Vulnerability of solar energy infrastructure and output to extreme events: climate change implications

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Abstract

This paper explores the potential vulnerability of solar energy systems to future extreme event risks as a consequence of climate change. We describe the three main technologies likely to be used to harness sunlight—thermal heating, photovoltaic (PV), and concentrating solar power (CSP)—and identify critical extreme event vulnerabilities for each one. We then compare these vulnerabilities with assessments of future changes in extreme event risk levels. We do not identify any vulnerabilities sever enough to halt development of any technology, although we do find a potential value in exploring options for making PV cells more heat resilient, and for improving the design of cooling systems for CSP.

Keywords: solar power, climate change, extreme events

1 Introduction

Climate change offers humanity two very different challenges. On the one hand, it will force people to have to adapt to changing climate conditions, making their infrastructure and their activities less vulnerable to changes in mean climate and to particular types of extreme events. On the other hand, in order to avoid climate change of a magnitude that may be beyond the range of possible adaptation, society will have to eliminate the emissions of greenhouse gases, most importantly carbon dioxide, within the next few decades. The latter challenge suggests that a move towards greater reliance on renewable energy sources will be necessary, in order to replace the fossil fuel sources that will have to be phased out. One of the most promising forms of renewable energy is sunshine, which can be harnessed for both heating purposes and electricity generation.

This paper examines the potential for conflict between these two challenges. The issue we address is the vulnerability of different technologies for transforming sunlight into usable energy to those extreme events that may become more severe as a consequence of climate change. In the following sections, we review each of the three main technologies currently being developed, and explore the potential extreme event vulnerabilities of each. After that, we review the recent climate literature to identify those types of extreme events that could become more problematic in the future because of climate change. In the final section we compare the two sets of information, to identify potentially problematic vulnerabilities.

2 Thermal heating

Solar thermal heating technologies capture heat from incoming solar radiation by transferring it to a transport medium, usually water or another liquid, or in some cases a gas such as air. The resulting hot medium can be used directly, or the heat can be used indirectly for space heating or cooling. Most solar thermal heating systems are installed in individual residences, but commercial use for apartment blocks and office buildings is increasing (ESTIF 2009).

There are three major types of collectors in use around the world (Weiss et al. 2009). Flat plate collectors consist of a covered flat plate containing a heat tube with a heat transfer liquid, and padded with various coating materials designed to maximize heat absorption. Evacuated tube or vacuum collectors consist of multiple glass tubes with the heat transfer liquid contained within a smaller tube separated from the outer by a vacuum, thus minimizing heat loss. The tubes are self-contained and transfer the heat to a secondary fluid cycle. Finally, unglazed collectors (usually made of plastic) are a simple collector with no covering plate, and used primarily for heating outdoor swimming pools. In systems producing hot water, a pressure tank is often mounted together with the collectors on the roof, or already integrated into the collector design.

Since solar thermal heating is a relatively mature technology (Seyboth et al. 2008), no radical changes or new technologies are to be expected that might affect the vulnerability of future solar thermal systems.

2.1 Current and future capacity

The current (as of 2007) distribution of solar thermal heating is shown in Figure 1. It is notable that China has by far the highest installed capacity and predominantly uses evacuated tube collectors. Europe and Japan predominantly use flat plate collectors, while in the United States and Australia, unglazed collectors for swimming pool heating make up the vast majority of installed systems.

<<Figure 1 about here>>

Looking at past growth rates for flat plate and evacuated tube collectors since the beginning of this century, the major growth markets have been China (including Taiwan) and Europe. In Europe, from about 600 MWth/a in 1999, annual installed capacity grew to about 2,000 MWth/a in 2007, while in China, even higher growth from about 3,000 MWth/a to almost 15,000MWth/a occurred in the same time (Weiss et al. 2009). These represent average annual growth rates of 16% and 22%, respectively. In North America, the market size for new unglazed collectors for pool heating has remained fairly constant.

For Europe, even with a business as usual growth scenario, capacity by 2050 would be more than 500 GWth (see Figure 2), more than 150 times the current European capacity (Weiss and Biermayr 2009). According to these projections, the potential for growth on such a scale exists in both southern and northern European countries. For other world regions, a similarly large potential exists. Solar thermal heaters work on latitudes ranging from regions close to the poles to the equator. In hot climates, solar water heaters generally have a lower net cost than alternative heating sources, such as gas boilers, whereas in colder climates such as many European countries, costs are higher due to lower energy output and the need for freeze protection (IEA 2008).

<<Figure 2 about here>>

2.2 Key vulnerabilities

2.2.1 Cold waves

When ambient temperature is lower than the temperature of the liquid inside the plate collector, heat loss to the environment directly reduces efficiency. Preparation for cold weather, which is not necessary in hot climates, indirectly reduces efficiency: the addition of antifreeze chemicals to the heat transfer fluid decreases its heat carrying capacity (Norton and Edmonds 1991). Anti-freeze addition also necessitates a heat exchanger and a secondary cycle for clean water, further decreasing efficiency (although secondary cycles may be used anyway). Evacuated tube collectors do not suffer from ambient temperature problems as much since their inner tube is insulated by a vacuum. For flat plate collectors, efficiency can decrease by more than 50% if ambient temperature is 50ºC lower than fluid temperature at the inlet. For evacuated tube collectors, performance stays more constant over a range of temperature differences, with only up to 20% efficiency decrease in the above scenario (Kalogirou 2004, Norton 2006). Nevertheless, solar thermal heating systems already operate in a wide range of climates today, including Nordic countries with a cold climate and severe winter. Therefore, one can expect the impact of future cold spells to be negative but not prohibitive.

