**Please cite as:** Lilliestam, J., Bielicki, J., Patt, A. (2012): Comparing carbon capture and storage (CCS) with concentrating solar power (CSP): potentials, costs, risks, and barriers, in: *Energy Policy* 47, pp. 447-455.
http://dx.doi.org/10.1016/j.enpol.2012.05.020

Post-print version of the article published in *Energy Policy* 47, pp. 447-455.

# Comparing carbon capture and storage (CCS) with concentrating solar power (CSP): Potentials, costs, risks, and barriers

**Johan Lilliestam[a,b], Jeffrey M. Bielicki[c], Anthony Patt[a]**

[a] International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, 2361 Laxenburg, Austria

[b] Potsdam Institute for Climate Impact Research (PIK), Telegrafenberg A31, 14473 Potsdam, Germany

[c] Center for Science, Technology, and Public Policy, Humphrey School of Public Affairs, University of Minnesota, 301 19th Avenue South, Minneapolis, MN 55455, US

**Corresponding author: Johan Lilliestam, johan@pik-potsdam.de.**

**Please cite as:** Lilliestam, J., Bielicki, J., Patt, A. (2012): Comparing carbon capture and storage (CCS) with concentrating solar power (CSP): potentials, costs, risks, and barriers, in: *Energy Policy* 47, pp. 447-455.
http://dx.doi.org/10.1016/j.enpol.2012.05.020

## Abstract

Coal power coupled with Carbon [Dioxide] Capture and Storage (CCS), and Concentrating Solar Power (CSP) technologies are often included in the portfolio of climate change mitigation options intended to decarbonize electricity systems. Both of these technologies can provide baseload electricity, are in early stages of maturity, and have benefits, costs, and obstacles. We compare and the contrast CCS applied to coal-fired power plants with CSP. At present, both technologies are more expensive than existing electricity-generating options, but costs should decrease with large-scale deployment, especially in the case of CSP. For CCS, technological challenges still remain, storage risks must be clarified, and regulatory and legal uncertainties remain. For CSP, current challenges include electricity transmission and business models for a rapid and extensive expansion of high-voltage transmission lines. The need for international cooperation may impede CSP expansion in Europe.

**Keywords**: Carbon dioxide capture and storage, concentrating solar power, electricity sector decarbonization

# 1 Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), preventing potentially catastrophic climatic changes with high likelihood requires atmospheric carbon dioxide ($CO_2$) concentrations be stabilized at or below 450 ppm (IPCC, 2007a). To do so, global $CO_2$ emissions must be reduced 50% from their 2006 levels by 2050, 100% by about 2075, and beyond 100% by 2100 (IPCC, 2007b). To accomplish the latter will require industry generating little or no net $CO_2$ emissions, as well as the removal of $CO_2$ from the air. Electric power provides a large fraction of final energy demand, and this share will likely grow over time (IEA, 2009b). Consequently, large amounts of reliable electricity must be provided in a low- or carbon neutral manner (ECF, 2010; MacKay, 2009).

Low carbon energy technologies fall into three categories: (1) use fossil fuels as a primary source of energy but capture the $CO_2$ that is produced before it is vented and inject it into deep sedimentary basins—a process known as Carbon [Dioxide] Capture and Storage (CCS); or replace fossil-fueled electricity generation with (2) "renewable" sources or (3) nuclear fission (IPCC, 2007c). Actual technology deployment portfolios entail decisions between each of these three categories, and here we focus on the choice between the first two. Specifically, we compare coal-fired electricity generation coupled with CCS with Concentrating Solar Power (CSP). Recent analyses suggest that CSP is one of the few renewable options that can supply fully dispatchable electricity (IEA, 2010b; EASAC, 2011, IPCC, 2011), just like the coal-fired electricity with CCS with which we compare it.

Many existing analyses suggest that the future energy system will contain a large amount of both technologies (e.g. IEA, 2009b). Consequently, these two technologies may compete for funding and political support. From a political perspective as well, they may be competitors because of the very different industrial lobbies behind them (Dinica, 2006; van der Zwaan and Gerlagh, 2009). The extent to which each technology is supported early on is important: investments in a technology should lead to technological learning and declining costs, which may improve that technology's position when costs and performance are compared (Manne and Richels, 2004). As a result, in addition to understanding the technologies in isolation, it is valuable to examine the potential choice between them.

To do so, we compare these two technologies over two broad sets of criteria: the benefits and opportunities of CSP and coal-fired electricity generation with CCS on one dimension, and the costs and challenges of each on the other. We consider costs dynamically because they depend on the scale and speed of deployment. Our multi-dimensional comparison also includes energy security, environmental, safety, and technical risks associated with commercial-scale deployment of each technology, as well as the political, regulatory, and legal challenges these risks imply.

# 2 Technology overview

Both coal-fired electricity generation with CCS and CSP can provide dispatchable electricity with little or no $CO_2$ emissions. Hence they can both provide one kilowatt-hour (kWh) of climate-friendly baseload electricity. Here, we briefly describe the technologies as a foundation for the comparisons that follow.

**Please cite as:** Lilliestam, J., Bielicki, J., Patt, A. (2012): Comparing carbon capture and storage (CCS) with concentrating solar power (CSP): potentials, costs, risks, and barriers, in: *Energy Policy* 47, pp. 447-455.
http://dx.doi.org/10.1016/j.enpol.2012.05.020

## 2.1 Coal-fired electricity generation with carbon capture and storage

CCS has three major steps: $CO_2$ capture, transportation, and storage. For $CO_2$ capture, there are three main approaches when applied to coal-fired power plants: 1) post-combustion, where $CO_2$ is separated from the exhaust stream after coal is combusted; 2) pre-combustion, whereby coal is gasified in a process that produces hydrogen ($H_2$) and $CO_2$, which are more easily separable than in post-combustion processes; and 3) oxy-combustion, where nitrogen ($N_2$) is separated from air prior to combustion, leaving mostly oxygen ($O_2$) to combine with coal (mostly C) to produce mostly pure $CO_2$. Proven technologies can capture approximately 90% of the $CO_2$ in the exhaust stream (CRS, 2010), but they require energy, which reduces plant conversion efficiencies by 25-50% (IPCC, 2005), with a theoretical limit of 11% for post-combustion processes (House et al., 2009). As a result, the amount of $CO_2$ produced per kWh increases with $CO_2$ capture.

Captured $CO_2$ is compressed to a liquid and transported, most efficiently by pipeline (Svensson et al., 2004), to geologic reservoirs where it is injected at least 1 km below the surface for long-term storage. The geologic reservoirs currently under consideration are depleted oil and gas fields, deep saline aquifers, and unmineable coal seams (Holloway, 2001). The fact that oil, gas, and brine has been contained in these geologic structures for hundreds of thousands of years provides a proof-of-principle that they could contain $CO_2$ for a comparable length of time (WRI, 2008). Other theoretically attractive storage options include deep-sea sediment (House et al., 2006), basalt formations (Goldberg et al., 2008), or stable compounds formed by mineralization reactions (Lackner, 2002).

