetime of 25 years, fuel price of 1.26 US cent/kWh, annual fuel price increase of two percent, annual inflation rate of two percent, solar field plus heat exchange cost is $220/m2, conventional combined cycle cost is $550/kW, conventional components for integrated solar combined cycle system is $600/kW, and thermal storage cost is $35/kWh.

Table 5
Summary of current CST operating characteristics.
Source: Kreith and Goswami (2007).

Operating characteristics of CST technologies

CST technology	Concentration ratio (times)	Operating temperature	Unit capacity range	Peak efficiency (%)	Average solar to electric efficiency (%)	Annual capacity factor	Status
Dish engine	500–1000	600–1500 °C	5–50 kWe	29	15–30	25% (p)	Demonstration and testing at 10 MWe scale
Power tower	10–100	400–600 °C	30–200 MWe	23	12–18	25–70% (p)	Prototypes tested at 25 kWe
Parabolic trough	600–3000	100–400 °C	30–100 Mwe	21	8–12	24% (d)	20 years of operating experience in Calif

(d) = demonstrated, (p) = projected based on demonstration testing.

Table 6
Summary of current cost estimates for different CST technologies.
Source: Aabakken (2006) and IEA (2008).

Cost estimates

CST technology	Dish engine			Power tower			Parabolic trough		
	2005	**2010**	**2020**	**2005**	**2010**	**2020**	**2005**	**2010**	**2020**
Levelized electricity costs (USD/kWh)	0.15	0.10	0.06	0.06–0.11	0.06–0.07	0.40	0.10	0.05–0.08	0.07
Capital cost (USD/W)	5.0	3.2	1.2	2.8–4.1	2.1–3.5	1.1–2.5	2.6–3.6	2.2–0.9	1.4
O&M costs (USD cents/kWh)	4.0	1.5	0.9	1.0–1.2	0.4–1.0	0.30	1.0	0.5–0.7	0.4
Surface costs (USD/m^2)	3000	1500	320	475	265	200	630	315	275
Uncertainty		Moderate			Moderate			Low	

Table 7
Summary of key siting factors.*Source*: Cohen et al. (2005).

Siting factors	Requirements
Solar resource	> 1800 kWh/m^2/yr or 5 kWh/m^2/day for economical operation
Land topography	0–3% grade as potential. Less than 1% grade most economical
Land space	5 acres or 20 km^2/MWe
Land use	Low biodiversity. Limited productive use.
Grid availability and capacity	Close by. Transmission lines costs \$50 K–\$180 K per mile for 100 MW capacity
Water availability	Water required for steam turbine. Dry cooling is an option with 10% increase in cost
Fossil fuel availability	Needed for hybridization, but not considered critical
Transportation infrastructure	Proximity to roads and railways necessary for access and construction

cleaning techniques to lower O&M costs; (4) improvements in manufacturing efficiencies and economies of scale for ramp up production to lower overall capital costs; all of which help to make parabolic troughs even more economically feasible than they are today. Furthermore, the parabolic trough has become the preferred technology for developers and investors in large-scale CST projects in Europe, United States and Combined Cycle CST projects in Algeria, Egypt, India, Iran, Mexico, and Morocco (Aringhoff et al., 2005).

Thus, in line with President Hu Jintao's scientific concept of development, China may wish to start the CST development with the commercially mature parabolic trough technology to leverage the knowledge and experience of previous parabolic trough learning while keeping a close eye on power tower advances and developments for future CST expansion. It appears that this approach would also offer Chinese industry a more viable opportunity to master and advance the state of the art for establishing a strong export capability.

3. Assessment of potential of CST use in China

The potential for CST implementation in China depends on identifying and analyzing the fit between parameters required of CST systems and China's respective characteristics. These parameters cover the inter-related geographic, grid infrastructure and power transmission, demand, and economic variables.

3.1. Geographic assessment

The 20 years of commercial operating experience at SEGS power plants in California pinpoints the key geographic CST parameters with the most significant impacts on cost. Specifically, the key parameters identified are (1) solar resource; (2) land topography; (3) land space; (4) land use, and (5) water (Table 7).

3.1.1. Solar resource assessment

Due to the nature of CST technology, only direct normal insolation (DNI) can be used which limits high-quality CST sites to areas with low levels of atmospheric moisture and particulates, little or no cloud cover, and high levels of year around DNI, deserts thus being the most typical for these conditions. Further, the required solar field size for CST is directly proportional to the level of DI. With the solar field representing about 50% of total project cost, the DI level will have the greatest impact on overall CST system cost (Cohen et al., 2005).

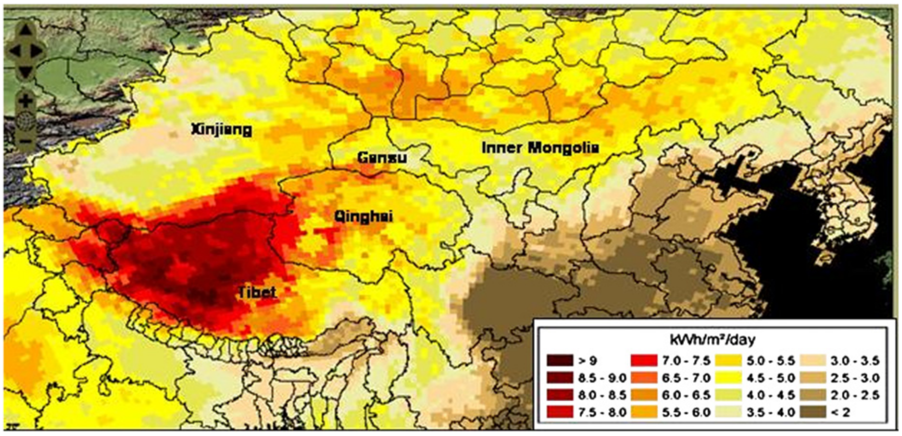

Fig. 1. Monthly and annual average (from 1985 to 1992) direct normal (DNI) GIS dataset at 40 km resolution for China.
Source: NREL (2005).

We used the satellite data from the US National Renewable Energy Laboratories (NREL) that provides 40 km resolution DNI GIS dataset with monthly and annual averages over a period of seven years (from 1985 to 1992) for China. This dataset uses NREL's Climatological Solar Radiation (CSR) Model, which accounts for cloud cover, atmospheric water vapor, trace gases, and aerosol in calculating the insolation with measurements checked against ground stations where available (NREL, 2005). At the time of this writing, the authors are not aware of any solar energy mapping activity by Chinese institutions. As solar resource mapping is an important first step in assessing China's solar potential, developing this capability should be a priority for China.

We note that actual practical CST design for the solar dataset should be of a higher resolution both in grid size and time. In addition, a correction factor should be computed across the satellite DNI data based on discrepancies between the satellite and ground measurements. For example, the California SEGS project used a 10 km grid and hourly averages over a five year period and reduced that value by 7% based on two ground measurement cross-checks. For the purposes of this paper, the DNI values from NREL will be used as is.

In general, over two-thirds of China's land surface areas receive more than $5.02 \times 106\ \mathrm{kJ/m^2/yr}$ of total solar radiation (Zhang et al., 2009). In terms of DNI resources, the values range from less than 2 $\mathrm{kWh/m^2/day}$ in the Eastern and Central regions to more than 9 $\mathrm{kWh/m^2/day}$ in the high altitude, arid areas of the Qinghai-Tibetan Plateau. With the assumption that the DNI values need to be greater than 5 $\mathrm{kWh/m^2/day}$ for CST to be economical (Hang et al., 2008), the Tibet Autonomous Region, Xinjiang Autonomous Region, central areas of Inner Mongolia Autonomous Region, parts of Qinghai, the western tip of Gansu, and the northwestern border of Sichuan are all potential candidates for CST (Fig. 1). However, if the minimal DNI criterion[3] is raised to 6 $\mathrm{kWh/m^2/day}$ (level used by the SEGS CST plants in California), only Tibet, Xinjiang, Inner Mongolia, Qinghai, and some parts of Northeast China would remain as potential areas for CST.

