Concentrating Solar Power in China and India: A Spatial Analysis of Technical Potential and the Cost of Deployment

Kevin Ummel

Abstract

Coal power generation in China and India is expected to double and triple, respectively, over the next 20 years, increasing exposure to fuel price volatility, exacerbating local air pollution, and hastening global climate change. Concentrating solar power (CSP) is a growing source of utility-scale, pollution-free electricity, but its potential in Asia remains largely unexamined. High-resolution spatial data are used to identify areas suitable for CSP and estimate power generation and cost under alternative land-use scenarios. Total technical potential exceeds current coal power output by a factor of 16 to 23 in China and 3 to 4 in India. A CSP expansion program and attendant transmission requirements are simulated with the goal of providing 20 percent of electricity in both countries by midcentury. Under conservative assumptions, the program is estimated to require subsidies of $340 billion in present dollars; coal-associated emissions of 96 GtCO2eq are averted at an average abatement cost of $30 per tCO2eq. Estimated costs are especially sensitive to the assumed rate of technological learning, emphasizing the importance of committed public policy and financing to reduce investment risk, encourage expansion of manufacturing capacity, and achieve long-term cost reductions. The results highlight the need for spatially explicit modeling of renewable power technologies and suggest that existing subsidies might be better used through integrated planning for large-scale solar and wind deployment that exploits spatiotemporal complementarities and shared infrastructure.

Keywords: solar thermal power, greenhouse gas mitigation, abatement cost, electricity generation, technological learning, energy economics, developing countries

Center for Global Development
www.cgdev.org

Working Paper 219
July 2010

Concentrating Solar Power in China and India:
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A supplemental annex with technical details is available at
http://www.cgdev.org/content/publications/detail/1424287

Many thanks to Aleh Cherp (CEU), Chris Elvidge (NOAA), Paul Gilman (NREL), Jonathan Godt (USGS), Chandra Govindarajalu (WB), Robert Hijmans (UCD), Jessica Jewell (CEU), Xiao Li, Nicholas Long (NREL), Anthony Patt (IIASA), Arijit Paul, Arvind Subramanian (CGD), and David Wheeler (CGD) for technical assistance, data, and comments. All remaining errors are the author's alone.

CGD is grateful for contributions from the Australian Agency for International Development and the UK Department for International Development in support of this work.

Kevin Ummel. 2010. "Concentrating Solar Power in China and India: A Spatial Analysis of Technical Potential and the Cost of Deployment." CGD Working Paper 219. Washington, D.C.: Center for Global Development.
http://www.cgdev.org/content/publications/detail/1424287

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FOREWORD

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The power sector accounts for about 29% of global greenhouse gas emissions. In this sector, mitigation requires switching from fossil fuels to low-carbon energy sources, principally solar, wind, biomass, geothermal, hydro and nuclear. The conventional narrative assigns the task of clean energy development to rich countries because it is perceived as too costly for poor countries. The reality, however, is far different: Since 1990, developing countries have accounted for 55% of the global increase in low-carbon energy generation. Since 2000, China and India have exceeded the U.S. and matched other rich countries in their share of national income devoted to subsidizing low-carbon energy (Wheeler 2010). And both have announced ambitious plans for renewable energy development during the coming decade (Wheeler and Shome 2010).

Kevin Ummel's pathbreaking new paper shows how concentrating solar power (CSP) can contribute to the realization of these plans. Kevin's paper builds on his prior work, which supported the Clean Technology Fund's pioneering investment in North African CSP (Ummel and Wheeler 2008). He demonstrates that India and China have enormous solar potential; identifies their feasible generation sites; and analyzes the cost of a CSP development program that can deliver 20% of their total power generation by 2050. Under reasonable assumptions about learning and scale economies, this program will make CSP cost-competitive with coal-fired power within two decades.

How much will this ambitious program cost, and will India and China be willing to pay for it? Kevin estimates that the forty-year subsidy cost will be about $211 billion for China and $129 billion for India. For comparison, Saurabh Shome and I estimate that India's recently-announced renewable energy plan entails a subsidy cost of about $50 billion *for the current decade alone* (Wheeler and Shome 2010). Let us assume that China and India sustain their recent economic growth and simply maintain their current income shares devoted to subsidizing renewable energy development (Wheeler 2010). In that case, China and India will spend $1.3 trillion and $243 billion respectively by 2050 – more than enough to finance Kevin's proposed program, with enormous sums remaining for further development of solar and other renewables.

The message here is clear: Kevin's visionary proposal for India and China falls squarely on the ambitious path that they show every indication of following. Now the onus shifts to the U.S. and other rich countries: Will they match this vision and level of ambition? If so, we may yet solve the carbon emissions problem.

I. Introduction

Concentrating solar power (CSP) refers to a class of utility-scale technologies that use sunlight and mirrors to generate electricity via steam turbines or Stirling engines (Figure 1). Given the abundance of solar energy and the comparative simplicity of required engineering and materials, CSP is a potential source of low-cost, renewable power in areas with appropriate terrain and radiation (Trieb et al. 2005; Richter et al. 2009; Staley et al. 2009). More than 500 MW of generating capacity are operating worldwide and more than 1,000 MW are under construction (NREL 2010). In California, authorities are reviewing plant proposals totaling nearly 5,000 MW and land permitting requests have been received for an additional 24,000 MW (CEC 2010).

CSP is also growing in Europe and North Africa, where the Union for the Mediterranean Solar Plan has called for the deployment of 20,000 MW by 2020. In December, the World Bank Clean Technology Fund approved $750 million in financing to support the deployment of 1,000 MW in five North African countries, with the aim of promoting cost and risk reductions. Proposals for rapid scale-up in the Mediterranean could make power generated in North African deserts and exported via high-voltage transmission lines cheaper than European coal power within a decade given moderate public subsidies (Ummel and Wheeler 2008; Williges et al. 2010).

In China and India, where business-as-usual scenarios project CO_2 emissions from coal-fired power plants to nearly double over the next 20 years, the need for large-scale, cost-competitive, clean electricity is urgent (IEA 2009). Both countries have outlined ambitious plans for solar power expansion, prompting growing interest in CSP (Hang et al. 2008a; Hang et al. 2008b; Hou et al. 2009; Li 2009; Zhou and Yang 2009; Purohit and Purohit 2010; Wang 2010). Partnering of domestic and foreign firms is emerging – Tata and BP in India; Penglai Electric and eSolar in China, for example – to facilitate the transfer of established CSP technology to these rapidly growing markets (Bradsher 2010; Purohit and Purohit 2010).

Recent efforts to estimate global potential show that China and India contain areas with suitable terrain and solar radiation, but detailed analyses of technical and economic feasibility are lacking (Breyer and Knies 2009; Trieb et al. 2009). This study provides an in-depth assessment of CSP potential in China and India using high-resolution spatial data for site selection and modeling of plant performance, assessment of alternative land-use scenarios, estimation of generating costs, and simulation of transmission requirements. The results are used to estimate the costs and GHG abatement of an illustrative CSP expansion program that provides 20% of Chinese and Indian electricity by midcentury.

Figure 1: Parabolic trough, tower, and dish CSP technologies

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II. TECHNICAL POTENTIAL

Data and methodology

The European Space Agency's Globcover product provides composite land cover classification at a cell resolution of ~300 meters (10 arc-seconds), allowing for high-resolution screening of potential CSP sites (Bicheron et al. 2008). Additional spatial screens were created from secondary datasets with native ~1 km resolution. Geomorphological features like sand dunes, rock outcrops, salt flats, and glaciers were excluded, as were areas with terrain slope greater than 3% or population density above 150 persons per km^2; safety buffers were applied to treacherous landforms or areas with evidence of water, flooding, or artificial surfaces (Verdin et al. 2007; ORNL 2008; FAO et al. 2009).

Suitable areas were identified according to three land-use scenarios. Scenario 1 is the most stringent, only allowing construction on ground that is bare or covered with sparse or herbaceous vegetation and excluding reserves, parks, and other protected areas (IUCN and UNEP 2009). Scenario 2 is the same as Scenario 1 but allows construction in protected areas. Scenario 3 is the same as Scenario 2 but also considers rainfed cropland. All other spatial screens (terrain, population, etc.) are the same across scenarios.

Hourly weather data were procured for about 2,000 sites globally, from which 40 were identified as representative of potential CSP locales. For each site, NREL's Solar Advisor Model (SAM) was used to simulate the cost-minimizing design and performance for a dry-cooled, parabolic trough CSP plant (Gilman et al. 2008). Regression analysis of results was used to estimate capacity factor and a relative cost index on the basis of site-specific solar radiation and latitude (Figures A1 and A2 in Annex). Data for average annual solar resource (direct normal irradiance) are modeled values derived from satellite and surface observations and are accurate to within approximately 10% of the true value (NREL 2005).[1] Land requirement is assumed to be constant across locales and is based on current proposals in California that suggest a 250 MW parabolic trough plant will require approximately 6.5 km^2. See the Annex for details.

Results of overlay analysis

Figures 2 through 5 show the spatial distribution of potential CSP sites for each of the three land-use scenarios in China and India and high-resolution insets for Beijing and Delhi. Note that the images display the *additional* terrain available under Scenarios 2 and 3. Insets for other urban areas are available in the Annex.