2.2.2 Hailstorms

Modern flat plate collectors use reinforced glass and are not damaged easily by hailstones. In a test of fifteen flat plate collectors, all withstood 35mm hailstones and ten withstood 45mm hailstones (SPF 2009). Evacuated tube collectors can more easily be damaged because the individual tubes are not protected by a reinforced glass plate, but in most systems single tubes can be removed without shutting down the system, and the system can continue working with reduced capacity despite one or several non-functional tubes. In a test, out of 26 evacuated tube collectors, 15 withstood 25mm hailstones without damage, but only one withstood 45mm (SPF 2009). The results suggest that although current evacuated tube collectors are vulnerable to heavy hailstorms, it is possible to engineer tubes with higher resistance without compromising price (the collector resistant to 45mm hailstones is characterized as an 'inexpensive mass-produced import from the Far East'). The results further show that there is room for improvement both for flat plate and evacuated tube collectors, but flat plate collectors are currently more suited to areas where heavy hailstorms can be expected.

2.2.3 Prolonged cloudy weather

Cloudy weather does not damage solar thermal collectors, but it does reduce their efficiency, simply because it results in a lower density of solar radiation reaching the ground, and in lower ambient air temperatures. Evacuated tube collectors have several advantages over flat plate collectors in instances with more diffuse than direct insolation (i.e. on a cloudy day). First, they do not suffer as much from temperature loss (see above). Second, because of their tubular form, they passively 'track' the sun. Experimental results confirm that evacuated tube collectors perform better in cloudy conditions (Trinkl et al. 2005), and this seems to hold even for hot climates where heat loss plays less of a role (Honeyborne 2009).

3 Photovoltaic

Photovoltaic (PV) cells directly convert solar radiation into electricity through the photovoltaic effect. Currently used cells can convert up to about 20% of incoming solar radiation into electricity. Two major PV technologies play a role at the moment and in the near future. The first is crystalline silicon (Si), which currently accounts for about 80% of the global market. It descends from semiconductor technology and is the most mature PV system.

Nevertheless, its importance will decrease as newer technologies become cheaper and more efficient (Wolfsegger et al. 2008).

Thin film technology is gradually expanding its market share. Thin film modules consist of very thin photosensitive layers grafted onto a carrier material of relatively low cost (plastics, metal, or glass). Their cost is lower than crystalline Si cells, but so is their efficiency. The photosensitive material can be silicon-based, but increasingly, it will not be (IEA 2008). Other, newer technologies exist and are under development, but have no significant market share yet (Frankl et al. 2005).

A major component of a PV power system is the inverter, which converts direct current power output into alternating current that can drive common household appliances. Literature studies consistently show that the inverter is the most unreliable component of a PV system, in one study accounting for 69% of unscheduled maintenance costs (Kurtz et al. 2009A). However, since the PV panels are the main weather-exposed component, our analysis focuses on them.

3.1 Current and future capacity

Currently, Europe is far ahead in PV installations, with 81% of worldwide capacity. The two major contributors to that are Germany and Spain, with 33% and 56% of European capacity, respectively (EPIA 2009). However, the potential for PV is much larger in other regions of the world, and consequently the IEA projects a considerable amount of PV electricity production in other world regions by 2050 (Figure 3).

<<Figure 3 about here>>

By the end of 2008, global installed PV capacity was just under 15 GW (EPIA 2009). A scenario by the European Photovoltaic Industry Association sees this rise to 1,864 GW in 2030 (Wolfsegger et al. 2008), a more than hundredfold increase. The IEA BLUE scenario predicts a global PV electricity production of 2 584 TWh in 2050, which would amount to 6% of total world electricity generation (IEA 2008). The majority of this capacity is expected to be located in North America, Latin America and China, covering a range of different climate zones.

<<Figure 4 about here>>

The PV market is projected to shift away from crystalline Si technologies, first primarily to thin films, then to other devices (Frankl et al. 2005). Figure 4 shows a scenario with high technological development, but even under more moderate assumptions, crystalline Si will decrease in importance. This may also have an impact on the vulnerability of PV installations to extreme weather, depending on the vulnerabilities of the devices prevalent in the future.

3.2 Key vulnerabilities

3.2.1 Hailstorms

The major physical component of PV systems exposed to weather are the modules. Hailstorms could cause fracturing of the glass plate covering most PV modules, resulting in direct damage to the underlying photoactive material or causing slower-onset problems through exposing the internal components to the environment and thus to chemical or physical degradation.

For the international standard qualification test IEC 61215 for crystalline Si, panels must withstand 11 impacts of 25 mm hailstones at 23 m/s (Kurtz et al. 2009A). The same requirements apply to IEC 61646, the test for thin film panels based on IEC 61215 (Wohlgemuth et al. 2006). However, these tests have been criticized as not being representative of real-life conditions and may not accurately predict lifetimes and resistance to real-world environmental impacts (Osterwald and McMahon 2009).

Generally, industry representatives (as well as insurers) see a need for more evaluation of the vulnerability of PV systems to weather-related stresses, which include hail, wind and extreme temperatures, as well as better coordinated testing (Speer et al. 2010). There is also evidence that failure rates in tests have increased in more recent years, which could partially be due to high market growth and entry of new manufacturers, and partially due to additional testing criteria (TamizhMani et al. 2008).