3.1.2. Land assessment

As described above, in addition to the high DNI requirement, the land for CST sites should have low value for agricultural or residential use and have low biological habitat. In other words, the most suitable potential sites for CST deployment are in desert regions.

China has about 2.63 million $\mathrm{km^2}$ (27.3% of China's territory) of desert with most of the areas covering northern parts of central China, parts of Northeast China, and most of the Northwest region of China (CCICCD, 2009). Tibet, Inner Mongolia and Qinghai alone have about 987,900 $\mathrm{km^2}$ of desert (Hang et al., 2008). Coincidentally, these are all areas identified above in the solar assessment as areas with high-quality direct solar insolation.

In terms of land space requirement, experts with experience on California's SEGS plants estimated the land space requirement for parabolic trough plants at 20,000 $\mathrm{m^2}$ per 1 MWe or about 1 $\mathrm{km^2}$ per 50 MWe of capacity not including thermal storage and hybridization. Using the DESERTEC perspective of leveraging deserts to fulfill civilization's electricity needs, this means China can match its 2006 total net installed electricity generation capacity of 602,570 GW (UN Stats, 2009) by utilizing only 12,031 $\mathrm{km^2}$ of its desert area (i.e., only 1.2% of the combined desert area of Tibet, Inner Mongolia and Qinghai) with parabolic trough technology.

Not all desert lands are suitable as land topography, geology and soil quality also need to be considered. In general, lands with less than 3% slope are considered to have potential (3% slope may increase costs of up to 10%) with lands less than 1% slope considered to be the most economical (Cohen et al., 2005). Other factors that require consideration include flood potential, seismic history, stability of soil, potential obstructions of the sun, and existence of dust or other debris that may degrade the effectiveness of mirror reflectors.

Wind conditions at the site should also be considered in the siting assessments. Since wind intensity determines the structural design of the collectors and the collector structures represent 40% of the solar field costs, the consideration of wind force is necessary to optimize this decision (Cohen et al., 2005). As reference, the SEGS plants are designed to operate at less than 35 mph winds and can operate in protected-mode (face down position) in 80 mph winds. Wind turbines, rather than CST systems should be considered in high wind areas.

A rigorous assessment should be performed, conveniently assisted using GIS software, to identify the areas that match all the land assessment criteria parameters listed above.

3.1.3. Water assessment

The primary requirement for water in a CST power plant is for cooling the power cycle, replenishment of the working fluid if a steam cycle is used, condensers, and for solar field maintenance

---

[3] Using NREL's Concentrating Solar Deployment System Model (CSDS), the DNI resource is divided into five classes: Class 1 is 6.75–6.99 $\mathrm{kW/m^2/day}$; Class 2 is 7.00–7.24 $\mathrm{kW/m^2/day}$; Class 3 is 7.25–7.49 $\mathrm{kW/m^2/day}$; Class 4 is 7.50–7.74 $\mathrm{kW/m^2/day}$; Class 5 is 7.75–8.06 $\mathrm{kW/m^2/day}$ (Blair et al. 2006).

(primarily for washing the mirrors). For current-use CST systems, the water requirement ranges between 3 and 3.5 m^3/kWh (Jones, 2008) with 95% of the water usage attributed to the cooling tower and the remaining 5% of water consumption committed to mirror cleaning and to steam cycle working fluid. High quality CST sites with high levels of DNI are, however, usually limited to arid and semi-arid deserts where water does not come easily or cheaply. As water-based cooling (cooling via evaporation) is technically considered the most efficient cooling technology available (Al-Soud and Hrayshat, 2009), the cost effectiveness of a CST system with water cooling becomes dependent on the cost of bringing water to the site and more importantly the cost of wasting a precious resource.

The best scenario, then, is for the CST site to be located close to an available and inexpensive water source. For example, two of the SEGS Mojave Desert parabolic trough sites use underground water, and one uses aqueduct water. If no water resources are available or economically feasible, dry cooling can also be considered with a cost and efficiency penalty. Table 8 shows that dry cooling technology equipment currently costs about 3.3 times more than water cooling equipment and also increases parasitic power consumption (from fans) and lowers the overall efficiency of the steam cycle, resulting in an overall increase in electricity cost by 10% or more. This gives strong motivation to the improvement and cost reduction of dry cooling technology, which is indeed expected.

Table 8
Comparison of dry and wet cooling in terms of costs and efficiency.
Source: Al-Soud and Hrayshat (2009).

Cooling	Wet	Dry
Steam cycle efficiency	37%	35%
Parasitic electricity consumption	5 MW	7 MW
Energy yield	117 GWh	109 GWh
Evaporated water	180 M3/MW	–
Investment (cooling component only)	4.09 M USD	13.54M USD

If the desert region considered has saline or otherwise unpotable water (as some deserts have, underground or in lakes) there is a good synergy in building a hybrid dual-purpose plant that uses solar energy to produce both electric power and fresh water by a water desalination process. Here, the desalting portion of the plant can use the low temperature reject heat of the electric power plant and thus increase the system's overall economic viability significantly and also provide some of the water needed for the plant's operation.

Thus a careful assessment of water and fossil fuel (for hybrid solar power generation systems) availability and cost assessments are important parts of the site section and system design process.

3.2. *Transmission and power grid assessment*

Access to appropriate electric power transmission lines is another crucial factor for site selection. As transmission line costs to connect into the grid are high, the proximity of CST systems to a transmission power grid is an important factor in the overall calculation. Experts estimate that transmission line costs in the United States can range from $50,000 to $180,000 per mile for a