[1] Cells with average DNI below 4.7 $kWh/m^2/day$ were considered un-exploitable and were not included.

Figure 2: Location of potential CSP sites in China

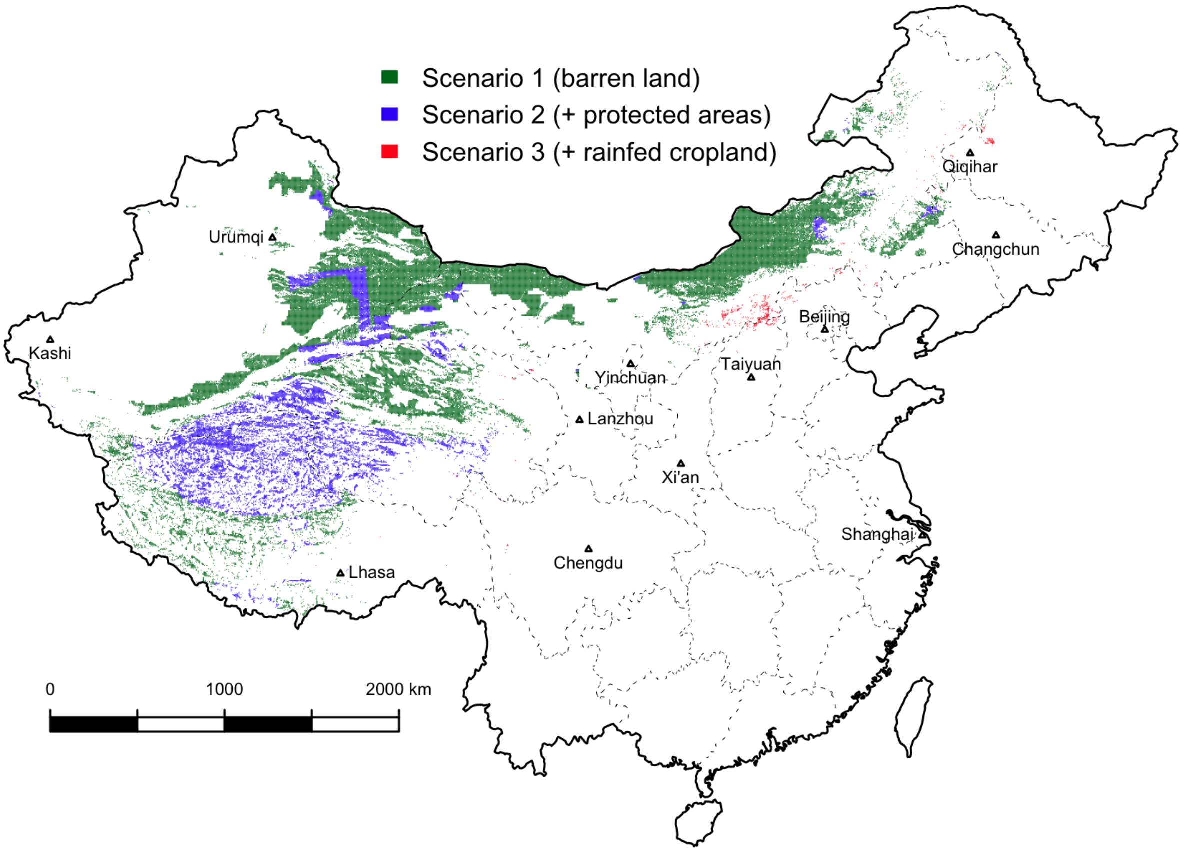


Figure 3: Inset of Beijing, China

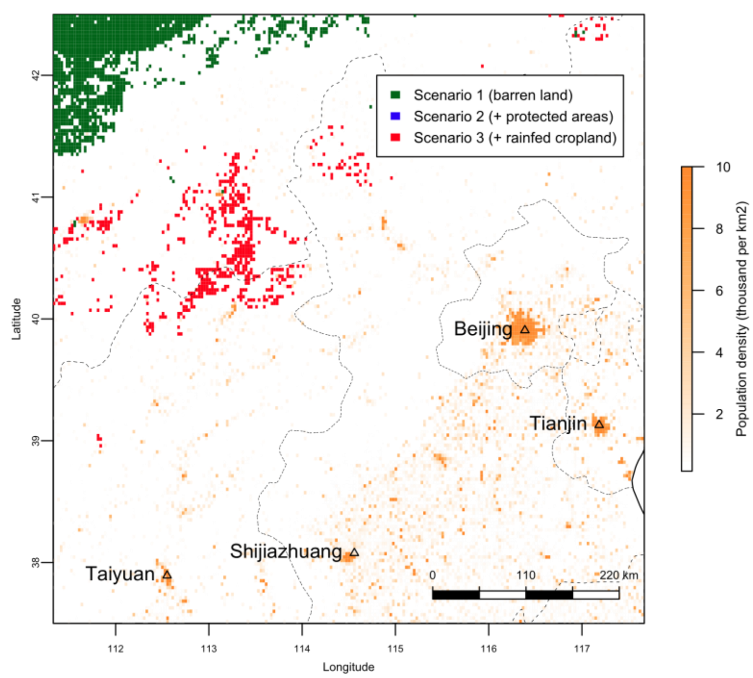


Figure 4: Location of potential CSP sites in India

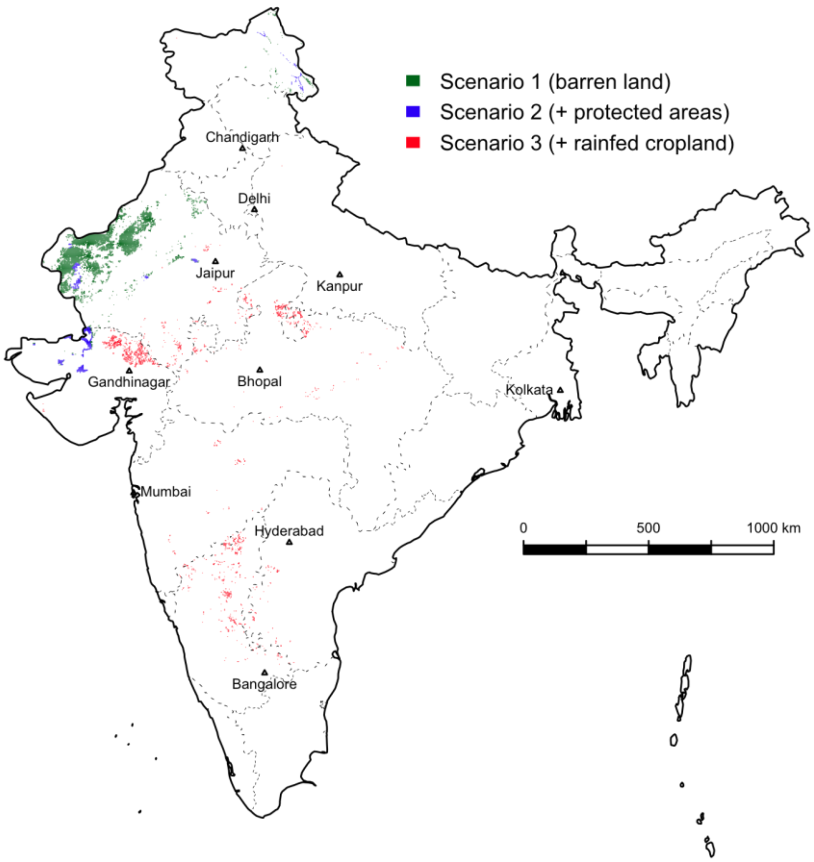
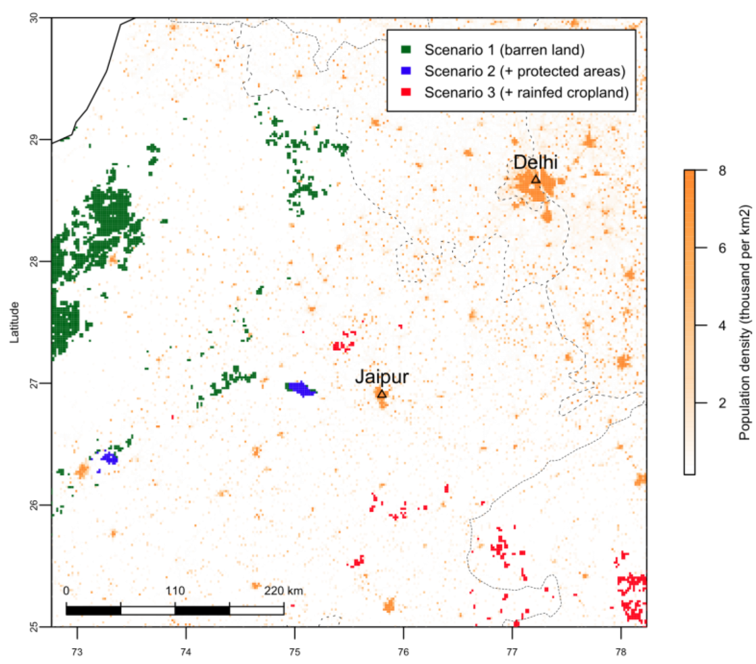


Figure 5: Inset of Delhi, India



Total technical potential

Table 1 reports national totals for potential CSP area and power output and the coal power generating capacity required to deliver an equivalent amount of electricity. The Annex provides totals by province.