Many industrial facilities emit $CO_2$ (e.g., cement and steel producers, oil refineries), but coal- and natural gas-fired power plants are the largest stationary emitters of $CO_2$. Consequently, CCS is often considered a technology for the fossil-fueled electricity sector. Biomass-fired power plants can have $CO_2$ capture, effectively removing $CO_2$ from the air (Rhodes and Keith, 2008). Retrofitting existing facilities for $CO_2$ capture requires that new equipment be added, and existing equipment be retuned; retrofits have effects that cascade through the system. Conceivably, power plants can be built to be "capture ready," in which the design of the system has taken into account the possibility of future retrofits, but capturing and non-capturing plants will have different optimal modes of operation (IEA, 2007).

Each CCS step is already operational at commercial scales, but industry has limited experience linking them together. For example, $CO_2$ separation is widely practiced in the oil and gas industry but little experience with $CO_2$ capture from power plants exists (IPCC, 2005; WRI, 2008). $CO_2$ transportation and geologic injection are based on standard techniques from the oil and gas industry. In the United States, approximately 5,000 km of $CO_2$ pipelines transport about 30-40 $MtCO_2$ per year, most of which is obtained from natural deposits, to depleted oil fields where that $CO_2$ is injected for enhanced oil or gas recovery (EOR, EGR). About 100 EOR projects are currently operating in the United States (Bielicki, 2009a). Despite all of this experience, only five projects throughout the world are testing its viability as an integrated system. Each of these projects injects 0.7-1.5 $MtCO_2$ per year (IEA, 2010a).

## 2.2 Concentrating solar power

CSP stations use direct sunlight to produce heat and make steam that drives turbine to generate electricity. To achieve high steam temperatures, sunlight is concentrated by mirrors onto one focal line (up to 400-500°C) or one focal point (up to 1,000°C). Parabolic trough CSP plants, currently the most mature CSP technology, use curved mirrors to concentrate light onto an absorber tube in the focal line of the mirror. Solar tower technology focuses light by thousands of flat mirrors onto one point in a central tower receiver. Solar towers are relatively new, but their higher steam temperatures produce higher conversion efficiencies. Other concentration technologies, such as Fresnel and dish sterling concentration technologies have only been tested at laboratory scales (IEA, 2010b; Richter et al., 2009, IPCC, 2011).

CSP technologies can incorporate thermal energy storage. In such a system, some of the heat is converted to power immediately, while the remainder is diverted to a storage facility where it can be used to power the turbine at a later time. Thermal storage units are very efficient; nearly all of the collected heat is eventually used in the turbine cycle (Sargent & Lundy, 2003). Several CSP plants built in Spain since 2007 incorporate thermal storage, and, in July 2011, the Gemasolar power tower, equipped with 15 hours of storage[1], was the first to generate electricity for 24 consecutive hours. This power station is expected to reach a yearly capacity factor of 80-85%, which is comparable to most fossil-fuel power stations (ReCharge, 2011). Storage increases total investment costs, but the higher investment is more than offset by the increased capacity factor, on a levelized cost basis. With present technology, adding more than 13 hours of storage slightly increases the levelized cost, because the average storage utilization decreases, but the availability of the plant increases (EASAC, 2011; Khosla, 2008). Present research and development is investigating larger and cheaper storage, and technical barriers that prevent longer storage times do not appear to be concerns. A solar field with a solar multiple[2] of 3-4 and large storage (>16 hours) could facilitate baseload power production for the whole year, but the increased reliability in winter would come at the cost of underutilization in summer (EASAC, 2011). Solar concentrators can also complement fossil fuel combustion in a hybrid solar-fossil power station (Sargent & Lundy, 2003).

CSP only uses direct sunlight and is suited for desert and arid areas, where the direct normal insolation (DNI) is high (Richter et al., 2009). To provide significant amounts of electricity to demand centers in Europe and North America, CSP would have to be deployed in the deserts of North Africa, southwestern United States, and Mexico. High-voltage direct current (HVDC) transmission lines would cost-effectively connect these supplies and demands. Typical full-load HVDC line losses are 2-3%/1000 km, which is less than half of the typical full-load losses in high-voltage alternating current (HVAC) lines (Bahrman and Johnson, 2007; Czisch, 2005; Trieb et al., 2009). There is plenty of experience with HVDC transmission lines: more than 100 GW of HVDC has been installed worldwide over more than seven decades, and on all continents (IEEE, 2008).

---

[1] The turbine can be run at full capacity for up to 15 hours using only the stored heat.

[2] The solar multiple relates the size of the mirror field to the turbine capacity: a solar multiple of three means
[2] The solar multiple relates the size of the mirror field to the turbine capacity: a solar multiple of three means
that the maximum heat collection is three times larger than the turbine capacity.

**Please cite as:** Lilliestam, J., Bielicki, J., Patt, A. (2012): Comparing carbon capture and storage (CCS) with concentrating solar power (CSP): potentials, costs, risks, and barriers, in: *Energy Policy* 47, pp. 447-455. http://dx.doi.org/10.1016/j.enpol.2012.05.020

# 3 Scaling up: how far?

## 3.1 Coal-fired electricity generation with CCS

A typical coal-fired power plant emits 0.8-1.2 kg of $CO_2$ for each kWh generated (Fritsche, 2007). The electricity sectors in the United States and European Union emit 2.2 $GtCO_2$ (2009) and 1.3 $GtCO_2$ (2007), respectively (IEA, 2011; Eurostat, 2010), for which coal-fired power plants are the major sources. Depending on the technology, coal power requires between 3,800 and 6,200 gallons per minute of cooling water for 550 $MWe_{net}$ generators. Adding CCS increases water requirements by 10-20% for Integrated Gasification Combined Cycle facilities and up to 120% for subcritical and supercritical pulverized coal facilities (WRI, 2008). These water requirements could reduce the feasibility of coal power with CCS at some locations, but overall water availability is unlikely to be a major constraint because coal can be transported to power stations at suitable sites.

As of April 2010, over $26 billion[3] in government support worldwide had been dedicated to CCS, and 80 large-scale industrial projects were in various stages of development as a result of government-industry collaborations (IEA, 2010a). The scale of CCS deployment could ultimately be constrained by worldwide geologic storage capacity, and estimates of storage capacities vary widely (Bradshaw et al., 2007; Dooley et al., 2006; NETL, 2008). Expert stakeholder opinion has estimated a "*technical potential of at least 2,000 $GtCO_2$ of storage capacity in geological formations worldwide*", but noted that important spatial, technical, and economic considerations may reduce this potential so that "*the final volumes of 'proven' storage reserves may be significantly smaller than the technical potential*". These viable storages "*are still likely to be very large*" (WRI, 2008). Other developments, such as hydraulic fracturing (which can remove the caprock integrity needed to contain injected $CO_2$ beneath it), may further reduce viable storage capacity. Still, available storage sites should be sufficient for at least 100 years of large-scale CCS operation[4], a timeframe over which the world is not expected to run out of coal reserves given the current economic environment (BP, 2010).

