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Vulnerability of solar energy infrastructure and output to climate change

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Abstract

This paper reviews 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 climate vulnerabilities for each one. We then compare these vulnerabilities with assessments of future changes in mean conditions and extreme event risk levels. We do not identify any vulnerabilities severe enough to halt development of any of the technologies mentioned, 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.

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1 Introduction

One of the most promising forms of renewable energy is sunshine, which can be harnessed for both heating purposes and electricity generation. To examine the climate vulnerability of different technologies for transforming sunlight into usable energy, we start by providing an overview of the anticipated climate changes. In some cases, details matter. For example, climate models suggest that warming will, in most places, be greater for nighttime temperatures than for daytime temperatures, partly because the greenhouse effect hinders nighttime cooling, and partly because of changes in cloud formation (Lobell et al. 2007). This is important for considerations of solar energy, which operates primarily in the daytime.

There are important regional differences in projected changes both for extreme events and for average conditions. In terms of average conditions, mid-latitude regions are projected to become less cloudy and drier (Meehl et al. 2007). This is consistent with observed trends (Trenberth et al. 2007). While past data show total cloudiness to have increased over many regions and decreasing over others (Trenberth et al. 2007), future projections are generally consistent with a pattern of decreasing cloudiness in low- to mid-latitude regions (Trenberth and Fasullo 2009).

In terms of extreme events, Meehl and Tebaldi (2004) show that a pattern of increasing heat waves is especially pronounced over western Europe, the Mediterranean, and the southeast and western United States, while a multi-model ensemble suggests the greatest warming over more arid areas (Meehl et al. 2007). 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. For precipitation, this will be increasingly concentrated in high precipitation events (Meehl et al. 2007), with any increase in intensity being greater than any local increases in total average precipitation (Kharin and Zwiers 2005). Consistent with the warmer sea surface temperatures that fuel more powerful convection over water, past data suggest an increase in the intensity, but not necessarily the frequency, of tropical cyclones (Emanuel 2005), something that model simulations suggest will continue (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 temper- atures (Trenberth et al. 2007). Past wind speed data are scarce, however, but 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 cannot be adequately explained.

Often associated with extra-tropical storms is hail, which forms from very high vertical convection and low temperatures at the top of the storm. Examining the case of Australia, Niall and Walsh (2005) found no significant changes in hailstorm frequency. Climate change may lead to a decrease in vertical temperature gradients, resulting in a decrease in the strength of vertical convection. The study found that this balances the effect of increasing surface storm intensity.

Finally, coupled to changes in both precipitation and wind patterns are levels of airborne dust. Prospero and Lamb (2003) and Jilbert et al. (2010) suggest that dust deposition in non- arid regions is heavily influenced by inter-annual climate variation, and hence potentially by climate change. While this is partly due to changes in dust emissions in source regions (e.g., the African Sahel, or the North African Mediterranean region, which emit greater quantities during dry years), it is more heavily influenced by changes in the wind patterns transporting the dust. Jacob and Winner (2009) suggest that there is no clear direction of change.

All these changes could have some effect on the performance and reliability of solar technologies. In the following three sections, we review the three main ones, and their particular weather vulnerabilities, before reaching final conclusions on any causes for concern.

2 Thermal heating

Solar thermal heating technologies capture heat from incoming solar radiation by transfer- ring it to a transport medium, usually water or another liquid. Most solar thermal heating systems are installed in individual residences, but commercial use for apartment blocks and office buildings is increasing (ESTIF 2009).

Solar thermal heating is a relatively mature technology (Seyboth et al. 2008), and works at latitudes ranging from regions close to the poles to the equator. There are three major types of collector. Flat plate collectors consist of a coated plate containing a heat tube with a heat transfer liquid. Evacuated tube or vacuum collectors consist of a heat transfer liquid contained within a smaller tube separated from an outer tube by a vacuum, that minimizes heat loss. Finally, there are unglazed collectors, usually made of plastic, that are used primarily for heating outdoor swimming pools.