Table 1: Country totals for CSP potential output, area, and coal capacity equivalent[2]

	Scenario 1	Scenario 2	Scenario 3
China	51,133 TWh_e/y	71,461	71,858
	689,103 km^2	912,356	918,290
	6,486 GW coal-eq	9,064	9,114
India	2,324	2,648	3,334
	28,364	32,432	41,476
	295	336	423

Under the most stringent land use scenario, potential CSP output in India is three times greater than coal generation today and exceeds projected coal power in 2030 by 20%. In China, potential output exceeds present coal generation by a factor of 16 and exceeds 2030 projections by a factor of seven (IEA 2009). Similar figures emerge when CSP potential is compared to domestic coal reserves. China's proved reserves could generate about 235 thousand TWh – equivalent to five years of CSP output under Scenario 1. India's reserves amount to about 120 thousand TWh – equivalent to 50 years of CSP output (BP 2009).[3]

Potential output in both countries is much lower than that estimated by Trieb et al. (2009) – 60% lower in China and 80% lower in India. About two-thirds of the difference in China and 95% of the difference in India is apparently due to different land-cover data and/or more restrictive land-use requirements (e.g. safety buffers near water and geomorphologic hazards and exclusion of areas not part of contiguous tracts). The remaining differences are presumably due to different solar radiation data, modeling of plant performance, and assumed space requirements.

III. Spatial Distribution of Supply

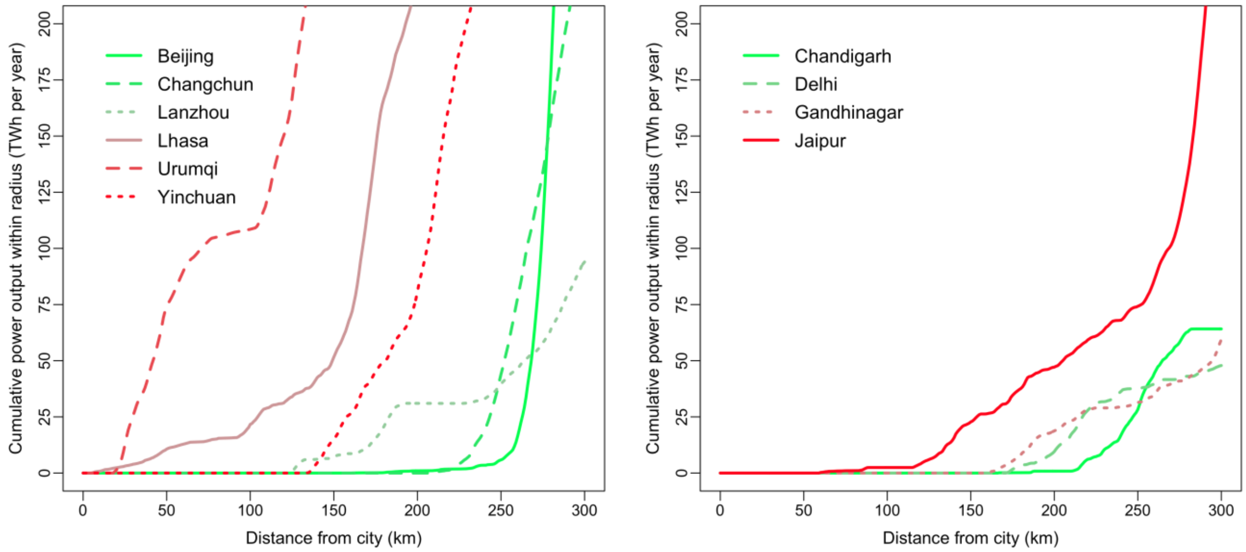
Proximity of supply to urban centers

The distance of CSP potential from demand centers is an important consideration. There are two options for power transmission over distance: high-voltage alternating current (HVAC) or direct current (HVDC). HVAC is typically the least-cost option for distances up to 500-800 km (Meah and Ula 2007). Large-scale CSP deployment will likely require dedicated HVDC infrastructure to exploit remote areas and integrate regional power grids, but *initial* CSP projects could attempt to utilize existing transmission infrastructure where possible, placing a premium on sites close to demand centers. Figures 6 and 7 report the proximity

[2] The coal capacity equivalent is the total coal power plant capacity required to generate an equivalent amount of electricity, assuming a capacity factor of 90%.
[3] Assumes an average coal consumption rate of 0.48 tons per MWh given total proved reserves of 114,500 million tons (China) and 58,600 million tons (India).

of potential CSP production to select cities in China and India for distances up to 300 km, assuming land use Scenario 1.

Figures 6 and 7: Proximity of select cities to CSP potential in China (left) and India (right) under Scenario 1



To put the scale of the figures in perspective, annual power consumption is about 70 TWh per year in Beijing and 25 TWh per year in Delhi. The results suggest there is sufficient CSP potential within 275 km of the Chinese capital and 225 km of the Indian capital to meet current electricity demand. Figures A12 and A13 in the Annex show the proximity of CSP potential under Scenario 3, which allows for utilization of rainfed cropland; small areas of such land (~14 km^2 per TWh per year) could supply a number of urban areas using short-distance transmission.

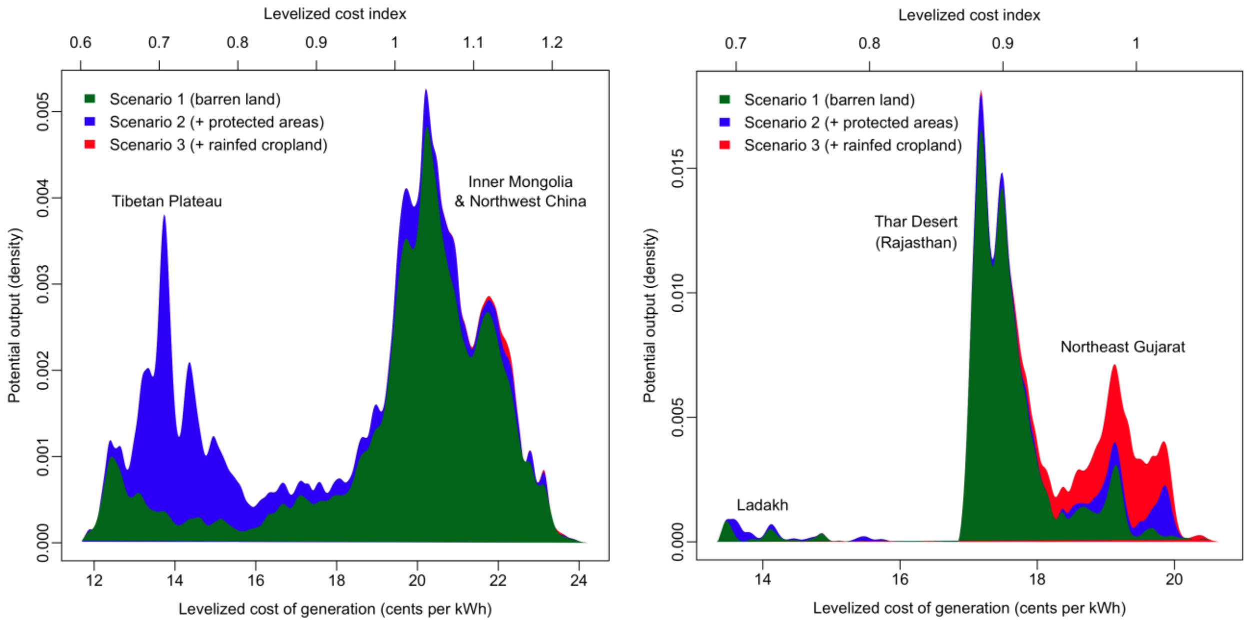
<u>*Distribution of generating costs*</u>

For a given level of capital and operating costs, the levelized cost of electricity (LCOE) for CSP plants exhibits a log-log relationship with available solar radiation and latitude (implied in Figures A1 and A2 in Annex). The corresponding *absolute* cost is difficult to estimate, especially since there is little experience with projects in China and India. Using reported capital costs from the ANDASOL-1 (trough) and PS-10 (tower) CSP plants in Spain, Purohit and Purohit (2010) calculate a LCOE of ~20 cents per kWh for areas in India's Rajasthan state. Costs reported by Williges et al. (2010) translate to a LCOE of ~21 cents per kWh for similar locales.

Actual costs are likely less due to lower in-country material and labor prices; reported capital costs for coal and gas power plants are 15-25% lower in India than in the U.S., and Chinese wind turbines cost ~30% less than in the U.S. (DOE 2008; ESMAP 2008; McElroy et al. 2009). A possibly conservative assumption of 15% lower in-country costs give a LCOE of ~17.5 cents per kWh for Rajasthan and is used to anchor the modeled relative cost index (17.5 cents per kWh ≈ 0.9 index value).

Figures 8 and 9 show the density distribution of generating costs for each of the land use scenarios. This is the cost of electricity without considering transmission. China exhibits a bimodal distribution, with large quantities of low-cost potential in high-radiation sites on the Tibetan Plateau and a vast amount of more costly generation potential to the north. Radiation levels on the Tibetan Plateau are exceptional and drive the 30-40% lower LCOE than that estimated elsewhere in the country, though much of this potential is in protected areas. India's potential is concentrated in the Thar Desert region, but significant amounts are also available on rainfed cropland in northeast Gujarat. A relatively small but still significant amount of low-cost potential exists in the Ladakh region of Jammu and Kashmir.