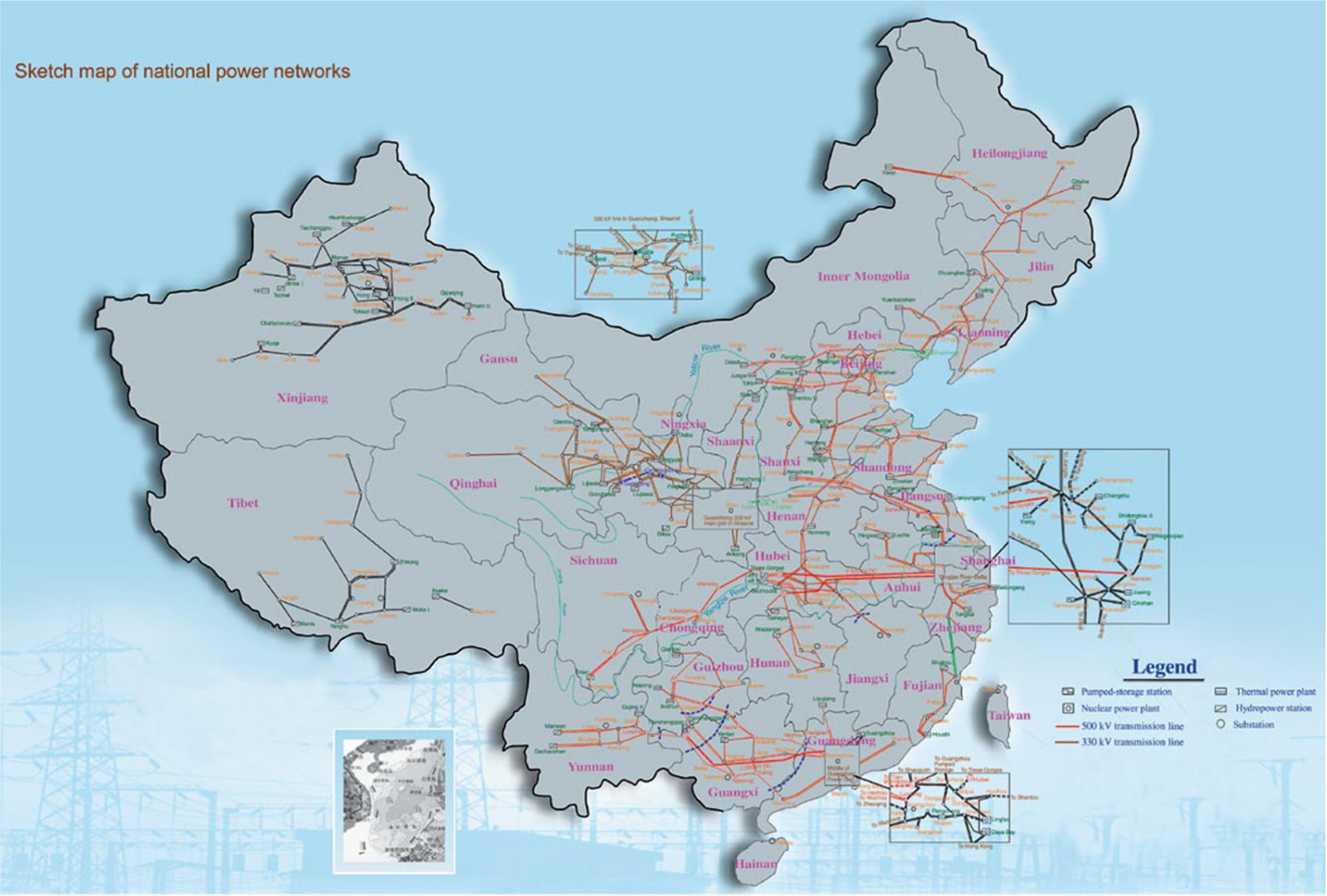

Fig. 2. Map of China's power grid (circa 2003, the latest we could find).
Source: CSPIN (2009).

100 MW capacity line depending on voltage level and length of required transmission line (Cohen et al., 2005). In China, a survey of recently approved grid construction projects suggests a 500 kV, 250,000 kVA transmission line costs about $350,000 per mile and a similar line with 750,000 kVA costs around $800,000 per mile (State Grid, 2009). Of course, in addition to line voltage, capacity, and length, line costs will vary depending on the need for substations, transformers, and the difficulty of the terrain. Thus, close proximity to a power grid is critically important to the viability of the CST system.

China's interconnected power grid network consists of different types of power generation stations (hydro, nuclear, thermal), power substations, and transmission lines mainly of the 330 kV and 500 kV variety. Currently, there are seven inter-provincial power grids (East China, Northeast, Central China, North China, Northwest, Sichuan-Chongqing, and South China) and four independent provincial power networks (Shandong, Fujian, Xinjiang, and Tibet) operating in mainland China. As of 2003, the Shandong power grid has joined the North China power grid, but has not yet interconnected; the Xinjiang power grid has joined the Northwest power grid, but has not yet interconnected; Tibet remains unconnected to the rest of China's power grid (CSPIN, 2009). Overall, China's power grid now extends to all cities and most villages throughout China but interconnection between grids are not complete, especially in the Western regions (Fig. 2).

Without interconnection to the rest of China, Xinjiang and Tibet are their own isolated "islands". Unfortunately, these two "island" regions are also the regions with the most potential (in terms of DNI and land slope and use) for CST system implementation. Since even CST electricity generation for local consumption in the sunny regions lacks an adequate grid, if the vision for CST systems to generate electricity in the West and export excess electricity to the East is to be realized, the interconnection between Xinjiang, Tibet and the rest of the country is a mandatory prerequisite.

Driven by China's current five year plan, China's grid is constantly updated with newer technology, higher capacity, and increases in new interconnections. As an example of new technology and higher capacity, China, in 2007, awarded Siemens a 300 million euro contract to construct the world's first high-voltage DC transmission (HVDC) system of an 800 kV and 5000 MW capacity between Yunnan and Guangdong – a distance that traverses 1400 km (870 miles) of challenging terrain – to be operational by mid-2010 (T&D, 2007). The purpose of this line is to bring the abundant hydroelectric power from Yunnan to the power hungry mega cities of Guangzhou and Shenzhen. China also connected its Hainan Island to the national power grid in March 2009 with a 32 km long seabed power transmission cable (500 kV, 600 MW of initial capacity to be doubled when the project is complete) at a cost of 2.5 billion RMB (368 million USD). A recent description of China's grid and of plans for its development was made by Zhou et al. (2010), pointing that its structure is relatively weak as a whole, with many potential security issues, and that it has a low transmission capability of the single circuit.

China's ongoing drive to modernize its power grid will clearly work in CST's favor. Based on the current five year plan, Xinjiang is expected to complete its 500 kV interconnection into the Northwest power grid by 2011 effectively connecting Xinjiang to the rest of China (Xinjiang, 2006). Tibet, another top ranked region in terms of DNI resources, is expected to be connected to the national grid by 2011. The Qinghai-Tibet power line will traverse 1100 km of diverse terrain from Goldmud, Qinghai heading westward to Lhasa, Tibet, mostly following the route already established by the Qinghai-Tibet railway line and will be the world's first transmission line at plateau altitude of 5000 m above sea level (China Power Web, 2008). This project, which started in 2009 and is expected to be complete in 2011, will consist of 500 kV of direct current transmission lines with an initial capacity of 750 MW (1500 MW when fully complete) at a cost of over 6 billion RMB ($857M USD) (CPNN, 2009). Notably, the purpose of this interconnection is to allow the Northwestern provinces to provide electricity to Tibet during winter and spring season shortages, to meet the demand for the development of local economies, and to allow for surplus electricity to be sold back into the national grid.

In sum, while the most optimal regions for CST may not currently be connected to the national grid, the drive to modernize China's electricity grid through their five year plan (which includes opening up the power transmission sector to foreign investments (WSJ, 2007)) will result in a modern, high capacity, nationally integrated power grid network connecting the power hungry mega cities in the East to the renewable energy rich regions of the West by 2011. As seen from China's many transmission line projects, the main reason for the interconnections is to optimize electricity allocation—selling surplus electricity from one region to other regions of high power demand. This trend is in line with the vision of this paper and gives added evidence that the time for CST in China is now.

4. Economic assessment

4.1. *Comparison of generated electricity costs with other generation methods, considering both nominal and true (including externalities cost)*

Costs of power generation include only the costs incurred by the utility, which typically do not (yet) include the costs of all the externalities, such as those of environmental, health, and social effects. We term these costs as the "nominal costs". The most commonly used nominal cost is the Levelized Electricity Costs (LEC) and to get an idea of how CST compares "nominally" with other electricity generating technologies (both conventional and renewable), Sovacool (2008) presents the average nominal LEC for each technology (Table 9). Sovacool referenced Karmis (2005) for biomass, nuclear, onshore wind, IGCC, scrubbed goal, advanced

Table 9
Nominal 2007 levelized electricity costs.
Source: Sovacool (2008) and Badr et al. (2003).

Rank	Electricity generation technology	Nominal LEC, $2007 (¢/kWh)	+more/-less expensive CST is to the other technologies (%)
1	Biomass (landfill gas)	4.1	230
2	Advanced nuclear	4.9	176
3	Onshore wind	5.6	141
4	Hydroelectric	6.0	124
5	Geothermal	6.4	111
6	Integrated gasification combined-cycle (CC)	6.7	102
7	Biomass (combustion)	6.9	96
8	Scrubbed coal	7.2	88
9	Advanced gas and oil combined-cycle	8.2	65
10	Gas oil combined-cycle	8.5	59
11	Adv gas and oil cc with carbon capture	12.8	6
12	Solar CST (parabolic trough)	13.5	0
13	Advanced combustion turbine	32.5	−58
14	Combustion turbine	35.6	−62
15	Solar photovoltaic (panel)	39.0	−65

Table 10
Descriptive statistics of electricity externality studies in 1998 US$.
Source: Sundqvist (2004).

US cents/kWh	Coal	Oil	Gas	Nuclear	Hydro	Wind	Solar	Biomass
Min	0.0600	0.0300	0.0030	0.0003	0.0200	0.0000	0.0000	0.0000
Max	72.42	39.93	13.22	64.45	26.26	0.80	1.69	22.09
Mean	14.87	13.57	5.02	8.63	3.84	0.29	0.69	5.20
SD	16.89	12.51	4.73	18.62	8.40	0.20	0.57	6.11
N	29	15	24	16	11	14	7	16

SD = standard deviation; *N* = sample size.

gas and oil combined-cycle, gas and oil combined-cycle, IGCC with carbon capture, advanced gas and oil combined-cycle with carbon capture, advanced combustion turbine, combustion turbine, and solar PV data.