## 3.2 CSP

Land use and availability are major determinants of CSP deployment potential (IEA, 2010b) because the mirror fields require large areas; ideally, this land would be flat and have high DNI. Current CSP technologies can generate 100-130 GWh/km$^2$ per year in desert regions (DLR, 2005). To satisfy the 2009 electricity demands of the United States and European Union (4,150 and 3,200 TWh/yr, respectively; BP, 2010), would require 32,000-42,000 km$^2$ (US), and 25,000-32,000 km$^2$ (EU). These areas roughly equal Michigan's Upper Peninsula (US) or Belgium (EU). But deserts within 3,000 km of the major load centers in the United States and European Union are very large:  the Chihuahuan, Sonoran and Mojave deserts

[3] Throughout the article, we give all costs in US$, using an exchange rate of 1 € = 1.3 US$.

[4] For example, capturing and injecting 4 $GtCO_2$ per year (approximately 25% of stationary source emissions in 2005) for 100 years equals only 20% of the 2,000 $GtCO_2$ quoted here.

total a combined 530,000 km$^2$, and the Sahara desert is 9 million km$^2$. Hence, even the unrealistic (and undesirable) prospect of fully powering the United States with only CSP would require 6-8% of desert land in North America, whereas the European Union would require 0.3-0.4% of the Sahara. Thus, land area and solar resource availability do not constrain CSP expansion.

Water availability could constrain large-scale CSP expansion. Dry-cooling greatly reduces water needs and lowers efficiency somewhat compared to wet-cooling (Damerau et al., 2011; Siddiqi, Anadon, 2011), but these efficiency losses are small compared to the benefits of operating CSP at drier sites with better solar resources. Wet-cooled plants require up to 3000 m$^3$/GWh, whereas dry cooling presently requires ~300 m$^3$ /GWh, including ~75 m$^3$/GWh to clean mirrors. Wet-cooling is thus hardly an option in deserts: only dry-cooling seems feasible. Projected CSP deployment levels, assuming dry-cooling, would consume less than 1% of North African renewable water reserves. The needed water can be made available through intelligent siting, especially near existing water bodies, but also close to cities or industry (re-processed wastewater), coasts, or by dedicated infrastructure—at manageable costs (Damerau et al., 2011). Water availability can be a site-specific problem, but neither the overall water availability nor the cost of solving most local problems significantly constrains CSP deployment in North Africa. We are not aware of similar studies for North America.

# 4 Costs

## 4.1 Coal-fired electricity generation with CCS

CCS costs must be estimated, in part because of the lack of experience with integrated commercial-scale CCS projects. $CO_2$ capture and compression is the most costly step, depending on the characteristics of the $CO_2$ in the exhaust stream, and can comprise 50-80% of the total cost of CCS. Significant opportunities to innovate new $CO_2$ capture technologies may exist (DOE, 2010) and thus reduce costs, where analogous learning rates—reduction of costs per doubling of capacity—have been estimated to be 1-8% (Rubin et al., 2007). A thorough review of estimated capture costs, which compared standardized estimates across studies, determined that the first wave of coal-fired power plants with $CO_2$ capture and compression could cost 120-180 $\$_{2005}$/t$CO_2$ avoided and add 0.08-0.12 $\$_{2005}$/kWh to the cost of electricity from a pulverized supercritical coal-fired power plant (Al-Juaied and Whitmore, 2009). Over time these authors suggest that these costs could reduce to 35-70 $\$_{2005}$/t$CO_2$ avoided (0.02-0.05 $\$_{2005}$/kWh).

$CO_2$ transportation by pipeline is a mature technology and future cost reductions are unlikely, but there are significant economies of scale in $CO_2$ transportation by pipeline (Bielicki, 2009a, b). Typical $CO_2$ transportation costs are estimated to be 0.5-7 $\$_{2004}$/t$CO_2$ (McCoy and Rubin, 2008), and differ strongly depending on the utilization of the pipeline system (Middleton and Bielicki, 2009).

$CO_2$ storage costs arise from drilling new injection wells, reworking existing production wells, operating them, and compressing $CO_2$ for injection. Typical estimates range between 1-9 $\$_{2004}$/t$CO_2$ injected, depending on geologic conditions, the effort required to characterize the reservoir, and the planning horizon for the $CO_2$ injection (McCoy, 2008; McCoy and

Rubin, 2009). The costs to monitor injection and the movement of $CO_2$ in the subsurface are expected to be less than 0.1 $\$_{2004}/tCO_2$ (Benson, 2004). The market values of oil and gas from EOR and EGR can offset some CCS costs, but more $CO_2$ will be produced when this oil or gas is combusted. Consequently, the net $CO_2$ flows must be considered in order to determine the amount of $CO_2$ emissions that are avoided in EOR/EGR applications (IEA, 2010a; Jaramilo et al., 2009).

Overall, mid-range values suggest that the total cost of CCS may add about 0.11 $/kWh (short term) to the levelized cost of electricity (LCOE) from unmitigated coal power plants, falling to about 0.04 $/kWh over time, with large uncertainties attached to these numbers. The costs of CCS will always be above those for conventional coal-fired electricity unless there is a financial incentive to use the captured $CO_2$ or a financial disincentive to emit $CO_2$.

Replacing all current coal-power capacity with coal power coupled with CCS—315 GW in the US, 214 GW in the EU (EC, 2008; EIA, 2010)—would require large investments, also when the substantial expected learning effects are considered. Using values from Al-Juaied and Whitmore (2009), learning rates from Rubin et al (2007), and a range of financial assumptions[5], the discounted investments for this amount of coal power with CCS is around $195 billion for the EU and $230 billion for the US, to be accomplished over 30 years, assuming a 25% annual growth rate (Williges et al, 2010).

## 4.2 CSP

Most existing CSP facilities were constructed before 1990, and cost data for newer stations is only partially public. Table 1 shows some observed costs for projects from 2007 and 2008. Fixed costs for CSP plants typically account for at least 80% of the LCOE. Low operational costs make the solar insolation a primary determinant of the variance in LCOE across sites. A typical CSP site in Spain has a DNI of 2,000 kWh/$m^2$/yr, whereas a typical site in the Sahara or the deserts of the southwestern United States is 25-30% better; very good sites may have a DNI of 2,900 kWh/$m^2$/yr (Czisch, 2005; Trieb et al., 2009).

---

[5] 20 years depreciation, 10% interest rate, 5% discount rate. We also assume that all investments done by the EU/US in the two cases are mirrored by the same investments in the rest of the world.