2.1 Vulnerability to 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 indirectly reduces efficiency, as the addition of antifreeze chemicals to the heat transfer fluid decreases its heat carrying capacity (Norton and Edmonds 1991). The addition of anti-freeze also necessitates a heat exchanger and a secondary cycle for clean water, further decreasing efficiency (although secondary cycles may be used anyway). For flat plate collectors, efficiency can decrease by more than 50 % if the ambient temperature is 50 °C lower than fluid temperature at the inlet, while for evacuated tube collectors, performance stays more constant over a range of temperature differences, with only up to a 20 % efficiency decrease in the above scenario because of the vacuum insulation (Norton 2006). However, because evacuated tube collectors lose little heat to the environment, snow and ice accumulates more easily on them than on flat plates, negating some of the theoretically higher efficiency in real-world conditions (Trinkl et al. 2005).

2.2 Hailstorms

Modern flat plate collectors incorporate reinforced glass and are not easily damaged by hailstones. In a test of 15 flat plate collectors, all withstood 35 mm hailstones, while 10 of them withstood 45 mm hailstones (SPF 2009). Evacuated tube

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collectors can be damaged more easily. In most systems, however, single tubes can be removed without shutting down the system, which can continue working at reduced capacity despite missing or broken tubes. In a test of 26 evacuated tube collectors, 15 withstood 25 mm hailstones without damage, but only one withstood 45 mm hailstones without damage (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 their cost-competitiveness (the collector resistant to 45 mm hailstones is characterized as an "inexpensive mass-produced import from the Far East"). The results further show that there is room for improvement in both flat plate and evacuated tube collectors, but that flat plate collectors are currently more suited to areas where heavy hailstorms can be expected.

2.3 Cloudy weather

Cloudy weather reduces efficiency, decreasing both the amount of solar radiation reaching the ground and the ambient air temperature. Evacuated tube collectors have an advantage over flat plate collectors in instances where insolation is more diffuse than direct and in particular where sunshine is intermittent. This is because of their reduced heat loss under such conditions. One experiment showed that this seems to hold true 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 photo-voltaic effect. Currently, they can convert up to about 20 % of incoming solar radiation into electricity, with higher values achievable for technologies that first concentrate sunlight. Two technologies have a role to play now and into the near future. Crystalline silicon (Si) derives from semiconductor technology, and accounts for about 80 % of the global market. Thin film is a more recent technology, with both costs and efficiency generally lower than crystalline Si. Various more advanced PV technologies are under development (IEA 2010).

PV systems can be mounted in a variety of configurations, such as on rooftops or directly on the ground, and with or without movable mounting to track the sun, but there are geographic dependencies. In cold climates, for instance, setting panels at an angle and with space between them allows snow to slide off (Deutsche Gesellschaft für Sonnenenergie 2008).

3.1 Hail and lightning

The major physical components of PV systems exposed to weather are the PV modules themselves. 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 2003). However, these accelerated stress tests have been criticized for not necessarily predicting lifetimes and resistance to real-world environmental impacts because the acceleration factors are mostly unknown (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 be due partly to high market growth and entry of new manufacturers, and partly to additional testing criteria (TamizhMani 2008). There is no literature to suggest that other components of the PV system—such as the mounting or tracking units—are particularly vulnerable to hailstorms.

One additional concern is the DC-AC inverter. Literature studies 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). As far as weather is concerned, it may be at risk of lightning damage. Current good practice is to construct appropriate lightning protection if the installation is at risk of lightning strikes, as is done for panels rack-mounted on flat roof areas of buildings.

3.2 Temperature

In general, the efficiency of PV modules drops by about 0.5 % for every 1 °C increase in temperature. 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) and crystalline Si modules (Vick and Clark 2005; Radziemska 2003). There is evidence that some types of module perform better in warm conditions (Makrides et al. 2009; Carr and Pryor 2003; Gottschalg et al. 2004). Differences vary between different manufacturers and the technologies used, but crystalline Si appears to fare worse than thin-film technologies.

Heat is also a concern. Long-term exposure to heat will cause the panel to age more rapidly, while some materials may not be able to withstand short peaks of very high temperatures (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 are the main coolants considered for systems that concentrate light on to PV cells; see Royne et al. 2005).