Figures 8 and 9: Distribution of potential generating cost in China (left) and India (right)



The levelized cost estimates presented throughout this paper assume that CSP construction costs do not differ across locales; that is, differences in the LCOE index are determined solely by the modeled relationship between solar radiation, latitude, and plant efficiency. In practice, some locales will face site-specific conditions (lack of transport access or nearby labor supply, for example) that impact costs and are not captured here.

IV. Cost of Transmission

<u>Data and methodology</u>

The economic potential of a given CSP locale depends on the tradeoff between on-site efficiency and off-site transmission costs. This tradeoff can be tested explicitly by estimating the cost of transmission between sites of supply and demand. Determining transmission requirements for large-scale, cost-effective CSP deployment ideally incorporates detailed data on the location, capacity, and loads of existing transmission infrastructure. In the absence of such data, a necessarily simplified algorithm was developed to approximate the additional cost of transmitting electricity from potential CSP sites to consumption centers under cost-minimizing conditions.

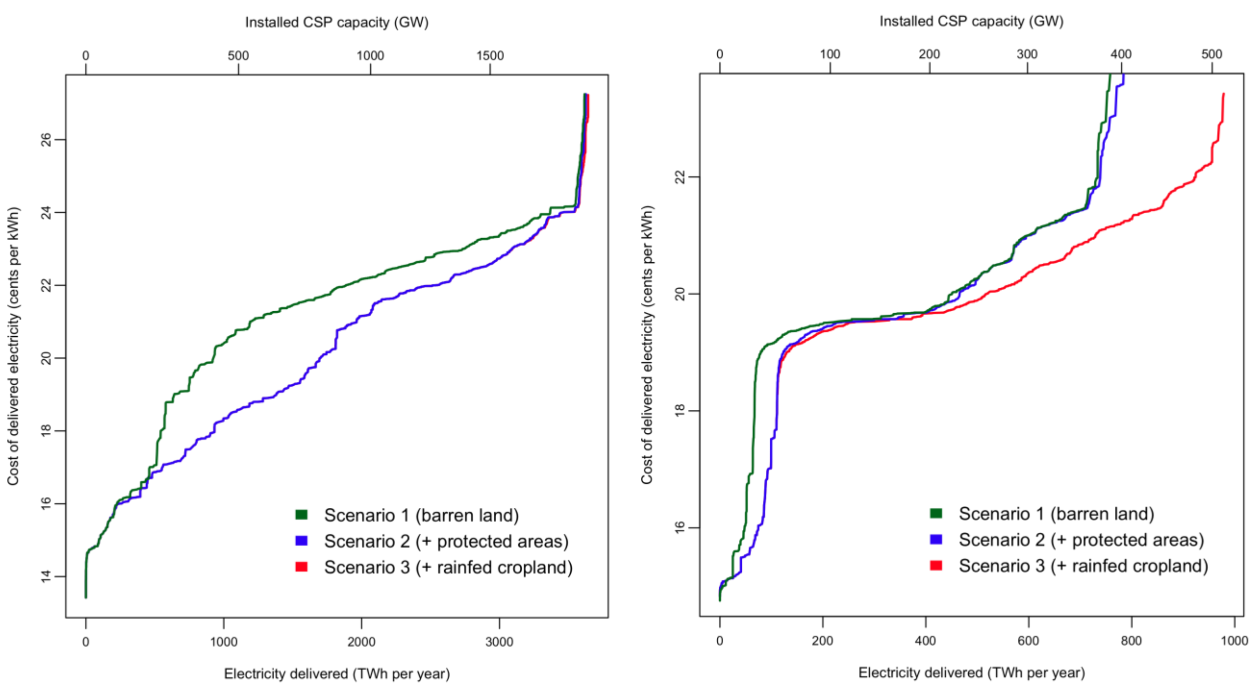
The algorithm requires information on the spatial distribution of electricity demand. The magnitude of stable nighttime light detected by satellites has been correlated with electricity consumption and is used here to allocate national consumption across grid cells (Amaral et al. 2005; Chand et al. 2009; Letu et al. 2009; NOAA 2009). After initial allocation, demand is summed at the provincial level and compared to official data; estimated and actual values show high correlation, suggesting nighttime lights is an acceptable predictor (Figures A4 and A5 in Annex). Grid cell estimates are then adjusted so that provincial totals match official data (see Annex for details). In order to capture the effect of rising electricity demand over time, projected changes in the spatial distribution of population in 2025 are used to “scale-up” present day electricity demand (Hachadoorian et al. 2007). The resulting data show the estimated location and magnitude of power consumption in 2025 and are used as the basis for allocating CSP supply.

The straight-line distance between every pair of supply (potential CSP sites) and demand cells was calculated, and the supply cell’s modeled LCOE index value was revised upward to reflect the additional costs of transmission infrastructure, load balancing, and power losses for the distance in question (see Annex for details and cost assumptions**)**. The algorithm begins with the lowest-LCOE pairing and allocates output to the demand cell, updating remaining supply and demand data before proceeding to the next least-cost pairing. It is assumed that no more than 50% of demand in a given demand cell can be met with CSP.

Cost of supply curve

Results from the transmission simulation provide an estimate of the relationship between the cost of delivered electricity and cumulative CSP output, providing insight into the economic potential of large-scale CSP deployment. The marginal cost of deployment rises as total (cumulative) CSP output increases and the best locales are exploited. Figures 10 and 11 show the results for China and India under alternative land-use scenarios.

Figures 10 and 11: Simulated CSP supply curve for China (left) and India (right) given current costs



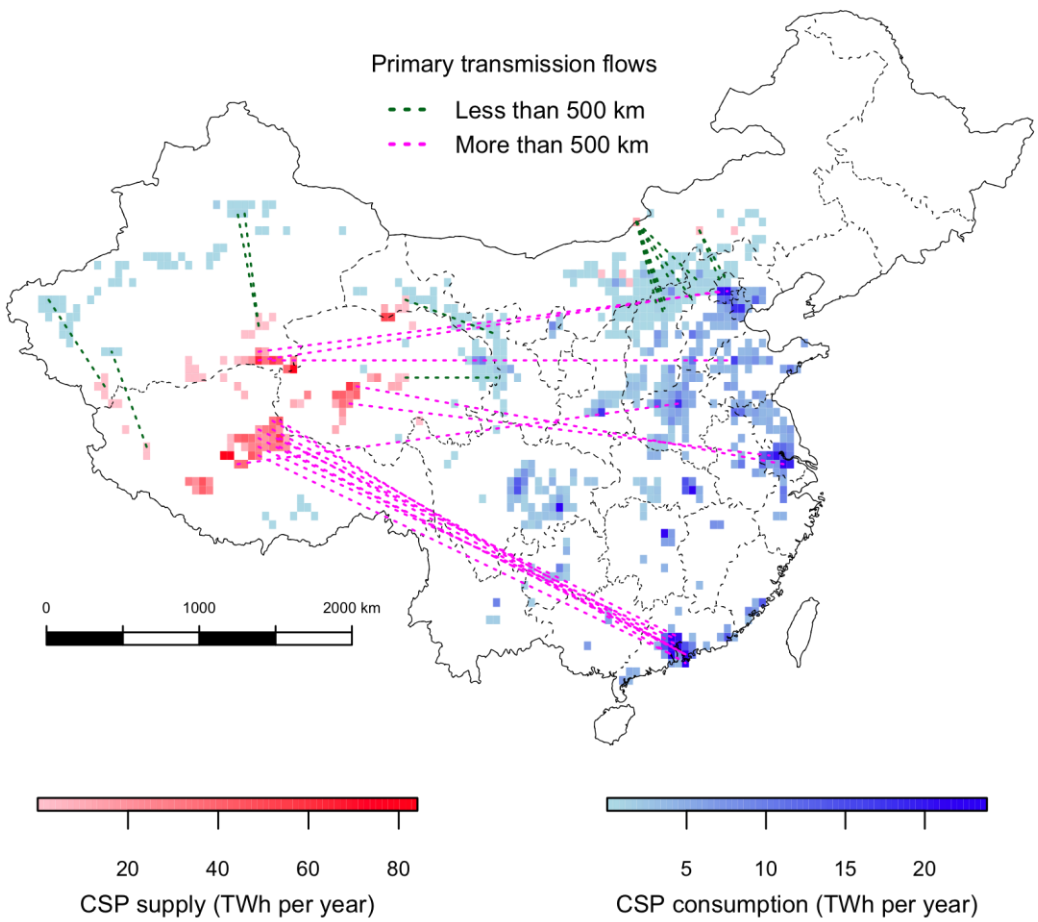
Experience with solar and other alternative energy technologies shows that capital costs typically fall 5% to 20% for every doubling of installed capacity (Junginger et al. 2008; Neij 2008). For an emerging technology like CSP, experience and economies of scale obtained at early stages of deployment can quickly drive down costs. The initial slope of the supply curve is important, because it determines how costly the learning period will be. In this respect, China has a considerable advantage with supply of ~500 TWh per year exploitable at costs up to 16 cents per kWh. In contrast, the cost of supply increases sharply in India before leveling off at about 19 cents per kWh at ~150 TWh per year.