These estimates assume a 25-year system life; All federal tax incentives and credits as of 2007; accelerated depreciation with half-year convention (MACRS); a discount rate of 7.0%; current costs and capacity factors (no cost and performance improvements over time); inflation rate of 2.5% per year; fixed and variable operations and maintenance costs escalated at the inflation rate; capital costs associated with the connection of centralized systems to the electricity grid are not included; fixed and variable costs associated with electricity distribution and transmission are not included. Detailed assumptions can be found in Karmis (2005).

For geothermal energy, hydro power, and solar thermal technology Sovacool's reference ultimately points to California Energy Commission's Final Staff Report on the comparative costs of California's electricity generation technologies. The main assumptions used by this report include 30 year system life, loan term of 12 years, inflation of 2%, Federal depreciation using MACRS 5 years, State depreciation using full system life, with investment tax credit, debt-equity ratio of 2.02, and a discount rate (weighted average cost of capital) of 10.8%. Capital costs associated with the connection of centralized systems to the electricity grid and fixed and variable costs associated with electricity distribution and transmission are not included. Detailed assumptions can be found at Badr et al. (2003).

While the paper uses the data of Sovacool (2008) and of Badr et al. (2003) LEC as reference, we note that LEC will vary depending on the assumptions used for each electricity generation technology. Thus, to be truly comparable, the different types of electricity generation technology should have a common basis of assumptions. In the absence of better information, their data was used nevertheless.

Based on this ranking, CST (parabolic trough) is ranked at 12th place at 13.5 cents/kWh electricity. Compared to renewables sources with major focus in China's plan, CST-generated electricity is thus estimated here to be 124% more expensive than hydroelectric, 141% more expensive than onshore wind, and 230% more expensive than biomass. Compared to non-renewable sources with a significant potential influence in China, CST is 176% more expensive than nuclear. Compared to China's dominant technology of electricity generation, CST is about 194% more expensive than coal-fired power plants located in Xinjiang (not listed in table) which have a cost of electricity of 4.6 cents/kWh (Fan et al., 2005).[4] Thus, based on the LEC ranking alone, the economics of CST would seem to have stiff competition in China, as they typically do in most of the world.

Nominal LEC does not, however, represent the true cost of producing electricity. All externalities should be included for sustainable development, and it has been proven time after time that avoiding to include them from the start typically ends up in much higher prices and negative consequences later. Such consequences often stymie further development and certainly thwart the governments' and people's goals for sustainable development. The environmental externalities can include various gaseous, including greenhouse gas, emissions, liquid, and solid waste some of which are toxic, and water and soil impairment. The social externalities include displacement of people (e.g. Three Gorges dam), and effects on health, employment, education, and net economic income. Because the pricing of externalities can result in a wide range of values depending on the assumptions used, it is useful to look at Sundqvist (2004) on the disparity of externality estimates to (1) understand some causes of these disparities and (2) get a better feel for the range of the data. Applying statistical analysis to 38 studies and 132 estimates of electricity externalities, Sundqvist's results indicate that the methodology used (e.g. abatement cost approach, damage cost approach top-down, damage cost approach bottom-up) and the fuel stages used (i.e. whether the individual studies have addressed the full fuel cycle or not) have statistical significance (at the 1% level) with the disparity of externality estimates. Specifically, the results show that the bottom-up approach produces the lowest external cost estimates compared to abatement and top-down and studies using the full fuel cycle produce higher estimates than studies using just generation (Table 10). While Sundqvist is the first to admit that his analysis is not sufficient to explain all the variability in externality estimates, his study provides good insight into some of the explanatory variables in the disparity.

With the large standard deviations, it is hard to pinpoint with certainty the best externality estimate to use. However, taking Sundqvist data at the aggregated level and using the Min and Max to define the range, it may be reasonable to assume that the correct externality estimate lies somewhere in between. For the purpose of comparison, Sovacool (2008) study used the mean value (averaged across studies) of the externality cost for each technology and added them to the nominal LEC to obtain what he called the true LEC (Table 11).

Based on this calculation and ranked by *true* LEC, CST moves up six places to number 6 with LEC of 14.4 cents/kWh. Compared to renewable sources with major focus in China's plan, CST is now only 31% more expensive than hydroelectric, 140% more expensive than onshore wind (about the same as nominal), and now 34% more expensive than biomass. Compared to the non-renewable sources with a significant influence in China, CST is now 10% cheaper than nuclear. Compared to scrubbed coal, a cleaner version of China's dominant coal-fired electricity, CST is 45% cheaper. Notably, hydro electricity externalities in the above table most likely did not include the social disturbance of large scale resettlement and environmental damages such as reduced biodiversity, degradation of water quality, fragmentation of the

---

[4] Cost of grid-connected coal-fired electricity for Xinjiang, Inner Mongolia, Liaoning, and Guangdong are 4.6, 5.0, 6.4, 8.6 cents USD/kWh, respectively, based on 1USD–7RMB.

Table 11
True cost of generating electricity. Nominal + externality = True LEC (2007).
Source: Sovacool (2008).

Rank	Electricity generation technology	Nominal LCOE, \$2007 (¢/kWh)	Nominal external Cost, \$2007 (¢/kWh)	True cost, \$2007 (¢/kWh)	+ more/-less expensive CST is to the other technologies(%)
1	Onshore wind	5.6	0.4	6.0	140
2	Geothermal	6.4	0.7	7.1	103
3	Biomass (landfill gas)	4.1	6.7	10.8	34
4	Hydroelectric	6.0	4.9	11.0	31
5	Biomass (combustion)	6.9	6.7	13.6	6
6	Solar CST (parabolic trough)	13.5	0.9	14.4	0
7	Advanced nuclear	4.9	11.1	16.0	−10
8	Advanced gas and oil combined-cycle	8.2	12.0	20.2	−29
9	Gas oil combined-cycle	8.5	12.0	20.5	−30
10	Adv gas and oil cc with carbon capture	12.8	12.0	24.8	−42
11	Integrated gasification combined-cycle	6.7	19.1	25.8	−44
12	Scrubbed coal	7.2	19.1	26.3	−45
13	Advanced combustion Turbine	32.5	6.5	39.0	−63
14	Solar photovoltaic (panel)	39.0	0.9	39.9	−64
15	Combustion turbine	35.6	6.5	42.1	− 66

ecosystem, land erosion, and other geological damages. If accounted for, these externalities would raise the true cost of hydro generated electricity and in turn, make it more expensive than CST technology. In sum, when costs of externalities are included in the calculation of true costs, CST becomes a very competitive electricity generation alternative.

4.2. *Risks to be addressed and the effect of experience on CST future cost, and competitiveness*

A recently published thorough review and study of the role played by renewable energies in China's sustainable energy supply at present with forecasts for the future by Zhang et al. (2010) points to important risks that must be dealt with. These include financial risks due to the high cost, some performance uncertainties, and insecurities associated with the government role in taxation, incentives and equitable accounting for externalities (which at this time strongly favor fossil fuel producers and users), technological risks due to the novelty of some of the technologies, and market entry risks due to competition from large established fossil fuel companies. Zhang et al. (2010) describe the important role of the "China Renewable Energy Law" (2006) that presented a comprehensive renewable energy policy framework, and that institutionalized several policies and instruments for China's renewable energy development and utilization, but they also note that the enabling environment for its implementation has not been well established yet. For example, specific mechanisms and methods for premium transfer and grid-connection cost management are not in place and arguments over feed-in tariff and public bidding persist, leaving risks for renewable energy power generation development. Suggestions for alleviating some of the risks are proposed.

Cost of systems is affected by learning and experience during their operation, usually tending to drop significantly, especially as many systems come on line. An "experience curve" incorporates the effects of economies of scale, economies of production, and technology and summarizes the effects as the relationship between historical cumulative production versus the price variation (Kreith and Goswami, 2007). As California (SEGS) has the longest operating history in the world with CST technology, the experience curve from SEGS has the potential to provide a reasonable road map to CST's future. It shows an observed 4-fold drop in LEC as the power generation capacity rose from 15 to 450 MWe, which can be extrapolated (but not guaranteed) to drop 10-fold if the capacity expanded to 100,000 MWe.