3.2.2 Heat waves

In general, performance of PV modules drops as their temperature increases. This means that high ambient air temperatures in situations with high direct solar irradiation can have a significant impact on the maximum possible power output. Increased temperature has a negative effect on current thin-film (Mohring et al 2004) as well as crystalline Si modules (Vick and Clark 2005, Radziemska 2003). There is evidence that certain types of PV modules are more suited to certain climates than others (Carr and Prior 2003, Gottschalg et al 2004). Some modules are less affected by temperature (Makrides et al. 2009), and could therefore be more suitable for hotter climates or areas where significant heat waves are expected.

Heat also has an effect on panel degradation. Long-term exposure to heat will have the panel age more rapidly, while some materials may not be able to withstand short peaks of very high temperature (Kurtz et al. 2009B). It is possible to cool PV panels, either passively through natural air flows (Tanagnostopoulos and Themelis 2010), or actively through forced air and liquid coolants (which is mainly considered for systems that concentrate light onto PV cells, see Royne et al. 2005).

3.2.3 Sand and wind storms

A side effect of strong wind is sand and dust deposition. One study found that higher wind speeds increase the performance loss due to deposition of aeolian dust on PV cells (Goossens and Van Kerschaever 1999) because the amount of particle drop is higher for increased wind velocities. An application study for a thin film system in the United Arab Emirates found that dust accumulation had a significant impact on power output over time (Mohandes 2009). Yet, siting PV in desert regions still results in a higher power output in comparison to countries in temperate zones where cloud cover reduces PV performance. Although sand storms can have an abrasive and thus damaging effect on panels, the selection of an appropriate coating material can prevent damage (Thornton 1992).

Thus, the negative effect of storms can be minimized by appropriate design. In addition, proper installation is important to prevent problems with storms, such as a sufficiently strong mounting to withstand expected wind strengths, or leaving free space so that snow can slide off the panel (Deutsche Gesellschaft für Sonnenenergie 2008).

3.2.4 Prolonged cloudy weather

The effect of clouds on PV energy output is, not surprisingly, negative, although the magnitude of this effect depends on different technologies, and on the degree of cloudiness. As clouds block the sun, the relative fraction of diffuse light increases. This means that devices that deal better with diffuse light would have a relative advantage under frequently cloudy conditions. Concentrating is not possible with diffuse light, so such systems are at a disadvantage. Rough-surfaced PV modules do a better job in diffuse light (Nelson 2003). Work has been done on the effects of moving clouds on grids with distributed photovoltaics for over 2 decades (e.g. Jewell and Unruh 1990), and it is possible that the maximum penetration rate of PV in a grid is limited by such cloud effects (Eltawil and Zhao 2010). These limits may become more relevant if prolonged periods of overcast skies occur with greater frequency. However, there are ways to improve output under overcast conditions by selecting an appropriate tilt angle (Armstrong and Hurley 2010, Kelly and Gibson 2009).

4 Concentrating solar power

Concentrating solar thermal power (CSP) stations collect and concentrate direct sunlight and use it to produce heat and drive a steam turbine to produce electricity. There are two major CSP technologies: Power towers, where flat mirrors focus the sun on one point in a high tower, and parabolic troughs, where curved mirrors focus the sunlight on a line running along the mirrors. Other technologies are under development, but these are the only two that are commercially viable today (DLR, 2005; Márquez Salazar, 2008; Pitz-Paal et al., 2004; Richter et al., 2009).

A key feature of the CSP technologies is the option of thermal storage. In such a system, some of the heat collected is used to power the steam turbine cycle immediately, while the rest of heat is diverted to a storage facility, to be used to power the turbine later on. Several of the CSP plants built in Spain have thermal storage, with the capacity to operate at full load for up to 7.5 hours, in the absence of direct sunshine (Khosla, 2008; Richter et al., 2009). These storage units show greater than 90% efficiency, and adding more storage, at least up to 15-16 hours capacity, possibly more, does not influence the levelized cost of electricity (LCOE) negatively. Extending storage to 16 hours would allow for continuous power production, while longer times (>24h) would make it possible to smooth out the effects of large storms (Khosla, 2008; Trieb et al., 2009).

4.1 Current and future capacity

Currently, some 700 MW of CSP capacity are installed around the world. The 350 MW SEGS power station in California was built in the late 1980s, but after that no more CSP stations were built for more than 10 years. Led by attractive support schemes, attention has now again turned to CSP. In 2007, the second US CSP station, Nevada Solar One, with a capacity of 64 MW was opened. Currently, the permission processes for some 5 GW are currently under way, and another 4 GW are announced in California alone (California Energy Commission, 2009). Strong growth can be observed also in Spain: in 2008 and 2009, about 250 MW CSP was built, and 800 MW CSP installations are under construction. In late 2009, 2 GW were reported to stand just before construction start, and another 10 GW are in planning (Richter et al., 2009).