Differences between land use scenarios are also of interest. In China, there is an advantage offered by sites in protected areas, mainly on the Tibetan Plateau, once exploitation exceeds ~500 TWh per year. In India, protected areas offer a small advantage at lower levels of deployment; rainfed cropland near population centers becomes an important means of restraining costs beyond ~400 TWh per year. With the exception of some protected areas in the Ladakh region, competition among land-use scenarios at low levels of deployment is minimal; initial construction on barren land is economically (and, most likely, environmentally) optimal.

Potential transmission flows

The transmission simulation provides information on the approximate flow of CSP electricity given the assumed cost structure and spatial distribution of supply and demand. Figures 12 and 13 show the simulated distribution of CSP output, consumption, and primary transmission flows under a CSP expansion program described in the following section. The results should *not* be interpreted as recommended transmission lines or corridors; they are meant only to show the major flows between regions. Actual transmission requirements depend upon the complex interaction of regional grids and local geography that are not captured here.

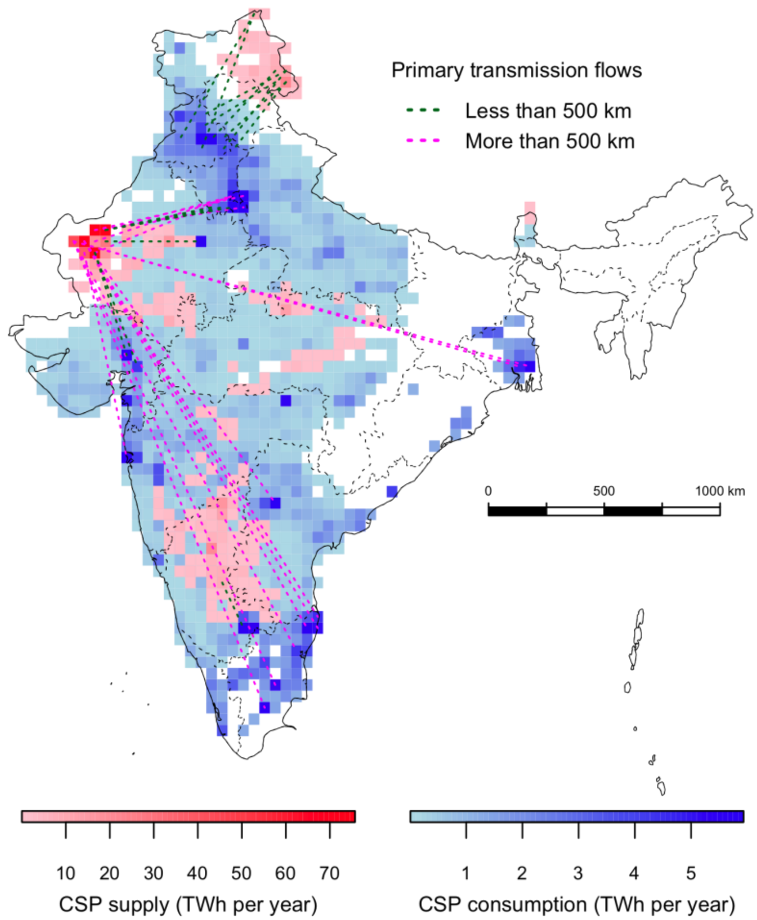
Figure 12: Simulation results for CSP expansion in China (20% of power by 2040-2050; land use Scenario 3)



The results for China reveal concentration of generation on the Tibetan Plateau, where higher efficiencies and lower generating costs offset the additional cost of transmission to eastern cities. Three primary, long-distance transmission flows bring power from the plateau to the Hong Kong, Shanghai, and Beijing areas.

Shorter distance transmission moves a large amount of power from limited sites in Inner Mongolia to population centers in Shanxi and Hebei. The western urban centers of Kashi and Urumqi utilize CSP output generated within Xinjiang.

Figure 13: Simulated results for CSP expansion in India (20% of power by 2040-2050; land use Scenario 3)



India exhibits high concentration of generation in the Thar Desert region, with considerable long-distance transmission to major population centers in the south and east. A large amount of Indian CSP output is consumed in Delhi, Haryana, and Punjab, drawing upon supply sites in both Rajasthan and Jammu and Kashmir. Population centers in Gujarat are also well positioned to extract power from Rajasthan. At higher levels of deployment, utilization of rainfed cropland becomes economically feasible (Figure 11), leading to smaller-scale generation in the south and center of the country.

Figures A14 and A15 in the Annex plot the relationship between cumulative CSP supply and the distance from production to consumption sites for each transmission dyad. The results show very different patterns between countries. Much of India's early CSP deployment requires relatively short linkages between supply and demand (typically <500 km); only beyond cumulative production of ~600 TWh per year do 1,000 km or longer linkages become desirable. China's deployment, on the other hand, utilizes long-distance (>1,500 km) transmission almost from the start, consistently moving large amounts of power from western production sites to eastern cities.

V. COST OF RAPID DEPLOYMENT

Data and methodology

A key question is whether alternative energy technologies like CSP can be driven down the “learning curve”, reducing costs over a short period of rapid deployment and eroding (or possibly eliminating) the financial advantage of coal power. An illustrative expansion program is simulated, whereby CSP meets 20% of power supply in both countries by the end of a 30 year period. This amounts to total deployment of ~1,000 GW (~2,100 TWh per year) in China and ~500 GW (~1,000 TWh per year) in India, following the expansion schedule in Figure A6.

The default power supply technology is supercritical coal combustion. Reported capital costs and “reference” (medium-variant) coal price projections give a present-day LCOE of 4.7 cents per kWh for new builds (Chen and Xu 2010). Supercritical technology is considered mature, and no capital cost reductions occur over time. The cost of steam coal changes according to extrapolation of IEA scenarios (low, reference, and high), resulting in an uncertainty band around the reference scenario through time. Costs are assumed to be equal in China and India.

CSP begins at the previously determined reference cost of 17.5 cents per kWh without transmission for an index value of 0.9; an uncertainty band of +/-15% is included. Results of the transmission simulation are used to deploy CSP in a cost-minimizing manner. The levelized cost of new builds changes over time according to the net effect of the assumed learning rate and program expansion (-) and movement up the supply curve (+) as prime sites are utilized. Despite the assumption of falling capital costs in response to deployment, it is possible for the cost of new builds to *increase* over time if the supply curve is sufficiently steep.

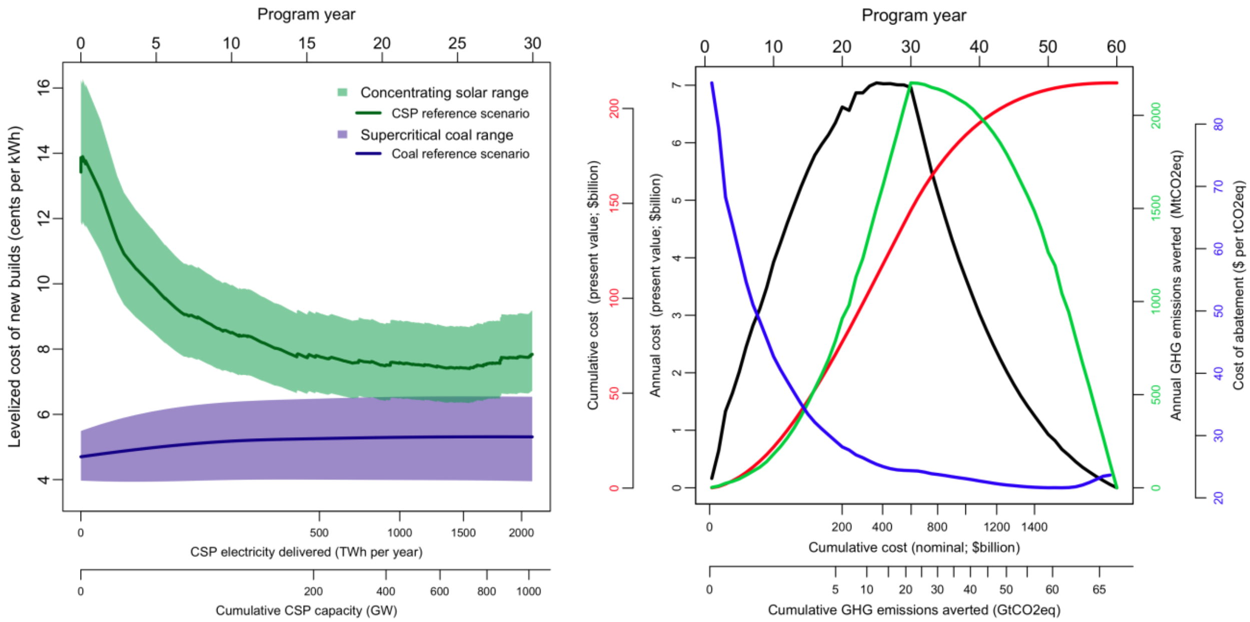
The cost differential between coal and CSP is covered by public subsidies and amounts to a preferential feed-in tariff for the 30-year life of a plant based on the cost gap at the time of construction. Consequently, program costs continue beyond the 30-year period of CSP construction as plants receive payments throughout their operating life.