The curve suggests that the LEC for CST will be around 5 cents/kWh (which would be competitive on a nominal basis with the cost of coal-fired electricity in Xinjiang) when the installed CST capacity reaches as little as 4000 MWe. It is important to note that there could be stepwise drops in the curves if major technology improvements are attained.

If the IEA outlook of 20,150 MWe of installed CST in 2020 is correct, then based on this curve, a very competitive LEC of around 4 cents/kWh can be realized. Thus, the CST technology will be able to compete with traditional peak and base load fossil fuel based electric power within ten years (Caldes et al., 2009).

5. Vision of reducing regional disparity

With Tibet and Xinjiang consistently identified as regions with the most CST potential, lowest population density and land productivity/value, and some of the lowest economic status, CST power plants will not only benefit a region in terms of providing the electric power needed to fuel regional development, but the large capital investment involved in building CST systems will also have socio-economic benefits to the region(s) that host the solar power plant. Specifically, China should build CST power stations in the sunny Western regions, and sell the generated electricity to the more industrialized Eastern region where the bulk of the demand occurs. By doing so, China can turn the less productive lands of the Western regions into competitive advantages and at the same time provide the much needed electricity to the Eastern regions driving economic growth. This will also bring economic benefits to the underdeveloped Western regions via construction, infrastructure build-up, maintenance, and other beneficial trickle-down effects. Ultimately, solar thermal electricity generation will continue to fuel China's growth cleanly while reducing regional socio-economic disparity.

While CST technology is currently emerging in many countries of the world in the form of a parabolic trough, power tower, or some combination of CST and traditional power generation technology (EU, 2007), China seems not to pursue any significant CST activity. Thus, to understand the potential regional economic impact that CST could bring to Tibet and Xinjiang, it is helpful to review lessons learned in the countries where CST deployments have been successful. The United States (mainly SEGS) and Spain (Andasol) are the two most developed CST markets and will serve as the basis of our reference.

Table 12
Estimated economic impact to region for a 100 MW CST station.
Sources: Stoddard et al. (2006), Schwer and Riddel (2008), and BEA (2009).

Impact to region (1)	California (3)	New Mexico	Nevada	Arizona
Private investment (2)	$2.8 B	$198.9 M	Not estimated	$400 M
Gross state product	$626 M	$465 M	$482 M	$420 M
Earnings	$195 M	$75 M	$406 M	Not estimated
Jobs	3955 job years	2120 jobs	7170 job years	3400 jobs
Taxes	Not estimated	$246M	Not Estimated	1.3–1.9 B over 30 yr
Size of economy (M USD)	2,312,968	76,178	127,213	387,028

M = millions; B = billions.
(1): Results may not be completely comparable as different economic impact models were used. For example, California used the Regional Input–Output Model, whereas Nevada studies used the Regional Economic Model (REMI) model of the Nevada economy.
(2): Private investment is the amount of capital flow to the region for plant, transmission facilities, ancillary businesses, and infrastructure. Gross State Output is the total value of goods and services produced within the state. Earnings are the value of wages and benefits earned by workers in the region. Jobs include direct and indirect full and part-time jobs. Taxes are impact to state and local government tax receipts. Size of economy is 2007 Gross Domestic Product for the state.
(3): California only assessed the economic impact in a few of the counties thus result does not reflect the entire state.

In general, the overall economic impact can be categorized into direct effects, indirect effects, and induced effects. Direct effects are money directly spent by the project in the host region on labor, materials, and equipments (i.e. the total project price). Indirect effects are impact of money spent by the project that stimulates secondary economic activities within the host region and creates new flows of purchase and sale from other sectors of the economy. In other words, one dollar spent by the project in the region is re-spent in the region in other sectors of the economy—also called the multiplier effect of each dollar; and induced effects are related to the expansion of private expenditure the consequent change in consumption pattern of goods and services (e.g. food, transportation, health, services, etc.) from workers in the project.

For the United States, NREL's document library contains a large number of economic impact studies performed for various regions in the Southwest including California, Nevada, New Mexico, and Arizona. Table 12 below presents a summary of results of the economic studies for these four regions. The result of the study shows that per MW economic impact to Nevada, New Mexico, and Arizona is about $5M per MW of CST capacity. California's economic impact assessment only applied to a few counties[5] within the state and thus explains the glaring outlier – an economy 20-fold larger than Nevada's, yielding a Gross State Product benefit only 30% higher than Nevada.

For Spain, the recent study by Caldes et al. (2009) on the economic impact of CST on Spain also provides useful data for our reference. That study fed the model with detailed sectoral breakdown and capital, operating, maintenance, and labor costs information. The results showed that the direct economic impact to Spain using parabolic trough and power tower technologies was $12.77 M and $20.60 M per MW, respectively and the total (direct plus indirect) economic impact was $24.5 M and $40.3 M respectively. This implies a multiplier effect – which represents the amount of total economic benefit received for every $1 of direct economic impact invested – of 1.92 and 1.96, respectively (Table 13).

Table 13
Estimated economic impact to Spain for CST implementation.
Sources: Caldes et al. (2009) and CIA (2009).

	Parabolic trough 50 MW	Power tower 17 MW	Parabolic trough per MW	Power tower per MW
Impact to GRP				
Direct	$638	$350	$12.77	$20.60
Indirect	$586	$336	$11.72	$19.74
Total	$1,224	$686	$24.48	$40.34
Impact to Employment				
Direct	5,554	3,213	111	189
Indirect	4,030	2,278	81	134
Total	9,584	5,491	192	323

Gross Regional Product (GRP) figure in millions USD. Exchange rate used is 1USD–1.3163Euro.
Spain's size of economy is 1,683,000 million in 2008 nominal or 1,337,000 million in 2006 PPP.

While the results from the US and Spain are not directly comparable (since economic impact depends on the size, structure, and interconnection of different sectors in the economy), a simple comparison accounting for the size of the economy can provide a rough idea of the degree of economic benefit expected for Tibet and Xinjiang. Excluding California from the comparison and taking the average of Spain's impact with parabolic trough and power tower technologies, the potential economic impact for China can range from $5 M to $30 M of additional GDP per MW of CST capacity installed depending on the region of CST deployment. For regional comparison, Xinjiang is approximately of the same size as New Mexico, based solely on GDP,[6] which suggests that Xinjiang may be able to enjoy $465 M of additional GDP or $22.20 of additional per capita GDP[7] if a 100 MW capacity CST is implemented. In Tibet, even using the most conservative estimate of $5 M per MW of capacity, a CST plant as small as 50 MW could increase Tibet's GDP by 4% (3% via 2006 PPP).[8]

Based on these comments, an economic impact assessment with a rigorous methodology similar to (or better than) that employed by the United States and Spain should be undertaken for China to obtain a more robust assessment of the impact of CST. Importantly, it is also necessary to ensure a fair sharing of the benefit from the positive regional economic impacts among the indigenous people of these regions and the corporations and people from other provinces who are likely to follow the flow of money and other benefits. It is also crucial to consider the social aspect of the change that CST might bring. Consideration should be given to the indigenous population and their willingness to change their lifestyle in pursuit of a higher standard of living. For example, would farmers and herders be willing to give up their agricultural based lifestyle to

---

[5] (Stoddard et al., 2006) Study was targeted at southern California with only the following counties included: Fresno, Imperial, Inyo, Kern, Kings, Los Angeles, Mono, Orange, Riverside, San Bernardino, San Diego, San Luis Obispo, Santa Barbara, Tulare, and Ventura.

[6] (BEA, 2009; NBS, 2009) GDP for Xinjiang is $60.6B USD 2008 nominal or 98.7B USD in 2006PPP. New Mexico 2007 GDP is $76.2B.

[7] (NBS, 2009) Population of Xinjiang in 2007 is 20,950,000.

[8] (NBS, 2009) GDP for Tibet in 2008 is $5.6B USD 2008 nominal or 9.7M USD in 2006PPP.

become employed in all businesses associated with solar power generation and distribution and their associated outcomes?