As CSP is still more expensive than conventional power, wind and biomass power, a large-scale CSP expansion is unlikely in the coming decade. The Med-CSP and Trans-CSP scenarios of the DLR see the largest growth from 2030 to 2050, a period that contains 80% of the total 360 GW installed around the Mediterranean in 2050. Because of the optics of concentration, CSP cannot utilize diffuse light, but requires direct sunlight. This makes desert areas especially suited for CSP, where the direct normal isolation is high and the air is typically cloudless and dry ((Richter et al., 2009)). In the DLR scenarios, almost all CSP capacity is located in desert areas: 30 GW in Algeria, Morocco, Yemen and Iraq respectively by 2050, 63 GW in Iran and 71 GW in Egypt, as compared to 5 GW in Spain[1] (DLR, 2005; DLR, 2006). However, even modest growth in CSP—consistent with existing development plans and similar growth over the next ten to fifteen years—could lead to its costs falling to below that of conventional power sources, such as coal (Williges et al., 2010); in such a case, one could expect CSP capacity to begin to boom.

4.2 Vulnerabilities

To a large extent, a CSP plant has the same vulnerabilities to extreme events as other thermal power plants. The differences apply to two factors: First, the primary energy is supplied by a mirror field. Second, CSP plants will typically be located in deserts or arid areas. Therefore, the key vulnerabilities are events that prevent the mirrors from functioning or destroy them completely, as well as extreme heat and, in some non-desert cases, droughts.

4.2.1 Sand storms

The Sahara experiences several sand storms each year. During these storms visibility drops to close to zero and CSP stations would thus have to rely on their thermal storages to maintain production for the duration of the storm. Only if the storm is very large or if the power plant is not equipped with a large enough storage, power generation will cease. Concerns that the mirrors would be “sand blasted” by a strong sand storm and rendered useless have been heard, but remain unconfirmed: the German Aerospace Centre (DLR) reports, on which Desertec is based, do not mention sand storms, and neither does the Greenpeace series on CSP (Aringhoff et al., 2005; DLR, 2005; DLR, 2006; DLR, 2007; Pitz-Paal et al., 2004; Richter et al., 2009; Trieb et al., 2009). It seems, however, that the mirrors can be protected from the sand, simply by turning them upside down (trough) or turning them out of the wind (tower heliostats). When the storm has passed, the mirrors may need to be cleaned, a process that will take up to a few days (Bradsher, 2009; Jacobson and Delucchi, 2010). Therefore, the effects of sand storms will likely be isolated to the period of the sand storm and immediately thereafter. Blackouts or system instability due to the simultaneous failing of numerous CSP plants across wide areas are very unlikely, due to the possibility of thermal storage.

4.2.2 Heat waves and droughts

As CSP plants are built in arid areas, only few will rely on water for cooling. Instead, most CSP plants will rely on dry cooling, which use no water and are thus resistant to droughts (Pitz-Paal et al., 2004). The efficiency of a dry-cooled power plant, however, depends on the ambient temperature. Depending on which design and which steam temperatures are used, the efficiency decreases by 3-9% when the ambient temperature changes from 30 to 50°C. During the hottest 1% of hours, efficiency may drop by 6% (tower) to 18% (trough) (DOE, 2007). Therefore, if both average temperatures and the incidence of extreme heat events increase with climate change, the general efficiency of CSP plants may decrease slightly, but production will be possible at all times.

This is an important difference to the wet cooled power plants at river sites in Europe. Many of these power stations, including large nuclear power stations, already today need to shut down during heat waves and/or droughts. In the future, this production reduction or complete

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[1] At least the number for Spain seems unrealistically low: at the moment, some 800 MW CSP installations are under construction in Spain, 2 GW stand just before construction start, and another 10 GW are in planning (
Richter, C., Teske, S. and Short, R., 2009. Concentrating solar power. Global outlook 09. Greenpeace, SolarPACES, ESTELA, Brussels.).

stoppage may increase to up to 16% of the total production during the summer months (Förster and Lilliestam, 2010; Koch and Vögele, 2009). Thus, although CSP production may be reduced due to lower efficiency during heat waves, the CSP system is less vulnerable to heat waves and droughts than the current, wet-cooled nuclear and coal power systems.

4.2.3 Prolonged cloudy weather

The effects of clouds on CSP are more marked than they are on PV or solar thermal heating; because solar concentrators rely on direct insolation, the diffusion that accompanies clouds makes them ineffective, and the output from the mirror field ceases. Where the combined period of cloudiness and darkness exceeds the thermal storage capacity, power output from the plant will cease. It is for this reason that CSP is seen as an appropriate technology only for very dry locations, where prolonged cloud cover is rare.

Unlike solar thermal heating (which is used entirely onsite) and PV (which is used both onsite and within the same power market), future CSP developments will likely be built largely to serve distant power markets. For example, in California, the SEGS CSP array is located in the arid region east of the Sierra mountains, while the power is consumed largely to the west of the mountains, where cloudy weather is much more common. A critical issue for maintaining the reliability of power systems that, in the future, rely on a large share of CSP will be to locate generating capacity over a geographically wide area, so that local incidents of cloudy weather only affect a small share of the capacity for the grid.