**Table 1: Observed costs, expected electricity production, and LCOE, for three recent CSP installations in Spain and the United States**

| | Investment (per kW) | Size (MW) | Storage (minutes) | Expected production | LCOE |
|---|---|---|---|---|---|
| **Andasol 1 (trough, ES, 2008)** | €5300-5900 | 50 | 450 | 176 GWh/yr (3500 FLh) | 0.27-0.30 $/kWh |
| **Nevada solar one (trough, US, 2007)** | $4100 | 64 | 30 | 128 GWh/yr (2000 FLh) | 0.29 $/kWh |
| **PS10 (tower, ES, 2007)** | €3200 | 11 | 25 | 23 GWh/yr (2100 FLh) | 0.30 $/kWh |
| LCOE based on Operations and Maintenance of 130 $/kW, 10% interest rate, and 20 years depreciation. Costs are in 2007 and 2008 US$ (1€=1.3$). Sources: CSP today, 2008; Richter et al., 2009; Sargent & Lundy, 2003; Schott, 2009; SolarPaces, 2009; Trieb et al., 2009. | | | | | |

Technological learning may significantly reduce capital costs. IPCC (2011) suggests a CSP learning rate of 10±5%, and the review in Williges et al. (2010) suggests 15%. Using the model and assumptions in Williges et al. (2010)[6], we estimate that replacing all (214 GW) current coal-fired electricity generating capacity in the European Union requires European discounted investments of $170 billion (using a 5% discount rate). This figure includes HVDC transmission, which adds around 10% (in 2010) to 40% (in 2050)[7] to the cost for CSP. Replacing the 315 GW of coal-fired electricity capacity, using the same assumptions as above, in the United States would require $210 billion of discounted investments. Thus, the total investment (EU+US) is around $380 billion. CSP would achieve current market prices (around 0.055 $/kWh) in the mid-2020s, at total discounted subsidy cost of $46 billion (EU) and $48 billion (US), assuming that the investments in the target regions (EU, US) is mirrored in the rest of the world in both cases. These results are consistent with the expected cost reductions of 20-35% by 2020 and up to 60% by 2050 in other studies (e.g. IEA, 2010b; Trieb et al., 2009). These subsidy costs will be incurred over fifteen years and are lower than Germany's current payments for wind-generated electricity within the feed-in tariff system—about $4-4.5 billion per year. The yearly required discounted investments are less than the $17 billion that Germany invested in renewable electricity in 2008 (Böhme et al., 2009).

HVDC transmission line costs must be added to CSP facility costs and are included in the numbers above. HVDC transmission costs are highly project specific, and may vary by a factor of 4. Typically, 0.01-0.03 $c/kWh must be added to the CSP LCOE for HVDC transmission over 2000 km, including a 200 km submarine/ground cable stretch (Bahrman and Johnson, 2007; Czisch, 2005; DLR, 2006). HVDC is a mature technology, and significant cost reductions from technological learning are unlikely.

[6] Operations and Maintenance = 130 $/kW, 10% internal rate of return, 15% learning rate, and 20 years depreciation, 25% constant growth rate, equal growth in target region and "rest of the world".

[7] The HVDC transmission cost share increases with time as we assume that the HVDC technology has no cost reductions due to learning whereas the CSP generation costs are reduced over time.

# 5 Technical risks

## 5.1 CCS

CCS does not add risks to the electricity supply beyond those associated with reliance on coal for primary energy. Technical risks specific to CCS arise from the characteristics of $CO_2$ and how it is handled and the extra amount of coal that must be mined and transported in order to compensate for the energy penalty. $CO_2$ is not explosive, but risks to human health are present when inhaled concentrations reach 3-5%, and concentrations above 15% can be deadly (Lambertson, 1971). Coal mining can pose significant risks to the health of the miners, and environmental risks include impacts on water quality, possibly significant disturbances to the land, and the release of another greenhouse gas (methane).

$CO_2$ could be suddenly released if a pipeline ruptures, an injection well blows out, or if stored $CO_2$ is suddenly released (Wilson et al., 2003; WRI, 2008). Large-scale deployment of CCS will likely entail an extensive network of $CO_2$ pipelines, but the hazards arising from $CO_2$ pipelines are likely less than those from natural gas pipelines, because $CO_2$ is not explosive. Similarly, standard industry practices could limit the risk of a $CO_2$ injection well blowout. Subsurface $CO_2$ migration is constrained by its flow through porous media. Geologically stored $CO_2$ could be suddenly released only if slowly leaking $CO_2$ accumulates in a manner that is not bound by the porous flow, which is extremely unlikely (WRI, 2008). While the actual risks are small, the public may see these differently, potentially reducing social acceptance. Catastrophic releases are highly unlikely and leaks, if they occur, will likely result from less abrupt processes.

Injected $CO_2$ will migrate and can be buoyant in terrestrial geology (Oldenburg, 2007), but various trapping mechanisms exist to impede this flow (Bachu et al., 1994; Bruant et al., 2002). Still, it is theoretically possible for $CO_2$, or the brine it displaces, to find migration paths, such as geologic faults or abandoned and poorly plugged wellbores, to underground sources of drinking water, or the surface where it could leak into the atmosphere (Hepple and Benson, 2004). If such seepage occurs, it is unlikely to be harmful to nearby humans or local flora and fauna, but the climate change mitigation benefits will be reduced. Injection operations and the search for appropriate sites will require wells to be drilled through the caprock, which should otherwise contain the injected $CO_2$, and these wells may be a point of leakage. Data from EOR operations, experiments, and analytical modeling, however, has shown that these risks are very small (Carey et al., 2007; Kutchko et al., 2007; Carey et al., 2009; Crow et al., 2009; Wigand et al., 2009). Measuring, monitoring, and verification activities can observe the mobility and effects of $CO_2$ underground and corrective action can be taken if necessary (Benson, 2007).

Even if it is not released, the presence of $CO_2$ in the geologic subsurface can present other risks (Wilson and Gerard, 2007). For example, chemical reactions enabled by the presence of $CO_2$ could degrade caprock and well cement integrity, or leach minerals or other contaminants in the subsurface (IPCC, 2005). Site selection and geologic characterization activities must choose sites where it is unlikely that the $CO_2$ storage has harmful impacts on groundwater.

## 5.2 CSP

Overall, CSP does not appear to be a risky technology (Patt et al., 2010; Trieb et al., 2009). The technology is well-known, and there are no large technological, environmental or safety risks specific to CSP generation in the desert beyond those generally applicable to the electricity sector. Because CSP with thermal storage can be fully dispatchable, intermittency risks to electricity supply security from CSP are much smaller than for most other renewable electricity technologies (IPCC, 2011).

The risk of disruptions may increase with the reliance on long-distance transmission, however, because of storms or other similar weather or environmental threats, but the risk of ice or falling trees downing transmission lines—among the most common sources of transmission failure—are unlikely within or near deserts. Terrorist threats against transmission lines are possible, but the redundancy of the system—the thermal limits of an HVDC line are usually twice the nominal capacity of the line, so that failures in single lines in a meshed grid can be compensated by the remaining ones (Czisch, 2005)—and significant reserve capacities should strongly mitigate all but the most extreme terrorist attacks. Severely disrupting the system operation of a full-fledged HVDC transmission grid by force requires a high number of simultaneous attacks and is essentially the task of a national army, not a terrorist group. Even if blackouts occur, normal operations will likely be restored within hours. The relatively unspectacular impacts of attacking a power line strongly reduce the incentives, and thus the probability, of a terrorist attack against CSP plants or HVDC lines (Toft et al., 2010), but such an attack could produce a large reaction by the media which could deter future investors and impede further expansion of CSP.