The economic impact assessment should also take into account the current economic profiles of Tibet and Xinjiang and explore the potential of economic captive effects of a CST deployment in this region. For example, Xinjiang is rich in natural resources (minerals, oil, and natural gas) and advantageously located to trade with eight neighboring countries, which positions it as a major economic growth driver in China's Western region (Chaudhuri, 2005). Rather than solely relying on the sale or export of its natural resources for income, Xinjiang has the potential to move up the value chain and expand its economy by attracting and developing energy-intensive industries (mining, refining, and chemical) to the region with CST-produced electricity, thereby further developing Xinjiang's economic base.

In addition to use CST as an anchor to attract industries to the region, the impact of Xinjiang, Tibet, or other parts of China playing a leadership role in CST component manufacturing can also be explored. China is already a world leader in terms of solar thermal heating (size of market and manufacturing capability) and is currently a significant player in solar PV manufacturing. If the transition from solar thermal heating and solar PV to concentrating solar thermal components is possible, CST deployments could be the catalyst needed to give China's government and China's solar industry a unique opportunity to take a leadership position in CST.

6. Conclusions

Having experienced traditional development issues and faced with increasing international and internal pressure on environmental pollution, Chinese leaders recognize the need for sustainable development – balancing economic, social, and environmental factors – in reaching the country's objective of quadrupling its GDP by 2020 versus the year 2000 while only doubling energy consumption. In tandem with economic growth, China's President, Hu Jintao, also declared the need to grow in a balanced way in which both the rural and the urban can benefit.

Chinese leaders recognize that the key ingredients in bridging regional disparity are economic and infrastructure integration. This integration involves not just roads and railways, but also the electrification of rural regions (Western and Central) which translates also to an increase in electricity demands. Additionally, the realization of a new socialist countryside with educated and technologically savvy peasants will almost certainly mean a drastic rise in China's growing middle class. As the standard of living in the underdeveloped regions improves, the "new peasants" may increase the demand for modern appliances leading to greater electric power consumption. Thus, while a necessary goal for China's social and political stability, the success in "building a new socialist countryside" will tend to hinder China's energy consumption diet plans as well as reduction objectives for CO_2 emission.

China could partially attain both these objectives through aggressively incorporating large-scale renewable energy supplies into China's energy mix. With over two-thirds of China's land surface areas receiving more than 5×10^6 kJ/m^2/yr of solar radiation and DNI resources ranging from 5 kWh/m^2/day to 9 kWh/m^2/day in China's Western region (mainly Xinjiang and Tibet), China has the key prerequisite to make CST power generation economical—making concentrating solar thermal power one of the most viable ways to reach this objective.

With China's western regions characterized by mostly flat and unproductive desert lands and concrete plans to connect Tibet and Xinjiang into the national power grid by 2011 with HVDC lines, China also has the land and grid infrastructure needed for successful CST deployment.

While CST is dependent on an intermittent source for fuel, CST systems can provide non-intermittent electricity generation (firm capacity) or to satisfy peaking or intermediate load capacity demands (dispatchability) when equipped with heat storage systems, and/or fossil fuel backups (hybridization), and, importantly by employing "grid storage" if an adequate smart grid becomes available. Such a grid would transmit electricity to further regions of China if and when needed. With demonstrated capacity factor of 24%, name-plate capacity at 100 s of MW scale, 20 years of operational experience, and virtually emissions free, CST can be a good utility-scale clean energy power plant option for China.

At 13.5 cents/kWh (predicted for the next trough plant based on California SEGS experience curve), cost of CST electricity is still nearly triple to that of coal-fired power plants located in Xinjiang, which have an electricity cost of 4.6 cents/kWh. However, when costs of externalities are considered, CST becomes 45% cheaper than scrubbed coal (a cleaner version of China's dominant coal-fired electricity) and 10% cheaper then nuclear (with externalities costs based on Sovacool's study). Thus, while externalities vary greatly due to different assumptions, the key point is that if externalities are accounted for CST becomes a very competitive electricity generation alternative. Furthermore, the 13.5 cents/kWh is the price estimated for the US, and it is likely to be lower for plants built in China.

Looking into the future, CST also has great potential for continued cost savings from both economies of scale and technological improvements in efficiency. If IEA's CST outlook of 20,150 MWe of installed capacity in the year 2020 is realized, based on California SEGS experience curve, CST can realize a LEC of around 4 cents/kWh, which makes CST competitive with traditional fossil fuel based electric power within ten years.

With Tibet and Xinjiang consistently identified as regions with the most CST potential, lowest population density and land productivity/value, and some of the lowest economic status, CST power plants will not only benefit a region in terms of providing the electric power needed to fuel regional development, but the large capital investment involved in building CST systems will also have socio-economic benefits to the region(s) that host the solar power plant. Specifically, China should build CST power stations in the sunny Western regions, and sell the generated electricity to the more industrialized Eastern region where the bulk of the demand occurs. By doing so, China can turn the less productive lands of the Western regions into competitive advantages and at the same time provide the much needed electricity to the Eastern regions driving economic growth. This will also bring economic benefits to the underdeveloped Western region via construction, infrastructure build-up, maintenance, and other beneficial trickle-down effects.

Using economic impact assessments of select US regions and Spain (two most developed markets for CST) as reference, the potential economic impact for China can range from $5 M to $30 M of additional GDP per MWe of CST capacity installed. On a regional basis, this could mean an additional $465 M of GDP or $22.20 of additional per capital GDP for Xinjiang if a 100 MWe capacity CST is implemented there. For Tibet, even using the most conservative estimate of $5 M per MW of capacity, building a 50 MW CST plant could increase Tibet's GDP by 4% (3% via 2006 PPP).

These regions also have the potential to move up the value chain and expand their economies by attracting and developing energy-intensive industries (mining, refining, and chemical) to the region with CST-produced electricity, thereby further developing Western regions economic base. Furthermore, the impact of Xinjiang, Tibet, or other parts of China playing a leadership role in

CST component manufacturing can also be explored. China is already a world leader in terms of solar thermal heating (size of market and manufacturing capability) and is currently a significant player in solar PV manufacturing. If the transition from solar thermal heating and solar PV to concentrating solar thermal components is possible, CST deployments could be the catalyst needed to give China's government and China's solar industry a unique opportunity to take a leadership position in CST.

Ultimately, our paper combines and applies different data and analyses on China's economic development challenges, CST technology and feasibility, and economic impact of CST implementations in a new and useful way to show that solar thermal electricity generation can continue to fuel China's growth cleanly while reducing regional socio-economic disparity.

In sum, based on this study, the recommendations we propose for consideration by China's policy makers are

- In comparing coal-fueled power generation, include the associated environmental and social impacts/externalities in a realistic manner,
- Adopt large-scale concentrating solar power as an alternate, renewable, and viable energy supply to achieve the country's energy security needs and social stability objectives.
- Vigorously continue expanding and enhancing existing electric power grid to facilitate the supply of electricity from Western China, where solar resources are abundant, to Eastern China, where electricity consumption is greatest.
- Form public–private initiatives that will attract domestic and foreign investors necessary to build the power generation facilities in the West as well as the necessary supporting infrastructures.
- Legislate policies that will ensure that the benefits of solar power generation will go not just to the investors, but also to local communities—to have a real impact on the local economy and thus bridge economic disparity.
- Finally, to reduce the dependency of the local economy on the sale of solar power generated electricity alone, policy makers should employ synergy to attract energy-intensive industries to the region to further develop the region's economic base.

References

Aabakken, J., 2006. Power Technologies Energy Data Book. National Renewable Energy Laboratory (p. 18 accessed on October 2, 2010)〈http://www.nrel.gov/docs/fy06osti/39728.pdf〉.

Al-Soud, M., Hrayshat, E., 2009. A 50 MW concentrating solar power plant for Jordan. Journal of Cleaner Production. 17 (6), 625–635.

Aringhoff, R., Brakmann, G., Geyer, M., Teske, S., 2005. Concentrated Solar Thermal Power—Now! IEA SolarPACES Implementing Agreement, 2005. 〈http://www.solarpaces.org/Library/CSP_Documents/Concentrated-Solar-Thermal-Power-Plants-2005.pdf〉 (accessed on October 2, 2010).