5 Observations and projections of climate extremes

Researchers analyze and describe climate anomalies—departures from historical mean conditions—over a range of time scales. The term climate change is often reserved for changes in mean states—such as for temperature—observed over multi-decadal time periods. Over multiple years, researchers describe climate variability, which often occurs because of the cyclical nature of important large-scale climatic drivers, such as the North Atlantic Oscillation (NAO) or the El Nino-Southern Oscillation (ENSO) phenomenon, which leads to years of drought or heavy rainfall in many parts of the world. The term "extreme event" describes climatic anomalies of shorter durations. These can include droughts (which can extend for multiple seasons), tropical cyclones (which typically last several days), to periods of heavy rain and wind (which can often last for less than a day). Importantly, the longer-term phenomena often include changes in the magnitude and/or frequency of the shorter-term phenomena. Thus, an important aspect of long-term climate change is that it can be associated with changes in average climate variability (such as due to an increase in the magnitude or frequency of El Nino events), or the average frequency of extreme events of a particular magnitude (McBean, 2004; Mirza, 2003; Patt et al., 2010). So too can climate variability be associated with changes in the likelihood of extreme events.

In this section, we summarize recent findings on the links between climate change and changing frequency and magnitudes of extreme events. At the outset, it is important to note that the science of projecting changes in extreme event magnitude or frequency is in general more difficult than projecting changes in mean states (Easterling et al., 2000). There are two main reasons for this. First, by their very nature, extreme events happen infrequently, and hence there is a limited observational record of their occurrence (Trenberth et al., 2007). This increases the uncertainty associated with estimates of the links between atmospheric forcing with the occurrence of extreme events. Second, many extreme events occur at fine spatial scales, which makes them more difficult to model. Cloud formation, for example, is central to many extreme events, and yet remains one of the most difficult challenges in climate modeling (Trenberth et al., 2007).

5.1 Temperature

Central to climate change is an increase in average temperature, caused by elevated greenhouse gas concentrations in the atmosphere absorbing outgoing longwave radiation, and re-radiating a portion of that energy towards the earth surface. To a great extent this means that the earth surface does not necessarily heat up more quickly, but rather cools down more slowly. In turn, this suggests that the greater change has been and will be in night-time temperatures, rather than daytime: this implies that major change in temperature extremes will be a reduction in extreme cold events, more than an increase in extreme hot events. Indeed, the evidence bear this out. Table 1, summarizes the observed changes in extreme temperatures for daytime and nighttime temperatures.

<<Table 1 about here>>

The future will likely continue these trends. Several studies show that extremes in hot weather track the average temperature changes, while the temperatures associated with extreme cold weather rising somewhat faster (Trenberth et al., 2007). There may be spatial and temporal patterns to this. Meehl and Tebaldi (2004) show that a pattern of increasing heat waves is especially pronounced over western Europe, the Mediterranean, and southeast and western United States, while a multi-model ensemble, shown in Figure 5, suggest greatest warming over more arid areas. Weisheimer and Palmer (2005) show that seasonal warm anomalies over land are more pronounced during the northern hemisphere summer (June, July, and August) than during the winter. While this latter result seems to contradict the projection that the decrease in cold events will outpace the increase in warm events, it could result from the important role that changes in soil moisture play in temperature extremes. Since drier soils allow for greater temperature variation, increasing summer dryness could lead to greater variation than simple changes in average temperature would account for. At the same time, the role that soil moisture and vegetation play make for a great deal of uncertainty in future estimates, and it is hard to go beyond suggesting qualitative changes in the magnitude and frequency of extremes.

<<Figure 5 about here>>

5.2 Precipitation and cloudiness

There are important regional differences in projected changes in average precipitation, with the general result that mid-latitude regions are projected to become drier, leading to an increased likelihood of drought (Meehl et al., 2007). At the same time, a core result across climate models is that more precipitation will be concentrated in high precipitation events (Meehl et al., 2007), with any increase in the intensity of extreme precipitation events being greater than any local increases in total average precipitation (Kharin and Zwiers, 2005). This is consistent with observed trends; in every place where data are abundant and have been analyzed (generally least the case in the tropics and subtropics), there has been an observed trend towards an increase in the proportion of precipitation occurring in the form of extreme events (Trenberth et al., 2007).

Changes in cloud cover are more regionally specific, and also result from a combination of factors affecting cloud formation at different altitudes. In general, climate models suggest an increase in the elevation of clouds under warming conditions (Meehl et al., 2007). While past data show total cloudiness to have increased over many regions (North America, North and Central Asia, Western Europe, and Australia), while decreasing over some others, such as central Europe and China (Trenberth et al., 2007), future projections are generally consistent with a pattern of decreasing precipitation in low to mid-latitude regions: in these regions cloud cover will also likely decrease. Figure 6 shows projections for the change in cloudiness over the coming century. There do not appear to be any projections for changes in the duration of long-term cloudy events.

<<Figure 6 about here>>

5.3 Wind and storms

A final issue is the change in the magnitude and frequency of storms, and the high winds that come with them. Consistent with warmer sea surface temperatures fueling more powerful convection over water, past data suggest an increase in the intensity, but not necessarily frequency, of tropical cyclones, typically the most intense large scale storms (Emanuel, 2005). Model simulations suggest a continuation of the same pattern for future tropical storm development, across ocean basins (Bengtsson et al., 2007; McDonald et al., 2005). Past data suggest a similar trend for extra-tropical storms, namely an increase in their strength with warming temperatures (Trenberth et al., 2007). Past wind speed data is scarce, however, and there have been studies of changes in actual wind speeds. One study found an increase in top wind speeds over southern New Zealand (Salinger et al., 2005), while another found a decrease in top wind speeds over the Netherlands (Smits et al., 2005). The differences in these results can not be adequately explained.