In the EU-North African case, increased import dependency and supply disruptions from hostile actions by an exporting government are concerns (Pearce, 2009). But Europe already imports more than 60% of its energy (Eurostat, 2010) and substituting primary energy imports with renewable power imports may *reduce* total European import dependency. It appears that Europe does not have much to fear from North African states wielding the "energy weapon", as long as the imports are diversified so that no single exporter has a capacity higher than European response capacities (Lilliestam and Ellenbeck, 2011). In the case of North America, the United States and Mexico are already trade partners, covered by the North American Free Trade Agreement, with no specific political risks anticipated.

# 6 Barriers to scaling up quickly

## 6.1 CCS

Barriers to scaling up CCS fall into four interrelated categories: financial, regulatory, legal, and public. Aside from the potential to use captured $CO_2$ for economically valuable products, such as EOR or EGR, CCS will not be commercially deployed without policy intervention, for example in the form of a significant cost imposed on emitting $CO_2$ or regulations that mandate quantities of $CO_2$ mitigation by CCS. Recent legislative activity in the United States has sought to address some of these issues with tax breaks, deployment subsidies, funding mechanisms, and other issues related to authorizing demonstration projects and long-term stewardship.

The European Union's Directive on the Geological Storage of $CO_2$ establishes a legislative and regulatory framework for CCS (2009/31/EC, 2009), including rules concerning liability, and a number of US states have enacted CCS legislation concomitantly with action by the US Environmental Protection Agency (IEA, 2010a). At present, however, legal and regulatory frameworks for CCS are not fully developed and associated uncertainties impede commercial deployment (Wilson and Gerard, 2007). Geologic reservoirs must be permitted, for example, and the means and mechanisms by which this will occur must be created. Similarly, legal frameworks must be developed to address who owns the pore space into which $CO_2$ is injected (Klass and Wilson, 2010), and ensure that a party is responsible, with funds available notwithstanding bankruptcy to take corrective action, remediate problems, and pay damages should an accident or adverse impact occur (de Figueiredo, 2007). Economic and regulatory impacts of leakage depend on the location of the leak and the extant property rights (Klass and Wilson, 2008). Such legal frameworks are necessary to stimulate the CCS industry, as companies are unlikely to provide $CO_2$ storage services in a geologic reservoir if it is *a priori* unclear what that company's rights and responsibilities are.

On the public side, CCS can "clean coal" by mitigating emissions at the end of the coal supply chain, but long-standing issues with coal mining and transportation, such as mountain-top removal, will remain. CCS might experience public opposition as a consequence of social concerns about mining and transportation in addition to the perceived storage risks outlined above. For the latter, CCS as a system that integrates today's individually proven and accepted components at industrial scales is embryonic, and must be successfully demonstrated to the public and to financial investors and project developers.

## 6.2 CSP

No significant technological developments or breakthroughs are required to scale CSP; deployment could begin now with current technologies, costs and performance will likely improve over time (Khosla, 2008). Instead, financing and siting are the major barriers. Currently, CSP electricity is not cost-competitive and is unlikely to be deployed in regions without sufficient policy support schemes. In some areas—most significantly Spain and California—public support has led to a surge of CSP activity, but other regions (e.g. North Africa, Mexico) have seen virtually no CSP deployment, mainly because these regions lack sufficient policy and economic support for the technology (Richter et al., 2009). As with CCS, lack of certainty about energy and climate policy impedes CSP deployment: power plants are long-term investments, and policy certainty is essential (Schellekens et al., 2010).

Transmission line projects have similar long-term characteristics, but policy certainty is more pressing because the markets are regulated. The conditions for cost recovery must be improved because investments in transmission infrastructure are presently not attractive (Battaglini and Lilliestam, 2010). Infrastructure siting is an issue on both sides of the Atlantic, especially for the European Union. The largest solar resource potentials are in North Africa, and developing them requires the establishment of frameworks for cooperative investment between EU and North African countries. Additionally, the HVDC transmission system would have to cross multiple national borders within the European Union; the patchwork of national legislation makes this difficult and time consuming, and the present regulatory environment would have to be changed (ENTSO-E, 2010).

Increasing public acceptance of, or limiting the ability to oppose, new transmission lines is a necessary but difficult task. At present, citizens and politicians utilize their ability to impede new transmission line siting very well. In Europe, for example, typical permission times for new transmission lines are 5-10 years (ENTSO-E, 2010). The number of denied projects is unknown. Siting transmission lines in the United States is somewhat easier because of the heterogeneity of population densities. Still, relative to the size of the system, transmission investments in the United States are only one-third of those in Spain or Denmark and one-fourth of those in Britain (National grid, 2005). Consequently, transmission line permitting processes must be accelerated otherwise large-scale expansion of desert CSP is unlikely (Battaglini and Lilliestam 2010).

# 7 Discussion

Table 2 summarizes the similarities and differences between CCS and CSP presented above. The scope and potential of both technologies is large: both CCS and CSP have the resource base to satisfy any reasonable demand. CSP has an advantage because CCS has natural constraints that limit the amount of $CO_2$ that can be captured, although $CO_2$ storage capacity is likely to suffice for at least a century. On the other hand, CCS can be applied to more than just coal-fired electricity generation. CCS with biomass-fired facilities may achieve negative net emissions, and CCS can also be applied to large industrial sources like steel and cement manufacturers, or oil refineries (IPCC, 2005; NETL, 2008). Approximately 20-25% of worldwide $CO_2$ emissions (which were roughly 30 $GtCO_2$ in 2008) come from such industrial sources. CSP can only displace emissions from the electricity sector.

Total investment costs are unlikely to be major obstacles for either of the technologies, but current business models are not attractive for large-scale expansion. In the short run, the costs of the two technologies are comparable, and both are more expensive than other options for generating electricity with minimal $CO_2$ emissions. Without targeted support schemes, neither coal power with CCS nor CSP is profitable today, but the costs of each should decrease as deployment increases. One important difference concerns the long-term cost outlook and the public subsidies required to reduce the costs to levels comparable with today's baseload electricity costs. Achieving cost-competitiveness in this sense means making the technologies cost-competitive with conventional, unmitigated coal-fired electricity generation. Modest subsidies—less than \$50 billion (US), respectively—for CSP can reduce its cost enough to be competitive with current baseload sources: long-term estimates indicate that 5.5 \$c/kWh or less is achievable, including HVDC transmission. CCS, by contrast, cannot be cost-competitive with unmitigated coal-fired electricity, and thus not under current market prices, because it imposes an energy- and cost-penalty on the facilities that install it: this cost-penalty, even in long-term estimates, is 4 \$c/kWh or more, and only includes the CCS part of the investment. If there is value to using captured $CO_2$, or in the presence of a high carbon price, CCS can be a cost-effective option for electricity generation. At present, value only exists by using captured $CO_2$ to produce oil or natural gas, conferring substantial cost advantages to CSP.