3.3 Wind and sand

A side-effect of strong wind is sand and dust deposition, which results in reduced power output (Goossens and Van Kerschaever 1999). An application study for a thin-film system in the United Arab Emirates found that dust accumulation is worse with higher humidity (Mohandes et al. 2009). Cleaning panels, and using tracking systems to rotate them out of the wind, are possible responses to this problem (Harder and Gibson 2011). Abrasive effects of wind-blown particles can be minimized by installing panels about 1 m above the ground where saltation is lower and using tracking systems to turn them out of the wind (Thornton 1992).

In addition, a properly built mounting structure is important to prevent damage through wind load (Deutsche Gesellschaft für Sonnenenergie 2008). It seems likely that tracking units and raised mounting structures are more vulnerable to wind damage because they have additional exposed mechanical parts compared to panels attached directly to roofs.

3.4 Prolonged cloudy weather

The effect of clouds depends on different technologies. 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. As it is not possible to concentrate diffuse light, such systems are at a disadvantage. Panels manufactured with rougher surfaces generally do a better job in diffuse light, as they capture light from multiple angles (Nelson 2003). Thus, for PV installations where diffuse light might frequently occur, it would be beneficial to evaluate different products based on that criterion. Work has been done on the effects that moving clouds have on grids with distributed photovoltaics for over two 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). For systems with fixed mounting, the mounting angle can be chosen to optimize for energy production under diffuse light conditions (Armstrong and Hurley 2010). Tracking systems can also show improved diffuse light performance by using a different angle depending on whether the sun is visible or behind clouds (Kelly and Gibson 2009).

4 Concentrating solar power

Concentrating solar thermal power (CSP, sometimes abbreviated CST) 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 (Márquez Salazar 2008; Pitz-Paal et al. 2004; Richter et al. 2009). A related technology, concentrating photovoltaic (CPV), uses mirrors to concentrate sunlight on to PV panels.

Because of the optics of concentration, CSP cannot utilize diffuse light, but requires direct sunlight. This makes desert areas especially suitable for CSP, as the direct normal insolation is high and the air is typically cloudless and dry (Richter et al. 2009). Another key feature of CSP technologies is the option of thermal storage. In such a system, some of the heat collected is used for immediate powering of the steam turbine cycle, while the rest of the 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, and thus the capacity to operate at full load for up to 7.5 h in the absence of direct sunshine (Khosla 2008; Richter et al. 2009). These storage units

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show greater than 90 % efficiency, and the addition of more storage, of at least up to 15–16 h' capacity, possibly more, does not negatively influence the levelized cost of electricity (LCOE) (Williges et al. 2010).

4.1 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 uses no water, and are thus resistant to drought (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 (Damerau et al. 2011). During the hottest 1 % of hours, efficiency may drop by 6 % (tower) to 18 % (trough) (DOE 2007). This would, *ceteris paribus*, increase the levelized generation costs by roughly the same percentage. 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.

4.2 Sand storms and dust

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 storage to maintain production for the duration of the storm. Concerns that the mirrors would be "sand blasted" by a strong sand storm and rendered useless have been heard, but remain unconfirmed (Aringhoff et al. 2005; DLR 2007; IEA 2010; Pitz-Paal et al. 2004; Richter et al. 2009). It seems, however, that the mirrors can be sufficiently protected from the sand simply by being turned upside down (trough) or out of the wind (tower heliostats). When the storm has passed, the mirrors may need to be cleaned quite carefully, a process that will take up to a few days (Jacobson and Delucchi 2010). Sand storms are acute events, but CSP facilities also suffer from the daily accumulation of dust, to a much more pronounced extent than other solar technologies. The primary effect of dust is not to block light but rather to scatter it, and this reduces the efficiency with which mirrors can concentrate direct sunlight on to a thermal receiver. The frequency with which CSP plant operators need to clean their mirrors, to minimize the effects of dust, differs according to local conditions; at a plant in Egypt, for example, mirrors are cleaned every 2 days, compared to the weekly rotation often found in Spain. In semi-arid locations that are likely to become more arid, such as the Mediterranean Basin, local dustiness may increase in the future, increasing costs and water use. Quantitative estimates are difficult to make, however, as the technologies for mirror cleaning are evolving so quickly (Stancich 2010).