Bureau of Economic Analysis (BEA), 2009. Regional Economic Accounts—Gross Domestic Product by State. 〈http://www.bea.gov/regional/gsp/〉 (accessed on October 2, 2010).

Badr, R., Benjamin, R., Alvarado, A., Ashuckian, D., O'Brien, T., Therkelsen, B., 2003. Final Staff Report—Comparative Cost of California Central Station Electricity Generation Technologies. California Energy Commission. 〈http://www.energy.ca.gov/reports/2003-06-06_100-03-001F.PDF〉 (accessed on October 2, 2010).

Blair, N., Mehos, M., Short, W., Heimiller, D., 2006. Concentrating Solar Deployment Systems (CSDS) a New Model for Estimating US Concentrating Solar Power (CSP) Market Potential: Preprint. National Renewable Energy Laboratory (accessed on October 2, 2010)〈http://www.nrel.gov/docs/fy06osti/39682.pdf〉.

China Climate Change Info Net (CCCIN), 2005. China Strives to Quadruple GDP with Low Energy Consumption by 2020, May 17, 2005. 〈http://www.ccchina.gov.cn/en/NewsInfo.asp?NewsId=4498〉 (accessed on October 2, 2010).

China National Committee for the Implementation of the UN Convention to Combat Desertification (CCICCD), 2009. China National Action Program to Combat Desertification. CCICCD. 〈http://www.desertification.gov.cn/xinxi/xdfa/1.htm〉 (accessed on 29.03.2009).

Central Intelligence Agency (CIA), 2009. The World Factbook. 〈https://www.cia.gov/library/publications/the-world-factbook/index.html〉 (accessed on October 2, 2010).

China Electrical Power News Network (CPNN), 2009. 西藏有望 2011 年解决电力紧缺 Tibet Looks Towards 2011 for Resolving Electricity Shortage. State Electricity Regulatory Commission (SERC), February 12, 2009. 〈http://www.serc.gov.cn/xyxx/dljs/200902/t20090212_10985.htm〉 (accessed on October 2, 2010).

China State Power Information Network (CSPIN), 2009. Power Networks—General Situations. China State Power Information Network. 〈http://www.sp-china.com/powerNetwork/gs.html〉 (accessed on October 2, 2010).

Caldes, N., Varela, M., Santamaria, M., Saez, R., 2009. Economic impact of solar thermal electricity deployment in Spain. Energy Policy 37 (5), 1628–1636.

Chaudhuri, D., 2005. A Survey of the Economic Situation in Xinjiang and its Role in the Twenty-First Century. China Report February 2005, vol. 41, no. 1, pp. 1–28. doi: 10.1177/000944550504100101.

Chien, T., Hu, J., 2007. Renewable energy and macroeconomic efficiency of OECD and Non-OECD economies. Energy Policy 35 (7), 3606–3615.

China Power Web, 2008. 青藏直流联网工程获准开展前期论证 Tibet-Qinghai Direct Current Connection Pre-Development Discussion Approved. 中国电力网 〈www.chinapower.com.cn〉, 〈http://www.chinapower.com.cn/article/1127/art1127198.asp〉 (accessed on October 2, 2010).

Cohen, G., Skowronski, M., Cable, R., Morse, F., Jaehne, C.H., Kearney, D., Kearney, S., 2005. Solar Thermal Parabolic Trough Electric Power Plants for Electric Utilities in California PIER Final Project Report. California Energy Commission. 〈http://www.energy.ca.gov/2005publications/CEC-500-2005-175/CEC-500-2005-175.PDF〉 (accessed on October 2, 2010).

Dersch, J., Geyer, M., Herrmann, U., Jones, S.A., Kelly, B., Kistner, R., Ortmanns, W., Price, H., 2004. Trough integration into power plants-a study on the performance and economy of integrated solar combined cycle systems. Energy 29 (5–6), 947–959.

Fan, J., Sun, W., Ren, M., 2005. Renewables portfolio standard and regional energy structure optimisation in China. Energy Policy 33 (3), 279–287.

Hang, Q., Jun, Z., Xiao, Y., Junkui, C., 2008. Prospect of concentrating solar power in china—the sustainable future. Renewable and Sustainable Energy Reviews 12 (9), 2505–2514.

He, J., Deng, J., Su, M., 2010. CO_2 emission from China's energy sector and strategy for its control. Energy 35 (11), 4495–4499.

Hvistendahl, M., 2008. China's 3 Gorges Dam: An Environmental Catastrophe? Scientific American, March 25, 2008. 〈http://www.scientificamerican.com/article.cfm?id=chinas-three-gorges-dam-disaster&print=true〉 (accessed on October 9, 2010).

International Energy Agency (IEA), 2003. Renewables for Power Generation: Status & Prospects, 2003 ed. OECD Publishing. doi:10.1787/9789264019195-en.

Jiang, B., Sun, Z., Liu, M., 2010. China's energy development strategy under the low-carbon economy. Energy 35, 4257–4264.

Jin, H., Lior, N., Zhang, X., 2010a. Energy and its sustainable development for China: editorial introduction and commentary for the special issue of Energy. Energy 35 (2010), 4246–4256.

Jin, H., Xu, G., Han, W., Gao, L., Li, Z., 2010b. Sustainable development of energy systems for western China. Energy 35 (11), 4313–4318.

Jones, W., 2008. How Much Water Does It Take to Make Electricity? IEEE Spectrum Online. 〈http://spectrum.ieee.org/energy/environment/how-much-water-does-it-take-to-make-electricity〉 (accessed on October 9, 2010).

Karmis, M., 2005. A Study of Increased use of Renewable Energy Resources in Virginia. The Virginia Center for Coal and Energy Research, Virginia Polytechnic Institute and State University (accessed on October 2, 2010)〈http://www.energy.vt.edu/Publications/Incr_Use_Renew_Energy_VA_rev1.pdf〉.

Knies, G., 2008. Clean power from deserts: the DESERTEC concept for energy, water and climate security. White Book, 4th ed. 〈http://www.gbv.de/dms/zbw/560021739.pdf〉 (accessed on October 2, 2010).

Kreith, F., Goswami, Y., 2007. Handbook of Energy Efficiency and Renewable Energy. CRC Press.

Li, Y., Oberheitmann, A., 2009. Challenges of rapid economic growth in China: reconciling sustainable energy use, environmental stewardship and social development. Energy Policy 37 (4), 1412–1422.

Lior, N., 1977. Solar energy and the steam rankine cycle for driving and assisting heat pumps in heating and cooling modes. Energy Conversion 16 (3), 111–123.

Lior, N., Koai, K., 1982. Solar-powered/fuel-assisted rankine cycle power and cooling system: simulation method and seasonal performance. Journal of Solar Energy Engineering 106 (2), 142–152.

Lior, N., Koai, K., 1984a. Comparative Economic Analysis of a Solar-Powered/Fuel Assisted Hybrid Rankine System. American Solar Energy Society, Including Invited Papers from the 1983 Annual Meeting.

Lior, N., Koai, K., 1984b. Solar-powered/fuel-assisted rankine cycle power and cooling system: sensitivity analysis. Transactions of the ASME Journal of Solar Energy Engineering 106 (4), 447–456.

National Bureau of Statistics of China (NBS), 2009. Statistical Communiqué of the People's Republic of China. 〈http://www.stats.gov.cn/english/〉 (accessed on October 2, 2010).

National Development and Reform Commission (NDRC), 2007a. 可再生能源中长期发展规划 (Renewable Energy Medium and Long Term Development Plan). NDRC. 〈http://www.sdpc.gov.cn/zcfb/zcfbtz/2007tongzhi/t20070904_157352.htm〉 (accessed on October 2, 2010).

National Development and Reform Commission (NDRC), 2007b. 核电中长期发展规划 2005-2020 年 (Nuclear Power Medium and Long Term

Development Plan 2005–2020). NDRC. 〈http://nyj.ndrc.gov.cn/zywx/t20071102_170108.htm〉 (accessed on October 2, 2010).