**Please cite as:** Lilliestam, J., Bielicki, J., Patt, A. (2012): Comparing carbon capture and storage (CCS) with concentrating solar power (CSP): potentials, costs, risks, and barriers, in: *Energy Policy* 47, pp. 447-455. http://dx.doi.org/10.1016/j.enpol.2012.05.020

**Table 2: Summary of scope, potential, costs, technical risks and barriers to scaling up quickly of CCS and CSP**

| | **Coal-fired electricity generation coupled with carbon capture and storage (CCS)** | **Concentrated Solar Power (CSP)** |
|---|---|---|
| **Scope** | • Electricity sector: low (fossil fuels) or potentially negative (biomass) $CO_2$ emissions.<br>• Other large stationary $CO_2$ point sources | • Electricity sector<br>• Electricity with no $CO_2$ emissions |
| **Resource base** | • Coal >>100 years<br>• Storage >100 years<br>• Local water scarcity possible, but water is unlikely to limit overall expansion. Requires *additional* 150 to 3300 $m^3$/GWh | • Renewable, unlimited in time, sufficient for all reasonable CSP expansions<br>• Local water scarcity possible, but water is unlikely to severely limit overall expansion. Requires ~300 $m^3$/ GWh (dry cooling) – ~3000 $m^3$/ GWh (wet cooling) including 75 $m^3$/GWh for mirror cleaning. |
| **Investment needed*** | • US: $230 billion<br>• EU: $195 billion | • US: $210 billion (incl. HVDC transmission)<br>• EU: $170 billion (incl. HVDC transmission) |
| **Subsidies**** | • More expensive than conventional coal-fired electric power plants, because CCS is an add-on and incurs an energy penalty, unless the captured $CO_2$ can be used for marketable products or there is a sufficient economic disincentive for emitting $CO_2$. | • $50 billion each for European Union and United States |
| **Technical risks** | • Primarily health, groundwater, and climate risks related to the transport and storage of $CO_2$<br>• Environmental and health risks of coal mining and transportation | • Primarily electricity supply risks linked to transmission failures |
| **Barriers to scaling up quickly** | • More expensive than conventional coal-fired electricity; support and business case needed<br>• Legal and regulator uncertainties about storage liability and ownership<br>• Needs to be tested as integrated system at utility scale | • Currently more expensive than conventional power; initial support needed<br>• Investment in generation and transmission: business case needed<br>• Transmission system permission too time consuming, complex, and uncertain<br>• EU treaty with North Africa, international power market needed |

* To replace all present coal-fired power (315 GW in the United States, 214 GW in the European Union)

** To achieve current market prices (assumed to be $0.055 c/kWh)

The loci of risks differ between the technologies. For CCS, the risks arise mostly from the transportation and geologic injection of $CO_2$. Concerns about sudden releases from a ruptured pipeline or a well-blowout, for example, are present, but these likelihoods are small and the risks are likely to be minimal. Migration and seepage of $CO_2$ in the subsurface are the primary risks, which could reduce the effectiveness of CCS as a climate change mitigation technology. CCS could perpetuate reliance on coal, with the associated health and environmental risks related to coal mining and transportation. In contrast, CSP risks arise from electricity supply considerations, mostly from a potential failure of a long distance transmission line from the desert production sites. Concerns of terrorism against long HVDC lines and, in the EU-North African case, about the reliability of the exporters exist, but the redundancy of the power system strongly reduces these risks. In sum, the risks associated with either technology are small but those for CCS are less certain. Because the risks run on different dimensions, neither technology has a clear advantage.

The non-cost barriers to scaling up are conceptually similar but differ in substance. The water needs for CSP and CCS are high, and CCS water requirements are on top of those necessary for the coal-fired power plant equipped with CCS. Investors will have to consider water availability, which may constrain an expansion locally/regionally, although the overall availability is likely to be sufficient. CCS faces large uncertainties about legal frameworks, issues of ownership, liability, and consistent policy enablers. These topics are currently being addressed in both the United States and the European Union, and legislation can be expected in the coming years. It remains to be seen whether this solves the uncertainty problem for CCS. Similarly, regulation and legal issues are major bottlenecks for the expansion of desert CSP. Constructing the necessary amounts of HVDC transmission lines is difficult in the present social and regulatory environment in the European Union, due to public opposition and to unsatisfactory cost recovery regulations for transmission. Without these transmission lines, desert CSP expansion cannot occur, and improving the policy framework is a crucial issue for policy-makers. For CSP, generating electricity in countries outside those being served by that electricity (Mexico for the United States, North Africa for the European Union) complicates expansion, while raising potential social and political issues. International treaties, or international power markets, will be required. Such treaties are certainly possible—they exist in gas markets—but they must assure economic benefits to both the importer and the exporter, otherwise there is no incentive to deploy CSP outside of EU/US borders. Absent such international relationships, other technologies that can be deployed domestically (e.g. wind turbines, or CCS) are preferred. In terms of required legislation and regulation, neither technology has a clear advantage. However, the international cooperation required for CSP deployment for the European Union stands out as a critical challenge.

On the technical side, the technologies have different levels of maturity: as an integrated system CCS is still in the “innovation” stage, with high costs and uncertain learning rates, even though CCS can be applied more broadly than the electricity sector, and thus provide more opportunities for cost reductions from technological learning. Importantly, the performance and economic viability of integrated CCS systems deployed at the utility scale still remain highly uncertain, although the single components are well-known. Assuming that this viability can be demonstrated, and in a socially acceptable manner, there will still be a delay, at least a decade, before CCS could be scaled up. CSP, on the other hand, is in the “niche market commercialization” stage, where learning-by-doing and standardization lead to high and rather well-defined learning rates (see Grübler et al., 1999). Thus, CSP—as opposed to CCS—is suitable for expansion now, although it is still an immature technology and improvements are both likely and desired.

Both technologies face barriers—mostly legal, political, and social—that could hinder their deployment. Consequently, a lack of political support could cause either technology to fall short of its potential. On the other hand, with clear and strong political support, both CCS and CSP could each significantly contribute, in an economically feasible way, to the decarbonization of the electricity sectors in the United States and the European Union. Overall, both technologies have considerable advantages and disadvantages, and the choice of technology needs to be the product of subjective assessments by policy-makers of these benefits and costs.

# References

2009/31/EC, 2009. Directive 2009/31/EC on the geological storage of carbon dioxide. European Parliament, Council of the European Union, Brussels.

Al-Juaied, M. and Whitmore, A., 2009. Realistic costs of carbon capture. Harvard University, Cambridge.