Often associated with extra-tropical storms is hail. Hail forms as a result of very high vertical convection and low temperatures at the top of the storm. One might assume that climate change would lead to an increase in the frequency and severity of hailstorms, given a general increase in the severity of storms in general. Examining the case of Australia, however, Niall and Walsh (2005) found this not to be the case. Climate change may lead to a decrease in vertical temperature gradients (i.e. the upper troposphere may be warmer in the future relative to ground level), resulting in a decrease in the strength of vertical convection. The study found this to balance the effect of increasing surface storm intensity, leading to no significant changes in hailstorm frequency.

6 Discussion

Clearly, each solar technology is vulnerable to different kinds of extreme events, either in the form of reduced energy output, a requirement for cleaning, or permanent damage to infrastructure. At the same time, the different extreme events may grow more or less problematic in the future than they are today, as a result of climate change. Table 2 aggregates this information.

<<Table 2 about here>>

From Table 2, several vulnerabilities stand out as potentially important, at least for some regions. First, the increase in heat waves that is projected for the future could pose a problem for both PV and CSP. Comparing the two technologies, the problems are greater for PV, which can suffer marked efficiency losses, as well as material damage, while the consequences for CSP are relatively minor. Fortunately, the greatest change in temperature anomalies will be in terms of warmer nights, which are largely unproblematic for solar energy generation. Only in the hottest conditions could CSP, utilizing thermal storage and hence generating through the night, be negatively affected by this trend.

Second, strong winds may prove to be a problem for all three technologies. While not as clear as for the increasing incidence of heat waves, there is a potential trend, at least in many locations, for an increase in the incidence of high winds. High winds can cause damage, in the case of flying debris, and because of dust deposition require the cleaning of solar collectors and mirrors. In the case of CSP, which is typically built in desert locations, high winds are often associated with sandstorms, which can require the shutdown of a facility.

Both hail and prolonged cloudiness could potentially be problems, although this is less clear as for heat waves and high winds. Both solar thermal and PV can be damaged by large hailstones; however, existing design standards seem to be adequate to ensure minimal damage. There is no clear evidence, at least now, that climate change will make hail a greater problem in the future than it is now. All three technologies suffer from prolonged cloudiness, and here the trend as a result of climate change is latitude specific. In general, high latitudes can expect greater cloudiness in the future. This is most likely to be a problem for thermal heating, which is the only one of the three technologies that is cost effective at high latitudes. Mid- and low-latitude regions can expect to see reduced cloudiness in the future, which could benefit all three technologies.

These results do not raise any particular red flags, in terms of signaling major vulnerabilities to climate change induced extreme events for solar technologies. However, there may be value in exploring technical options for making PV less heat sensitive, and for improving the designs of CSP cooling systems. In the absence of such technological development, it may prove to be the case that PV in particular becomes a technology generally inappropriate for extremely hot locations.

We have reached these results in qualitative terms, and have not engaged in the attempt to model quantitative changes in energy output or costs of different technologies. Primarily, this is because the uncertainties—both with respect to future climatic conditions and in the case of possible future technological developments—are simply too high to justify the latter analysis. Should that uncertainty fall in the coming years, it may become possible to engage in quantitative modeling of high enough reliability to provide useful results.

Figures and tables

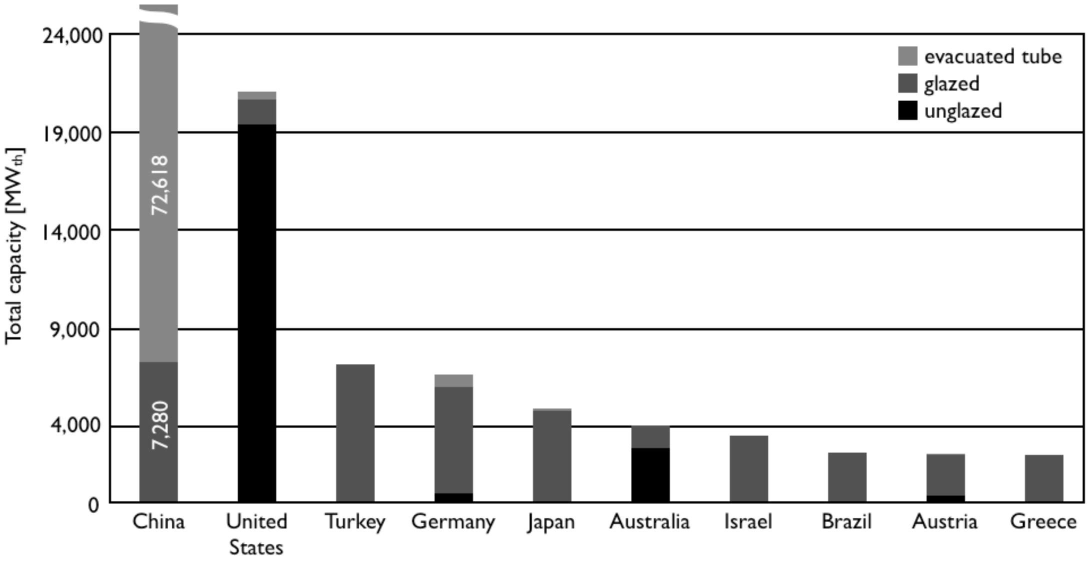

Figure 1: Installed solar thermal heating in top 10 countries Source: Weiss et al. (2009)