Naik, G., Oster, S., 2009. Scientists link China's dam to earthquake, renewing debate. Wall Street Journal.

Office for Official Publications of the European Communities (EU), 2007. Concentrating Solar Power: From Research to Implementation. Office for Official Publications of the European Communities. 〈http://ec.europa.eu/energy/res/publications/doc/2007_concertrating_solar_power_en.pdf〉 (accessed on October 2, 2010).

Palgrave, R., 2008. Innovation in CSP. Renewable Energy Focus, vol. 9, no. 6, November—December 2008, pp. 44–49, ISSN 1755-0084, doi: 10.1016/S1755-0084(08)70066-8. 〈http://www.sciencedirect.com/science/article/B8JJF-4V2HCWB-15/2/cb504dc6ef7d1f94f8e72ddc1f8007de〉 (accessed on October 2, 2010).

Prabhu, E., 2006. Solar Trough Organic Rankine Electricity System (STORES). National Renewable Energy Laboratory (accessed on October 2, 2010) 〈http://www.nrel.gov/docs/fy06osti/39433.pdf〉.

Rhinelander, M., 2008. Damned Rivers. Damned Lives. The Case Against Large Dams. International Rivers. 〈http://www.internationalrivers.org/files/IRfactsheet_dammed_rivers_lores.pdf〉 (accessed on October 2, 2010).

Schwer, R., Riddel, M., 2008. Potential Economic Impact of Constructing and Operating Solar Power Generation Facilities in Nevada. National Renewable Energy Laboratory, US Dept. of Energy (accessed on October 2, 2010)〈http://www.nrel.gov/csp/pdfs/35037.pdf〉.

Shealy, M., Dorian, J., 2007. Growing Chinese Energy Demand: Is the World in Denial?. Center for Strategic and International Studies (CSIS) (accessed on October 8, 2010)〈http://csis.org/files/media/csis/pubs/071019-growingchineseenergy-a.pdf〉.

Sherburne, D., Lior, N., 1986. Evaluation of Minimum Fuel Consumption Control Strategies in the Solar-powered/fuel-Assisted Hybrid Rankine Cycle. American Solar Energy Soc. (11–14 June 1986).

State Grid of China Corporation (State Grid), 2009. 国家电网公司网站首页＞电网建设＞项目核准 Grid Construction—Approved Projects, 国家电网公司 State Grid of China Corporation. 〈http://www.sgcc.com.cn/dwjs/xmhz/default.shtml〉 (accessed 29.03.2009).

Sovacool, B., 2008. Renewable energy: economically sound, politically difficult. The Electricity Journal 21 (5), 18–29.

Stoddard, L., Abiecunas, J., O'Connell, R., 2006. Economic, Energy, and Environmental Benefits of Concentrating Solar Power in California, vol. 69, SR-550-39291 ed. National Renewable Energy Laboratory (accessed on October 8, 2010) 〈http://www.nrel.gov/docs/fy06osti/39291.pdf〉.

Sundqvist, T., 2004. What causes the disparity of electricity externality estimates? Energy Policy 32 (15), 1753–1766.

Transmission & Distribution World (T&D), 2007. A New Dimension of HVDC Technology: Siemens Constructs HVDC Link in China, Taking Power Capacity to New Heights. Transmission & Distribution World, vol. 59, no. 7, p. 10. 〈http://tdworld.com/overhead_transmission/power_new_dimension_hvdc/index.html〉 (accessed on October 8, 2010).

Taggart, S., 2008. Parabolic troughs: CSP's quiet achiever. Renewable Energy Focus 9 (2), 46–48 50.

Tester, J., 2005. Sustainable Energy: Choosing among Options, vol. 846. MIT Press (p. 569).

Tillou, S., Honda, Y., 1997. Three Gorges Dam, Environment and Trade Aspects. American University, the School of International Service, Trade and Environment Database Case Studies, vol. 5, no. 1. 〈http://www1.american.edu/TED/threedam.htm〉 (accessed on October 8, 2010).

The Wall Street Journal (WSJ), 2007. China Opens Power-Grid Investment. Wall Street Journal—Eastern Edition, vol. 250, no. 141, December 15 2007, p. A4. 〈http://proquest.umi.com/pqdlink?did=1398973041&sid=1&Fmt=3&clientId=48051&RQT=309&VName=PQD〉 (accessed on October 9, 2010).

United Nations Statistics Division—Energy Statistics Database (UN Stats), 2009. Electricity, Net Installed Capacity of Electric Power Plants. United Nations. 〈http://data.un.org/Data.aspx?q=installed+capacity&d=EDATA&f=cmID%3aEC〉 (accessed on October 9, 2010).

US Department of Energy (DOE), 2009. Concentrating Solar Power. US Department of Energy. 〈http://www1.eere.energy.gov/solar/csp_program.html〉 (accessed on October 2, 2010).

US Department of State (DOS), 2009a. Toward a Deeper and Broader Relationship with China. Hillary Rodham Clinton. Secretary of State Remarks with Chinese Foreign Minister Yang Jiechi in Beijing, China, February 21, 2009. 〈http://www.state.gov/secretary/rm/2009a/02/119432.htm〉 (accessed on October 2, 2010).

US Department of State (DOS), 2009b. Dialogue on US–China Partnership on Clean Energy. Hillary Rodham Clinton. Secretary of State with Special Envoy for Climate Change Todd Stern and President of GE Energy China Jack Wen at Taiyang Gong Power Plant, Beijing, China, February 21, 2009. 〈http://www.state.gov/secretary/rm/2009a/02/119433.htm〉 (accessed on October 2, 2010).

US National Renewable Energy Laboratory (NREL), 2005. Solar: Monthly and Annual Average Direct Normal (DNI) GIS Data at 40 km Resolution for China from NREL. 〈http://swera.unep.net/index.php?id=35&idx=255#〉 (accessed on October 2, 2010).

Wang, Y., 2010a. The analysis of the impacts of energy consumption on environment and public health in China. Energy 35 (11), 4473–4479.

Wang, Z., 2010b. Prospectives for China's solar thermal power technology development. Energy 35 (11), 4417–4420.

Wolff, G., 2008. CSP concentrates the mind. Renewable Energy Focus 9 (1), 42–47.

World Bank, 2009. World Development Indicators Database. The World Bank (accessed on October 9, 2010) 〈http://data.worldbank.org/products/data-books/WDI-2009〉.

Xinhua News Agency (Xinhua), 2007a. Full Text of Hu Jintao's Report at 17th Party Congress, October 24, 2007. 〈http://news.xinhuanet.com/english/2007-10/24/content_6938749.htm〉 (accessed on October 8, 2010).

Xinhua News Agency (Xinhua), 2007b. China Warns of Environmental 'Catastrophe' from 3 Gorges Dam. Xinhua New Agency. 〈http://news.xinhuanet.com/english/2007-09/26/content_6796636.htm〉 (accessed on October 8, 2010).

Xinjiang.gov.cn (Xinjiang), 2006. Xinjiang to Complete Power Grid Incorporation in 5 Years. Gov.cn—Chinese Government's Official Web Portal. 〈http://english.gov.cn/2006-02/18/content_203547.htm〉 (accessed on October 8, 2010).

Yao, Q., Li, S., Xu, H., Zhou, J., Song, Q., 2009. Studies on formation and control of combustion particulate matter in China: a review. Energy 34, 1296–1309.

You, C., Xu, X., 2010. Coal combustion and its pollution control in China. Energy 35 (11), 4468–4473.

Zhang, P., Yang, Y., Shi, J., Zheng, Y., Wang, L., Li, X., 2009. Opportunities and challenges for renewable energy policy in China. Renewable and Sustainable Energy Reviews 13 (2), 439–449.

Zhang, X., Wang, R., Huo, M., Martinot, E., 2010. A study of the role played by renewable energies in China's sustainable energy supply. Energy 35 (11), 4392–4399.

Zhou, X., Yi, J., Song, R., Yang, X., Li, Y., Tang, H., 2010. An overview of power transmission systems in China. Energy 35 (11), 4302–4312.