Averted coal plant emissions are assumed to be 913 kg CO_2 per MWh (Wang and Nakata 2009). In addition to this direct mitigation is the indirect avoidance of GHG emissions associated with upstream (coal mining, transport, and plant construction) and downstream (decommissioning and waste disposal) processes over the lifetime of a counterfactual coal plant. Estimates of the indirect component are less certain; 175 kg CO_2eq per MWh is taken as representative of existing studies (Weisser 2007). Lifecycle emissions from CSP operation are thought to be ~50 kg CO_2eq per MWh, giving a *net* abatement of 1,038 kg CO_2eq per MWh (Piemonte et al. 2010).

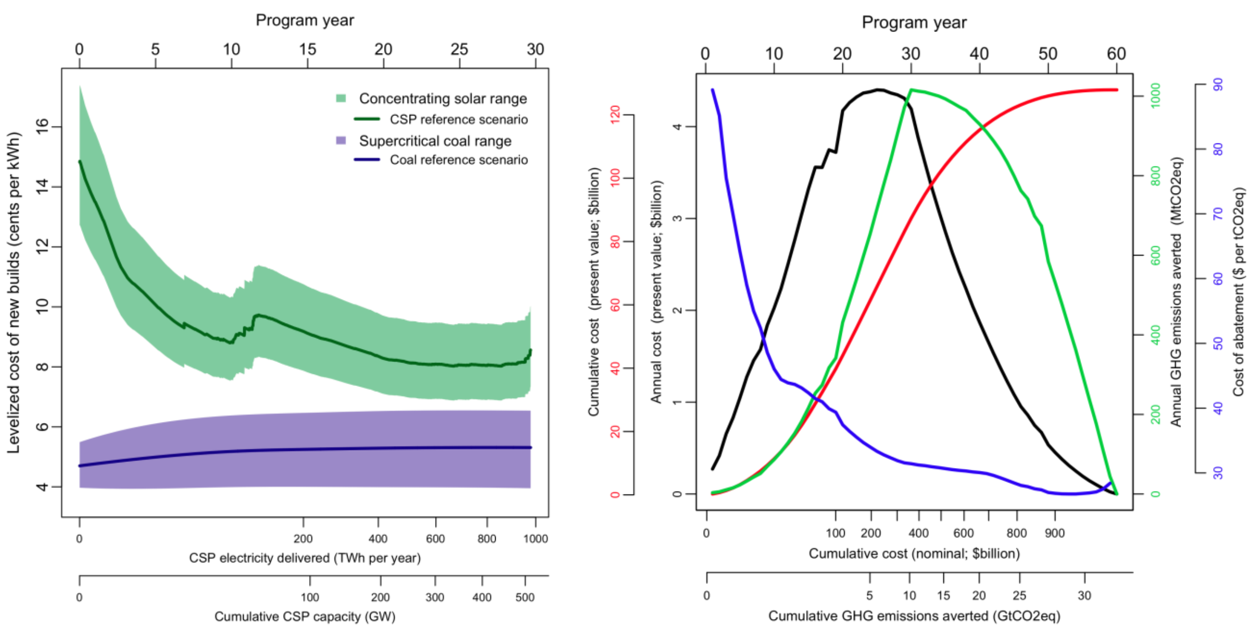
Expansion program results

Figures 14 through 17 report complete model results for China and India. A learning rate of 10% is assumed and a discount rate of 7% used in all calculations of present value. The financial and abatement calculations (right side) assume the reference cost scenario.

Figures 14 and 15: Expansion program results for China (10% learning rate, 7% discount rate)



Figures 16 and 17: Expansion program results for India (10% learning rate, 7% discount rate)



Under the reference cost scenario and a 10% learning rate, the total cost (required subsidization) of the expansion program is ~$340 billion in present dollars (62% in China; 38% in India). Since the costs are spread over 60 years, the nominal cost is far higher (~$2.5 trillion) and amounts to subsidizing one-third of the total cost of CSP over the life of the program.[4] To put these figures in comparison, consider that the *highest* annual subsidies occur in year 30 at a cost of $53 billion in China and $32 billion in India. Even if

[4] Meeting 20% of projected electricity demand in 2040-2050 with coal costs nearly $5 trillion under the reference cost scenario. CSP, then, requires total investment of ~$7.5 trillion, of which one-third is subsidized.

the populations of those countries paid the full bill, it would amount to perhaps a 0.15% reduction in per capita income in 2045.[5]

The levelized cost of new CSP builds (including transmission) falls about 40% in both countries over the course of deployment. On the basis of the learning rate effects alone, one would expect the cost to fall about 60%, implying that treating CSP potential in a spatially explicit manner – that is, taking into account the constraints imposed by the spatial distribution of CSP supply and demand – offset one-third of capital cost reductions over time. This can be seen most clearly in Figure 16, where the cost of new CSP builds in India increases substantially after program year 10; this corresponds with a sharp increase in the supply curve (Figure 11).

Total GHG emissions averted are ~96 GtCO_2eq over the life of the program – equivalent to more than 12 ppm of atmospheric CO_2. The average cost of abatement is ~$30 per t$CO_2$eq in present dollars. The cost of abatement (nominal) declines rapidly over time, from an initial cost of ~$90 per t$CO_2$eq to $22-$27 per tCO_2eq by year 60. The behavior of the abatement cost over time highlights the effect of early funding for technologies with high potential for cost reductions over time.

Uncertainty, diurnal pricing, and co-benefits

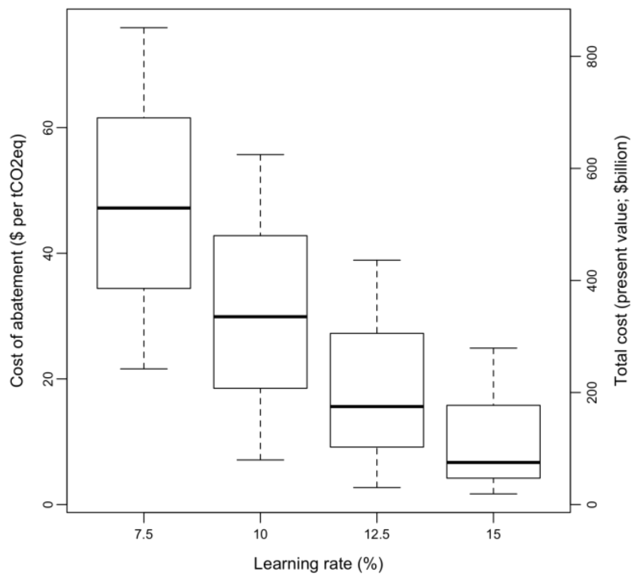
Results vary considerably depending on the assumed learning rate and cost trend. For the default learning rate of 10%, assuming low steam coal and high initial CSP costs increases total subsidies by ~85% relative to the reference scenario. Assuming the reverse cost structure reduces subsidies by ~75%. This is not surprising given the ~30% difference between high and low cost assumptions for both steam coal and initial CSP construction costs. The probability of such extremes should be considered low, however, given the unlikelihood of CSP and coal costs exhibiting a strong negative correlation.

The more important source of uncertainty is the assumed learning rate, which, along with the supply curve, determines the degree of CSP cost reduction over time. A value of 10% is typically reported as reasonable learning rate for CSP and other renewable energy technologies based on their experience so far. Assessment of published learning rates for wind power gives the probability distribution in Figure A7 in the Annex and suggests a mean value of ~12.5% (Junginger et al. 2008; Kahouli-Brahmi 2008). Assuming wind is an appropriate comparator, this learning rate results in a total program cost of ~$180 billion in present dollars and an abatement cost of ~$16 under reference cost assumptions. Figure 18 summarizes total program and abatement costs under varying cost and learning rate assumptions; the dark horizontal lines refer to the reference cost scenario.

At learning rates above ~14%, assuming reference case costs, CSP achieves cost parity with coal in both countries before the end of expansion. At a 15% learning rate, Chinese CSP reaches parity at about program year 15; India in year 20. This is a critical point as no subsidies are required beyond it; the cost of program-wide abatement is almost negligible in such cases since emissions averted after parity are the indirect result of cost reductions spurred by earlier subsidies. Figures A16 through A19 in the Annex report expansion program results for the case of a 15% learning rate.

[5] Based on author's extrapolation of IEA reference scenario for GDP (PPP) and population.

Figure 18: Total program cost with varying learning rates and cost assumptions



Using learning rates calculated from past and comparatively limited experience to project cost reductions 30 years into the future is an admittedly tenuous proposition that ignores the particular circumstances of manufacturing, procurement, and policy. Nor is it clear that the *total* increase in CSP capacity in Asia should drive cost reductions in both China and India, as is assumed here. Perhaps efficiency and manufacturing improvements will be entirely local, with little experience sharing between countries – or perhaps the global expansion of CSP, driven by deployment in the U.S. and Mediterranean, will demand the mass production of key CSP components, reducing costs more quickly.