4.3 Prolonged cloudy weather

The diffusion that accompanies clouds makes mirrors ineffective at concentrating sunlight, and causes the output from the mirror field to cease. Where the combined period of cloudiness and darkness exceeds the thermal storage capacity, power output from the plant will cease. A critical issue for maintaining the reliability of power systems that will rely on a large share of CSP in the future, will be to locate generating capacity over a geographically wide area, so that local incidence of cloudy weather affects only a small share of the grid capacity.

5 Discussion

The impacts of changes in mean climate conditions do not appear to be particularly serious for any of the three main types of technology. Rising average temperatures will improve the performance of solar heating modules in cold climates, but will have a somewhat negative impact on the efficiency of PV panels, especially crystalline silicon, and in CSP plants where the water supply for cooling purposes is constrained. Average changes in cloudiness will vary across the globe, but in general it is expected that outside the polar regions, most places will experience a slight decrease in cloudiness, which is favorable for solar energy production. The cumulative effects of changes in cloudiness should cause no concern.

Crook et al. (2011) conducted a quantitative analysis using model-derived climate projections through 2100 and found the efficiency of both CSP and PV to vary by no more than a few percentage points in any world region, although the direction of change was primarily contingent on local changes in cloudiness. The only exception was for CSP production in Europe, the efficiency of which the same authors project to improve by 10 % as a result of markedly drying conditions in the Mediterranean region. Any of these changes, however, are trivial in comparison with projected cost reductions for either of the technologies, which often exceed 10 % per year. Even a 3 % reduction in efficiency, for example, would slow down the pace of cost reductions by only a few weeks.

As Table 1 summarizes, there are several potential vulnerabilities to extreme events, namely, in the form of reduced energy output, cleaning requirements and hence increased operating costs, and permanent damage to infrastructure.

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Table 1: 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
Dustiness			Increased operating cost and water use for more frequent mirror cleaning	May increase in semi-arid environments that are growing drier
Prolonged cloudiness	Reduced output	Reduced output	Reduced or eliminated output	Increase at high latitudes, decrease at low latitudes

The increase in heat waves projected for the future could pose a problem for both PV and CSP, albeit one that is minor in the context of anticipated cost reductions. At the same time, 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, which utilizes thermal storage and hence generates throughout the night, be negatively affected by this trend.

Strong winds may prove to be a problem for all three technologies. There is a potential trend, in many locations, for an increased incidence of high winds. These can cause damage like flying debris and also dust deposition, the latter necessitating 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.

All three technologies perform less well in the event of prolonged cloudiness. Where this trend results from climate change, it will be latitude-specific. In general, greater cloudiness can be expected at high latitudes in the future. This is most likely to be a problem for thermal heating technology, which is the only one of the three technologies that is cost-effective at high latitudes. Reduced cloudiness in the future can be expected in mid- and low-latitude regions, which could benefit all three technologies.

Again, these results do not raise any particular red flags. For example, both solar thermal and PV can be damaged by large hailstones, but existing design standards seem to be adequate to ensure minimal damage, and there is no clear evidence that climate change will make hail a greater problem in the future than it is now. However, there may be value in exploring technical options for making PV less heat-sensitive, and for improving the designs of CSP cooling systems.

We have reached these results in qualitative terms, and have not attempted to model quantitative changes in output or the costs of different technologies. As described, Crook et al. (2011) have conducted a quantitative analysis of PV and CSP efficiency due to projected changes in cloudiness and temperature. Making quantitative projections of the changing vulnerability to extreme events, as a result of climate change, would be fraught with high uncertainty, and we do not engage in that here. At a qualitative level, it appears that the cumulative effects of climate change on the cost, and hence attractiveness, of any of the solar technologies, are likely to be trivial when put into the context of the rapid pace of technological change and the cost reductions related to it.

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