Bachu, S., Gunter, W. and Perkins, E., 1994. Aquifer disposal of CO2: Hydrodynamic and mineral trapping. Energy conversion and management, 35(4): 269-279.

Bahrman, M.P. and Johnson, B.K., 2007. The ABCs of HVDC transmission technologies. An overview of high voltage direct current systems and applications. IEEE Power & Energy Magazine, 5(2): 32-44.

Battaglini, A. and Lilliestam, J., 2010. On transmission grid governance. Heinrich-Böll-Stiftung, Berlin.

Benson, S., 2004. From a geological perspective. Third annual conference on carbon capture and sequestration. VA Monitor exchange publications, Alexandria.

Benson, S., 2007. Monitoring geological storage of carbon dioxide. In: E. Wilson and D. Gerard (Eds.), Carbon capture and sequestration: Integrating technology, monitoring, and regulation. Blackwell, Oxford.

Bielicki, J., 2009a. Integrated systems analysis and technological findings for carbon capture and storage deployment. Ph.D. Thesis. Harvard University, Cambridge.

Bielicki, J., 2009b. Spatial Clustering and Carbon Capture and Storage Deployment. Energy Procedia (1), 1691-1698.

Böhme, D., Dürrschmidt, W. and van Mark, M., 2009. Erneuerbare Energien in Zahlen. Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU), Berlin.

BP, 2010. Statistical review of world energy. June 2010. British Petroleum (BP), London.

Bradshaw, J., Bachu, S., Bonijoly, D., Burruss, R., Holloway, S., Christensen, N. P., and Mathiassen, O. M., 2007. CO2 storage capacity estimation: Issues and development of standards. International journal of greenhouse gas control, 1(1): 62-68.

Bruant, R., Guswa, A., Celia, M. and Peters, C., 2002. Safe storage of carbon dioxide in deep saline aquifers. Environmental science and technology, 36(11): 240A-245A.

Carey, J. W., Svec, R., Grigg, R., Lichtner, P., Zhang, J., and Crow, W., 2009. Wellbore integrity and CO2-brine flow along the casing-cement microannulus. Energy procedia, 1(1): 3609-3615.

Carey, J.W., Wigand, M., Chipera, S., WoldeGabriel, G., Pawar, R., Lichtner, P., Wehner, S., Raines, M. and Guthrie, G., 2007. Analysis and performance of oil well cement with 30 years of CO2 exposure from the SACROC unit, West Texas, USA. International journal of greenhouse gas control, 1: 75-85.

Crow, W., Williams, B., Carey, J., Celia, M. and Gasda, C., 2009. Wellbore integrity analysis for a natural CO2 producer. Energy procedia, 1: 3561-3569.

CRS, 2010. Carbon capture: A technology assessment. Congressional research service report, Washington D.C.

CSP today, 2008. Lower cost of production is actually a by-product of Andasol 1's energy storage. CSP today, London, http://social.csptoday.com/taxonomy/term/83/lower-cost-production-actually-product-andasol-1s-energy-storage, 2011-12-06.

Czisch, G., 2005. Szenarien zur zukünftigen Stromversorgung. Kostenoptimierte Variationen zur Versorgung Europas und seiner Nachbarn mit Strom aus erneuerbaren Energien. Universität Kassel, Kassel.

Damerau, K., Williges, K., Patt, A. and Gauché, P, 2011. Costs of reducing water use of concentrating solar power to sustainable levels: Scenarios for North Africa. Energy policy, 39: 4391-4398.

de Figueiredo, M., 2007. Property interests and liability of geologic carbon dioxide storage. In: E. Wilson and D. Gerard (Eds.), Carbon capture and sequestration: Integrating technology, monitoring, and regulation. Blackwell, Oxford.

Dinica, V., 2006. Support systems for the diffusion of renewable energy technologies – an investor perspective. Energy Policy, 34(4): 461.

DLR, 2005. Concentrating solar power for the Mediterranean region. German Aerospace Centre (DLR), Stuttgart.

DLR, 2006. Trans-Mediterranean interconnection for concentrating solar power. German Aerospace Centre (DLR), Stuttgart.

DOE, 2010. Carbon capture: Beyond 2020. U.S. Department of Energy (DOE), Gaithersburg.

Dooley, J., Dahowski, R., Davidson, C., Wise, M., Gupta, N., Kim, S., Malone, E., 2006. Carbon dioxide capture and geological storage. Global energy technology strategy program, Battelle.

EASAC, 2011. Concentrating solar power: its potential contribution to a sustainable energy future. European Academies Science Advisory Council (EASAC), Halle.

EC, 2008. European energy and transport. Trends to 2030 - update 2007. European Commission (EC), Brussels.

ECF, 2010. Roadmap 2050. European Climate Foundation, Den Haag.

EIA, 2010. Electric power annual 2008. Energy Information Administration (EIA), Washington D.C.

ENTSO-E, 2010. Ten-year network development plan 2010-2020. European Network of Transmission System Operators for Electricity (ENTSO-E), Brussels.

Eurostat, 2010. Energy and transport in figures. Statistical pocketbook 2010. Eurostat, European Commission, Brussels.

Fritsche, U.R, 2007. Treibhausgasemissionen und Vermeidungskosten der nuklearen, fossilen und erneuerbaren Strombereitstellung. Öko-Institut, Darmstadt.

Goldberg, D., Takahashi, T. and Slagle, A., 2008. Carbon dioxide sequestration in deep-sea basalt. Proceedings of the National Academy of Sciences, 105(29): 9920-9925.

Grübler, A., Nakicenovic, N., Victor, D., 1999. Dynamics of energy technologies and global change. Energy Policy 27: 247-280.

Hepple, R. and Benson, S., 2004. Geologic storage of carbon dioxide as a climate change mitigation strategy: performance requirements and the implications of surface seepage. Environmental Geology, 47(4): 576-585.

Holloway, S., 2001. Storage of fossil-derived carbon dioxide beneath the surface of the Earth. Annual reviews of energy and environment, 26: 145-166.

House, K., Harvey, C., Aziz, M. and Schrag, D., 2009. The energy penalty of post-combustion CO2 capture and storage and its implications for retrofitting the U.S. installed base. Energy and environmental science, DOI: 10.1039/b811608c.

House, K., Schrag, D., Harvey, C. and Lackner, K., 2006. Permanent carbon dioxide storage in deep-sea sediments. Proceedings of the National Academy of Sciences, 103(33): 12291-12295.

IEA, 2007. CO2 capture ready plants. International Energy Agency (IEA), Paris.

IEA, 2009a. IEA CCS technology roadmap. International Energy Agency (IEA), Paris.

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

IEA, 2010a. Carbon capture and storage: Progress and next steps. International Energy Agency (IEA), Paris.

IEA, 2010b. Technology roadmap. Concentrating solar power. International Energy Agency (IEA), Paris.