It is also admittedly unrealistic to suppose identical demand curves for CSP and coal, as is the implicit assumption here. In both China and India, CSP potential is generally located west of major demand centers (often by a few hours), allowing production to coincide with midday and early evening peak use periods. In the European context, where time of use pricing is common, the resulting discrepancy in *average* revenue per kWh between coal and CSP significantly benefits the latter's financial outlook.[6] Though retail power *prices* in China and India may exhibit little diurnal variation, this is unlikely to reflect the underlying economic *cost* of peak-time generation and reflects an indirect subsidy to coal power that could be redirected to CSP.

Reduced coal power generation also improves air quality, primarily via reduced particulate matter. Studies of air quality co-benefits in response to GHG mitigation estimate a median benefit of $43 per tCO_2 averted in developing countries (Nemet et al. 2010). Markandya et al. (2009) estimate reduced health costs of ~$6 and ~$46 per tCO_2 averted in China and India, respectively. This translates to indirect savings in India of ~$150 billion in present dollars over the course of the CSP expansion program, more than offsetting total subsidies. Smaller but still significant savings of ~$40 billion occur in China, offsetting nearly 20% of subsidies.

An additional benefit is reduced water consumption. Dry-cooling of turbine exhaust significantly reduces water needs of steam-based CSP plants. Total water demand of dry-cooled systems (as modeled here) is

[6] Due to the diurnal variation of CSP output and electricity market prices, the potential average revenue for non-storage CSP plants in North Africa exporting to European markets is estimated to be roughly 30% higher than that of coal plants within Europe (Ummel and Wheeler 2008).

only 6 to 10% of wet-cooled CSP alternatives or conventional coal or nuclear power stations (DOE 2010). It is possible to imagine on-site rainfall collection and storage, using the solar arrays for catchment while in the stowed position during downpours. Assuming one-quarter of rainfall is captured, meeting parabolic trough water requirements would require annual precipitation of at least 100 mm. Overlay of precipitation data suggests that more than 99% of potential CSP sites in India exceed this minimum. About one-half of Chinese sites do, with exclusion limited to remote areas in the northwest.

V. CONCLUSION

Total technical CSP potential is estimated to exceed current coal power output by a factor 16 to 23 in China and 3 to 4 in India. The expected cost of generation varies considerably across locales; the largest source of low-cost CSP is the Tibetan Plateau (China), followed by the Thar Desert (India). A necessarily simplified simulation of transmission requirements and costs results in different patterns of least-cost deployment. China requires long-distance transmission from the Tibetan Plateau to eastern consumption centers, though limited sites in Inner Mongolia provide significant power to areas around Beijing. India is able to exploit overall greater proximity of supply and demand, requiring long-distance transmission from Rajasthan to the south and east only at later stages of deployment.

Modeling of a CSP expansion program designed to provide 20% of power in China and India by midcentury suggests the cost of delivered electricity (including transmission) declines ~40% over 30 years, assuming a learning rate of 10%. Future costs are about one-third *higher* than predicted by the learning rate alone due to the use of supply curves that account for utilization of increasingly higher-cost sites.

Under a moderate cost scenario, the expansion program requires subsidies of ~$340 billion in present dollars. Greenhouse gas emissions of 96 $GtCO_2eq$ are averted, with the cost of abatement declining from ~$90 to ~$22 per tCO_2eq over the course of the program, yielding a project-wide abatement cost of $30 per tCO_2eq. Assuming an alternative learning rate comparable to the past experience of wind power (~12.5%) reduces costs by nearly 50%.

These values are subject to considerable uncertainty, especially concerning the degree of technological learning in response to rapid deployment, but the large technical potential suggests CSP could play an important role in the energy futures of both China and India. Existing solar power targets are small compared to the available resource. In India, for example, the government plans to install 20 GW of solar power by 2020 and 200 GW by midcentury; this analysis suggests CSP alone could reach far higher levels of penetration.

With respect to GHG mitigation, the long-term, marginal cost of abatement in the reference scenario compares favorably with economy-wide estimates and suggests that a CSP expansion program is economically defensible at global GHG stabilization targets of 550 to 650 ppm CO_2eq or lower (Enkvist et al. 2007; Kuik et al. 2009). Yet existing mitigation proposals imply stabilization (if any) at far higher levels (Sawin et al. 2009).

In the absence of biting, market-based mechanisms to reduce GHG emissions, "technology picking" via subsidization becomes the *de facto* mitigation tool. This is especially true in China and India, where, despite steps to slow the growth of emissions, aggressive domestic pricing of carbon appears practically impossible – at least in the near-term. Under these circumstances, high potential (e.g. combination of significant technical potential and opportunities for cost reductions) technologies like CSP are appealing because of their ability to radically and permanently transform energy supply.

But this potential, which rests largely on cost reductions achievable through manufacturing and deployment at scale, is only possible with long-term financial and political commitment that closes the cost gap, prioritizes projects, and reduces investment risk. Commitment to a long-term carbon tax of at least \$30 per tCO_2eq would probably be needed to spur the private sector investment required for widespread CSP deployment.

Without carbon pricing, however, subsidies equivalent to an implied carbon charge of ~\$90 per tCO_2eq are required to make CSP competitive with coal at present. That is a tall order for both developed world treasuries (which should be expected to provide at least some of the required concessionary financing) and the Chinese and Indian governments, especially given the political incentive to disperse subsidies across many industries – a strategy that may lead to limited cost reductions. Economy-wide carbon pricing will, hopefully, be politically feasible in China and India in the medium-term, but in the short-term available subsidies should target options with the greatest long-term potential.

CSP is clearly a viable candidate for large-scale, transformational renewable power in China and India, but whether it will be among the short-list of politically preferred options remains an open question. Wind power has considerable technical potential along with an established manufacturing base and lower generating costs at present, though there are still many barriers to exploitation (Golait et al. 2009; McElroy et al. 2009; Li 2010). Compared to CSP, photovoltaic power enjoys greater government support, though this is aimed as much at the development of manufacturing capacity for export as the displacement of domestic coal power.

Ultimately, what is needed is a vision of how these renewable energy technologies – which are essentially competing with each other for political favor and subsidies – can be *integrated* in the Chinese and Indian contexts to maximize economic and environmental benefits in the long-term. This study provides a first step in that direction. Further work exploring the spatial and temporal implications of large-scale CSP, photovoltaic, and wind deployment may identify opportunities to exploit complementarities and shared infrastructure, ultimately easing cost and constraints for all. An example in this vein is the effort of the U.S. Department of Energy, in collaboration with research labs and the private sector, to assess the full implications of large-scale wind and solar power adoption in the U.S. (DOE 2008; Lew et al. 2009).

Such information could be generated by the private sector in the presence of long-term carbon pricing but is sorely missed when industry subsidies are the primary means of directing markets. It will be difficult for the Chinese and Indian governments and international donors to make smart choices about the type and degree of renewable energy support without knowledge of the spatial, temporal, and technical patterns of deployment that would be most advantageous from a long-term, national perspective. Such analysis can help utilize scarce domestic and international clean technology financing more effectively, ultimately leading to a competitive advantage for renewable energy sources on the basis of cost alone.

REFERENCES

Amaral, S., Camara, G., Monteiro, A.M.V., Quintanilha, J.A., and Elvidge, C.D. 2005. Estimating population and energy consumption in Brazilian Amazonia using DMSP night-time satellite data. *Computers, Environment and Urban Systems* 29 (2): 179-195.

Bicheron, P., Defourny, P., Brockmann, C., Schouten, L., Vancutsem, C., Huc, M., Bontemps, S., Leroy, M., Achard, F., Herold, M., Ranera, F., and Arino, O. 2008. Globcover: products description and validation report. ESA Globcover Project led by MEDIAS France/POSTEL.

BP. 2009. BP statistical review of world energy. BP Amoco PLC, London, June.

Bradsher, K. 2010. China tries a new tack to go solar. *New York Times*, 8 January 2010.

Breyer, C. and Knies, Gerhard. 2009. Global energy supply potential of concentrating solar power. Presented at SolarPACES Conference, 15-18 September, Berlin, Germany.

CEC. 2010. Large solar energy projects. California Energy Commission. Accessed 5 July 2010. Available at: http://www.energy.ca.gov/siting/solar/index.html

Chand, T.R.K., Badarinath, K.V.S., Elvidge, C.D., and Tuttle, B.T. 2009. Spatial characterization of electrical power consumption patterns over India using temporal DMSP-OLS night-time satellite data. *International Journal of Remote Sensing* 30 (3): 647-661.

Chen, W. and Xu, R. 2010. Clean coal technology development in China. *Energy Policy* 38 (5): 2123-2130.

DOE. 2008. 20% wind energy by 2030: increasing wind energy’s contribution to U.S. electricity supply. U.S. Department of Energy, DOE/GO-102008-2567, July.

DOE. 2010. Reducing water consumption of concentrating solar power electricity generation. U.S. Department of Energy. Report to Congress. Accessed 12 April 2010. Available at: http://www.nrel.gov/csp/pdfs/csp_water_study.pdf

Enkvist, P.A., Nauclér, T. and Rosander, J. 2007. A cost curve for greenhouse gas reduction. *The McKinsey Quarterly* 1: 35-45.

ESMAP. 2008. Technical and economic assessment of off-grid, mini-grid, and grid electrification technologies. Energy Sector Management Assistance Program, World Bank, Technical Paper 121/07, August.