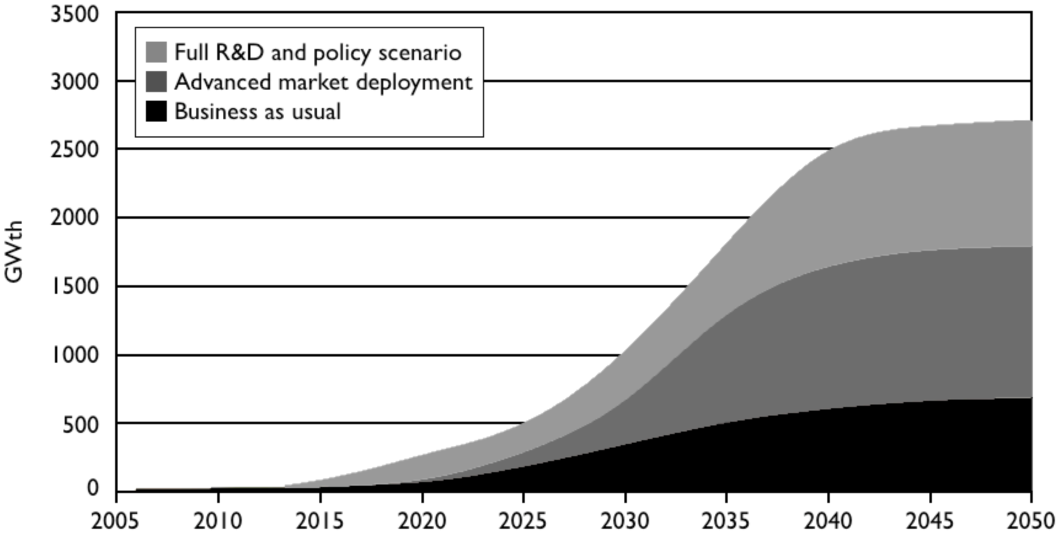

Figure 2: Total installed European capacity up to 2050 for 3 scenarios. Source: Weiss and Biermayr (2009)

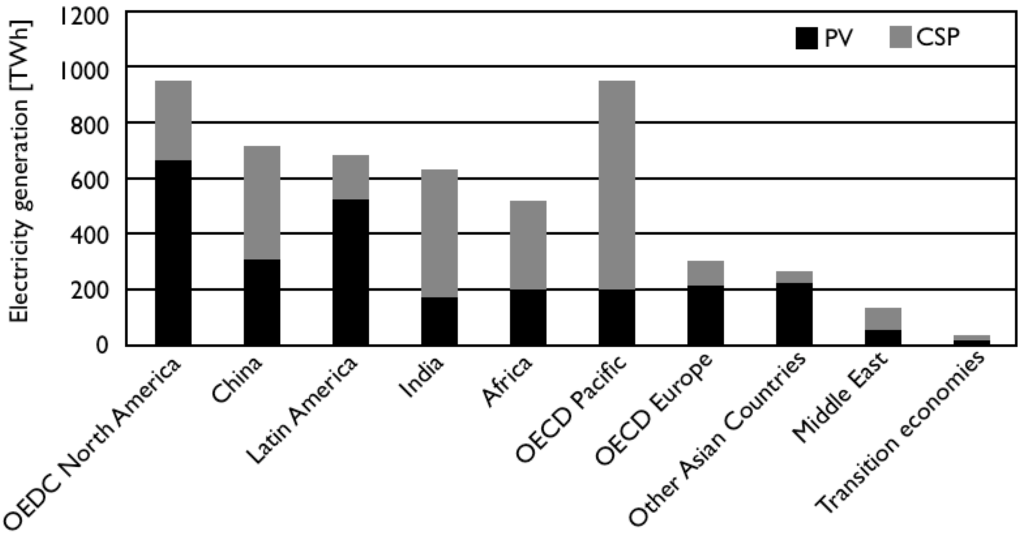

Figure 3: IEA BLUE scenario projections for PV and CSP in 2050. Source: IEA (2008)

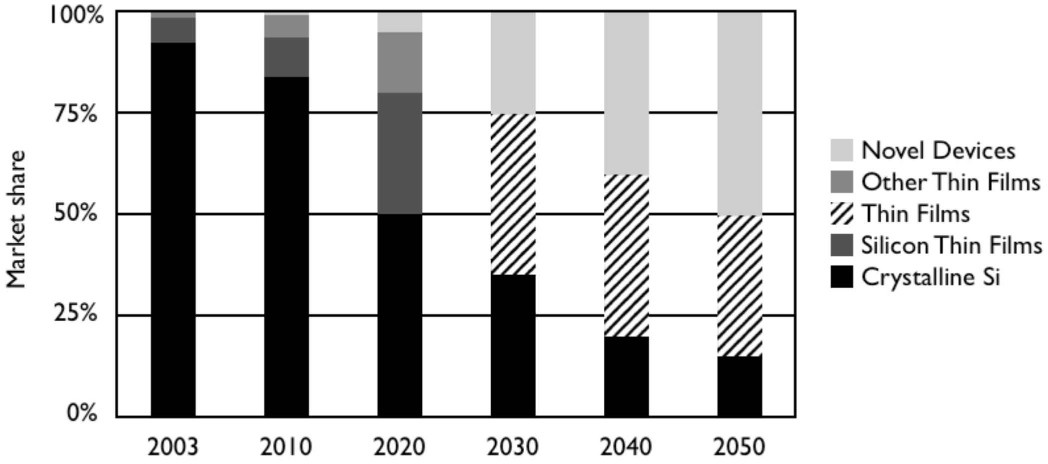

Figure 4: Projected market share of major PV technologies. Source: Frankl et al. (2005)