IEA 2011. CO2 Emissions from fossil fuel combustion. 2011 Edition. International Energy Agency (IEA), Paris.

IEEE, 2008. HVDC projects listing. IEEE Transmission and Distribution committee, Teshmont consultants LP, Winnipeg.

IPCC, 2005. Carbon dioxide capture and storage. Intergovernmental Panel on Climate Change (IPCC), Cambridge university press, Cambridge.

IPCC, 2007a. Climate change 2007: Impacts, adaptation and vulnerability. Parry, M.L., Canziani, O.F., Palutikof, J., van der Linden, P. and Hanson, C. (Eds.), Cambridge University Press, Cambridge.

IPCC, 2007b. Climate Change 2007: Mitigation. Metz, B., Davidson, O., Bosch, P., Dave, R. and Meyer, L. (Eds.), Cambridge University Press, Cambridge.

IPCC, 2007c. Climate change 2007: the physical science basis. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H. (Eds.), Cambridge University Press, Cambridge.

IPCC, 2011. IPCC special report on renewable energy sources and climate change mitigation. Edenhofer, O., et al. (Eds.), Cambridge University Press, Cambridge.

Jaramilo, P., Griffin, W. and McCoy, S., 2009. Life cycle inventory of CO2 in an enhanced oil recovery system. Environmental science and technology, 43(21): 8027-8032.

Khosla, V., 2008. Scalable electric power from solar energy. The Climate Group, Brussels.

Klass, A. and Wilson, E., 2008. Climatic change and carbon sequestration: Assessing a liability regime for the long-term storage of carbon dioxide. Emory law review, Fall 2008.

Klass, A. and Wilson, E., 2010. Climate change, carbon sequestration, and property rights. University of Illinois law review, 2: 363-428.

Kutchko, B., Strazisar, B., Dzombak, D., Lowry, G. and Thaulow, N., 2007. Degradation of well cement by CO2 under geologic sequestration conditions. Environmental science and technology, 41: 4787-4792.

Lackner, K., 2002. Carbonate chemistry for carbon sequestration. Annual review of energy and environment, 27(193-232).

Lambertson, C.J., 1971. Carbon dioxide tolerance and toxicity. University of Pennsylvania Medial Center, Philadelphia.

Lilliestam, J. and Ellenbeck, S., 2011. Energy security and renewable electricity trade—Will Desertec make Europe vulnerable to the “energy weapon”? Energy policy, 39:3380-3391.

MacKay, D., 2009. Sustainable energy – without the hot air. UIT, Cambridge, UK, 366 pp.

Manne, A.S. and Richels, R., 2004. The impact of learning-by-doing on the timing and costs of CO2 abatement. Energy Economics, 26: 603-19.

McCoy, S., 2008. The economics of CO2 transport by pipeline and storage in saline aquifers and oil reservoirs. Carnegie Mellon University. Pittsburgh.

McCoy, S. and Rubin, E., 2008. An engineering-economic model of pipeline transport of CO2 with application to carbon capture and storage. International journal of greenhouse gas control, 2(2): 219-229.

McCoy, S. and Rubin, E., 2009. Variability and uncertainty in the cost of saline formation storage. Energy procedia, 1(1): 4151-4158.

Middleton, R. and Bielicki, J., 2009. A scaleable infrastructure model for carbon capture and storage: simCCS. Energy policy, 37: 1052-1060.

National grid, 2005. Transmission: the critical link. National grid, Westborough.

NETL, 2008. National carbon sequestration atlas of U.S. and Canada - Version 2. National Energy Technology Laboratory (NETL), Pittsburgh.

Oldenburg, C., 2007. Migration mechanisms and potential impacts of CO2 leakage and seepage. In: E. Wilson and D. Gerard (Eds.), Carbon capture and sequestration: integrating technology, monitoring and regulation. Blackwell, Oxford.

Patt, A., Pfenninger, S. and Lilliestam, J., 2010. Vulnerability of solar energy infrastructure and output to extreme events. ICTP/IAEA, Trieste.

Pearce, F., 2009. Sunshine superpower, New Scientist, pp. 40-43.

ReCharge, 2011. Big day for CSP as Gemasolar feeds the grid for 24 hours, ReCharge, London, http://www.rechargenews.com/energy/solar/article265281.ece, 2011.12.06.

Rhodes, J. and Keith, D., 2008. Biomass with capture: Negative emissions within social and environmental constraints. Climatic change, 87: 321-328.

Richter, C., Teske, S. and Short, R., 2009. Concentrating solar power. Global outlook 09. Greenpeace, SolarPACES, ESTELA, Brussels.

Rubin, E., Yeh, S., Antes, M., Berkenpas, M. and Davidson, J., 2007. Use of experience curves to estimate the future cost of power plants with CO2 capture. International journal of greenhouse gas control, 1: 188-197.

Sargent & Lundy, 2003. Assessment of parabolic trough and power tower solar technology cost and performance forecasts. National Renewable Energy Laboratory (NREL), Golden.

Schellekens, G., Battaglini, A., Lilliestam, J., McDonnell, J. and Patt, A., 2010. 100% renewable electricity - A roadmap to 2050 for Europe and North Africa. PriceWaterhouseCoopers, London.

Schott, 2009. Nevada solar one. Schott AG, Mainz.

Siddiqi, A., Anadon, L., (2011): The water-energy nexus in Middle East and North Africa. Energy policy, 39: 4529-4540.

SolarPaces, 2009. PS10. SolarPaces, Brussels.

Svensson, M., Odenberger, F., Johnsson, F. and Strömberg, L., 2004. Transportation systems for CO2 - application to carbon capture and storage. Energy conversion and management, 45: 2343-2353.

Toft, P., Duero, A., Bieliauskas, A., 2010. Terrorist targeting and energy security. Energy Policy, 38: 4411-4421.

Trieb, F., O'Sullivan, M., Pregger, T., Schillings, C. and Krewitt, W., 2009. Characterisation of solar electricity import corridors from MENA to Europe. German Aerospace Centre (DLR), Stuttgart.

van der Zwaan, B. and Gerlagh, R., 2009. Economics of geological CO2 storage and leakage. Climatic Change, 93(3): 285-309.

Wigand, M., Kaszuba, J., Carey, J. and Hollis, W., 2009. Geochemical effects of CO2 sequestration on fractured wellbore cement at the cement/caprock interface. Chemical geology, 256(1-2): 122-133.

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: 3089-3097.

Wilson, E. and Gerard, D., 2007. Risk assessment and management for geologic sequestration of carbon dioxide. In: E. Wilson and D. Gerard (Eds.), Carbon capture and sequestration: Integrating technology, monitoring, and regulation. Blackwell, Oxford.

Wilson, E., Johnson, T. and Keith, D., 2003. Regulating the ultimate sink: Managing the risks of geologic CO2 storage. Environmental science and technology, 37: 3476-3483.

WRI, 2008. Guidelines for carbon dioxide capture, transport and storage. World Resources Institute (WRI), Washington D.C.