FAO, IIASA, ISRIC, ISSCAS, and JRC. 2009. Harmonized world soil database (version 1.1). Food and Agriculture Organization, Rome, Italy and International Institute for Applied Systems Analysis, Laxenburg, Austria.

Gilman, P., Blair, N., Mehos, M., Christensen, C., Janzou, S., and Cameron, C. 2008. Solar advisor model user guide for version 2.0. National Renewable Energy Laboratory Report No. TP-670-43704.

Golait, N., Moharil, R.M., and Kulkarni, P.S. 2009. Wind electric power in the world and perspectives of its development in India. *Renewable and Sustainable Energy Reviews* 13 (1): 233-247.

Hachadoorian, L., Gaffin, S.R. and Engleman, R. 2007. Projecting a gridded population of the world using ratio methods of trend extrapolation. In *Human Population: The Demography and Geography of Homo Sapiens and their Implications for Biological Diversity*, eds. R.P. Cincotta, L. Gorenflo and D. Mageean. Berlin: Springer-Verlag.

Hang, Q., Jun, Z., and Xiao, Y. 2008a. Simulation of parabolic trough solar power generating system for typical Chinese sites. *Proceedings of the Chinese Society of Electrical Engineering* 28 (11): 87-93.

Hang, Q., Jun, Z., Xiao, Y., and Junkui, C. 2008b. Prospect of concentrating solar power in China – the sustainable future. *Renewable and Sustainable Energy Reviews* 12: 2505-2514.

Hou, H.J., Yang, Y.P., Cui, Y.H., Gao, S., and Pan, Y.X. 2009. Assessment of concentrating solar power prospect in China. Presented at the International Conference on Sustainable Power Generation and Supply, 6-7 April, Nanjing, China.

IEA. 2009. World energy outlook 2009. International Energy Agency, Paris.

IUCN and UNEP. 2009. World database on protected areas (WDPA). International Union for Conservation of Nature and United Nations Environment Programme (World Conservation Monitoring Centre), Cambridge, United Kingdom.

Junginger, M., Lako, P., Lensink, S., van Sark, W., and Weiss, M. 2008. Technological learning in the energy sector. Netherlands Research Programme on Scientific Assessment and Policy Analysis for Climate Change, April.

Kahouli-Brahmi, S. 2008. Technological learning in energy-environment-economy modeling: a survey. *Energy Policy* 36 (1): 138-162.

Kuik, O., Brander, L., and Tol, R.S.J. 2009. Marginal abatement costs of greenhouse gas emissions: a meta-analysis. *Energy Policy* 37 (4): 1395-1403.

Letu, H., Hara, M., Yagi, H., Tana, G., and Nishio, F. 2009. Estimating the energy consumption with nighttime city light from the DMSP/OLS imagery. Presented at Urban Remote Sensing Joint Event, 20-22 May, Shanghai, China.

Lew, D., Milligan, M., Jordan, G., Freeman, L., Miller, N., Clark, K., and Piwko, R. 2009. How do wind and solar power affect grid operations: the western wind and solar integration study. Presented at the 8th International Workshop on Large Scale Integration of Wind Power and on Transmission Networks for Offshore Wind Farms, 14-15 October, Bremen, Germany.

Li, J. 2009. Scaling up concentrating solar thermal technology in China. *Renewable and Sustainable Energy Reviews* 13: 2051-2060.

Li, J. 2010. Decarbonising power generation in China – is the answer blowing in the wind? *Renewable and Sustainable Energy Reviews* 14 (4): 1154-1171.

Liu, Q., Shi, M., and Jiang, K. 2009. New power generation technology options under greenhouse gas mitigation scenario in China. *Energy Policy* 37 (6): 2440-2449.

Markandya, A., Armstrong, B.G., Hales, S., Chiabai, A., Criqui, P., Mima, S., Tonne, C., and Wilkinson, P. 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: low-carbon electricity generation. *The Lancet* 374 (9706): 2006-2015.

McElroy, M.B., Lu, X., Nielsen, C.P., and Wang, Y. 2009. Potential for wind-generated electricity in China. *Science* 325 (5946): 1378-1380.

Meah, K. and Ula, S. 2007. Comparative evaluation of HVDC and HVAC transmissions systems. Presented at IEEE Power Engineering Society General Meeting, 24-28 June, Tampa, USA.

Neij, L. 2008. Cost development of future technologies for power generation – a study based on experience curves and complementary bottom-up assessments. *Energy Policy* 36 (6): 2200-2211.

Nemet, G.F., Holloway, T., and Meier, P. 2010. Implications of incorporating air-quality co-benefits into climate change policymaking. *Environmental Research Letters* 5 (1): 014007.

NOAA. 2009. DMSP-OLS nighttime lights time series (1992-2008). Image and data processed by the National Oceanic and Atmospheric Administration's National Geophysical Data Center; DMSP data collected by U.S. Air Force Weather Agency. Available at: http://www.ngdc.noaa.gov/dmsp/downloadV4composites.html

NREL. 2005. Monthly and annual average direct normal irradiance at 40km resolution for East Asia. National Renewable Energy Laboratory, Golden, Colorado. Available from the Solar and Wind Energy Resource Assessment (SWERA/UNEP). Available at: http://swera.unep.net/

NREL. 2010. SolarPACES concentrating solar power projects. National Renewable Energy Laboratory, Golden, Colorado. Accessed 5 July 2010. Available at: http://www.nrel.gov/csp/solarpaces/

ORNL. 2008. LandScan™ global population dataset. Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Piemonte, V., De Falco, M., Tarquini, P., and Giaconia, A. 2010. Life cycle assessment of a high temperature molten salt concentrated solar power plant. Presented at 20th European Symposium on Computer Aided Process Engineering,.

Purohit, I. and Purohit, P. 2010. Techno-economic evaluation of concentrating solar power generation in India. *Energy Policy* 38 (6): 3015-3029.

Richter, C., Teske, S., and Short, R. 2009. Concentrating solar power: global outlook 2009. Greenpeace International, Amsterdam, Netherlands.

Sawin, E.R., Jones, A.P., Fiddaman, T., Siegel, L.S., Wright, D., Franck, T., Barkman, A., Cummings, T., von Peter, F., McGlade, J., Correll, R.W., and Sterman, J. 2009. Current emissions reductions proposals in the lead-up to COP-15 are likely to be insufficient to stabilize atmospheric CO_2 levels. Presented at Climate Change – Global Risks, Challenges, and Decisions Conference, 10 March, Copenhagen, Denmark.

Staley, B.C., Goodward, J., and Rigdon, C. 2009. Juice from concentrate: reducing emissions with concentrating solar thermal power. World Resources Institute, Washington, D.C.

Trieb, F., Schillings, C., Kronshage, S., Viebahn, P., May, N., Paul, C., Klann, U., Kabariti, M., Bennouna, A., Nokraschy, H., Hassan, S., Georgy Yussef, L., Hasni, T., Bassam, N., Satoguina, H. 2005. Concentrating solar power for the Mediterranean region (MED-CSP). German Aerospace Center (DLR), Institute of Technical Thermodynamics, Stuttgart, Germany.

Trieb, F., Schillings, C., Kronshage, S., Viebahn, P., May, N., Paul, C., Klann, U., Kabariti, M., Bennouna, A., Nokraschy, H., Hassan, S., Georgy Yussef, L., Hasni, T., Bassam, N., Satoguina, H. 2006. Trans-Mediterranean interconnection for concentrating solar power (TRANS-CSP). German Aerospace Center (DLR), Institute of Technical Thermodynamics, Stuttgart, Germany.

Trieb, F., Schillings, C., O'Sullivan, M., Pregger, T., and Hoyer-Klick, C. 2009. Global potential of concentrating solar power. Presented at SolarPACES Conference, 15-18 September, Berlin, Germany.

Ummel, K. and Wheeler, D. 2008. Desert power: the economics of solar thermal electricity for Europe, North Africa, and the Middle East. Working Paper No. 156, Center for Global Development, Washington, D.C.

Verdin, K.L., Godt, J.W., Funk, C., Pedreros, D., Worstell, B., and Verdin, J. 2007. Development of a global slope dataset for estimation of landslide occurrence resulting from earthquakes. United States Geologic Survey, Colorado, Open-File Report 2007-1188.

Wang, H. and Nakata, T. 2009. Analysis of the market penetration of clean coal technologies and its impacts in China's electricity sector. *Energy Policy* 37 (1): 338-352.

Wang, Z. 2010. Prospectives for China's solar thermal power technology development. *Energy* (in press).

Weisser, D. 2007. A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies. *Energy* 32 (9): 1543-1559.

Wheeler, D. 2010. Fair shares: crediting poor countries for carbon mitigation. Center for Global Development Working Paper (forthcoming), Washington, D.C.

Wheeler, D. and Shome, S. 2010. Less smoke, more mirrors: where India really stands on solar power and other renewables. Working Paper No. 204, Center for Global Development, Washington, D.C.

Williges, K., Lilliestam, J. and Patt, A. 2010. Making concentrated solar power competitive with coal: the costs of a European feed-in tariff. *Energy Policy* 38 (6): 3089-3097.

Zhou, X. and Yang, J. 2009. A novel solar thermal power plant with floating chimney stiffened onto a mountainside and potential of the power generation in China's deserts. *Heat Transfer Engineering* 30 (5): 400-407.