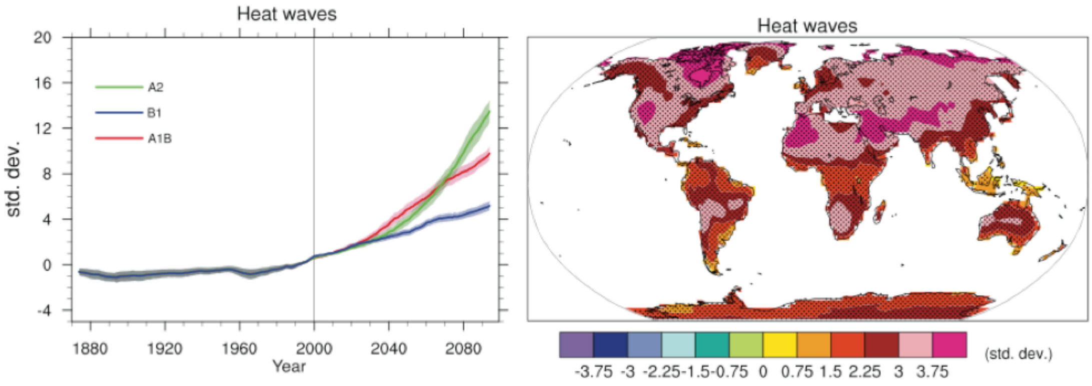

Figure 5: Changes in heat waves according to a multi-model simulation. The left hand graph shows globally averaged past data and future projections according to multiple emissions scenarios, capturing the changes in heat wave duration, defined as the longest period of the year with at least five consecutive days of temperatures at least 5°C above the historical average for that day of the year. The right hand map shows the spatial distribution of these changes, projected for the period 2080 – 2099 and compared to the period 1980 – 1999. Source: Meehl et al. (2007)

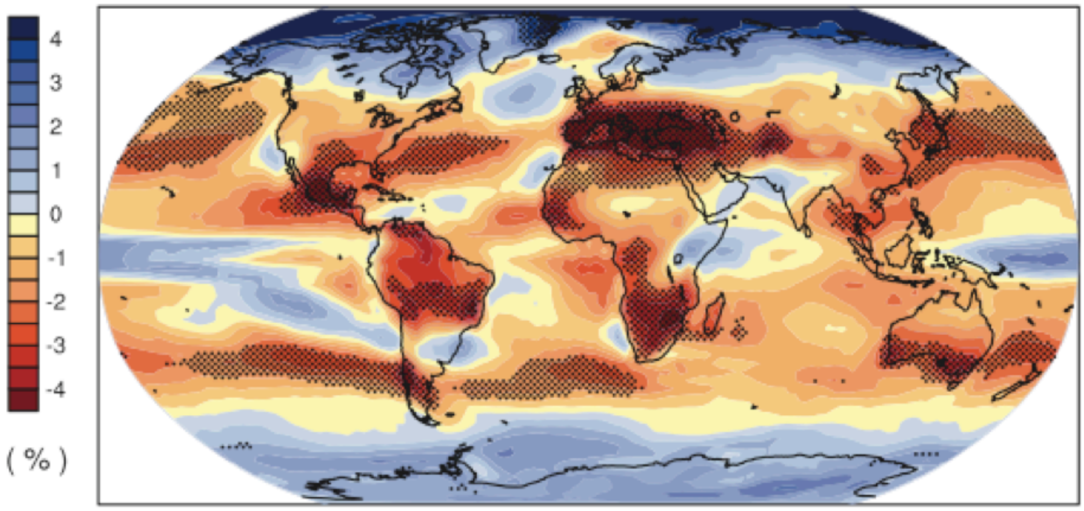

Figure 6: Changes in the percent of cloud cover between 1980 – 1999 and 2080 – 2099. Red areas show regions with decreasing future cloudiness, based on a multi-model ensemble, while areas in blue show increases in cloudiness. Areas stippled in black show significant changes, i.e. the average change across models was greater than the variation between individual model results. Source: Meehl et al. (2007)

Table 1: Trends of changes in temperature extremes. Values are percent change in the frequency of temperature ranges, defined by 10% and 90% probability thresholds for the period 1961 – 1990. Sources: Trenberth et al. (2007), Alexander et al. (2006).

	1951 – 2003	1979 – 2003
Cold nights	– 1.17 +/– 0.20	– 1.24 +/– 0.44
Warm nights	1.43 +/– 0.42	2.60 +/– 0.81
Cold days	– 0.63 +/– 0.16	– 0.91 +/– 0.48
Warm days	0.71 +/– 0.35	1.74 +/– 0.72

Table 2: Summary of key vulnerabilities and climate projections

	Thermal heating	*PV*	*CSP*	*Future trend*
Heat waves		Reduced output and potential material damage	Reduced output due to cooling problems	Increase
Cold waves	Reduced output			Decrease
Hail	Potential material damage	Potential material damage		No clear trend
Strong wind	Material damage from debris, and need for cleaning	Material damage from debris, and need for cleaning	Reduced output, material damage, and need for cleaning	Potential increase, but regionally variable
Prolonged cloudiness	Reduced output	Reduced output	Reduced or eliminated output	Increase at high latitudes, decrease at low latitudes

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