The sensitivity of concentrated solar power yield to climate change

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Highlights

- We examine the effect of climate change on a concentrated solar power plant's yield
- We use a case study: proposed linear Fresnel Reflector at Collinsville, Australia.
- We use three global climate models for 'most likely', 'hottest' and 'coolest' cases
- We find an increase in yield of less than 0.3% in the 'most likely' case.
- Therefore, we can ignore climate change effects on yield but consider effects on electricity prices

Abstract

Renewable energy not only helps to mitigate climate change but the latter also affects the yield and financial feasibility of renewable energy. In this paper, we assess the sensitivity of the proposed linear Fresnel Reflector plant for Collinsville, Queensland, Australia to climate change. The objective is to determine whether it is necessary to include climate change effects within a feasibility study to avoid additional complex calculations.

We use the Systems Advisor Model from the US National Renewable Energy Laboratory to model the yield from DNI, temperature, relative humidity and pressure. We assess the effect of climate change on the four yield drivers using three global climate models representing the 'most likely', 'hottest' and 'coolest' cases. Additionally, we compare our results with an existing regional study.

We find a 0.3% increase in yield from 1990 to 2040 in the most likely case. The lifetime of the proposed plant is 2017 to 2047. Therefore, we can ignore climate change effects on yield in the feasibility study. This result is consistent with the other regional study. However, climate change also increases electricity demand and, consequently, wholesale electricity prices. The effect on prices requires further consideration because prices also affect the project's financial feasibility.

Keywords

Climate change, power purchase agreement, concentrated solar power, electricity yield, systems advisor model, feasibility study

1 Introduction

Renewable energy not only helps to mitigate climate change but it also affects the yield and financial feasibility of renewable energy. A number of studies have investigated the effect of climate change on the yield of renewable energy and, consequently, its financial feasibility (Breslow & Sailor 2002; Burnett, Barbour & Harrison 2014; Crook et al. 2011; Foster et al. 2013; Pan et al. 2004; Pryor & Barthelmie 2010; Sailor, Smith & Hart 2008). These researchers find that there is considerable variation in the effect of climate change on yield, depending on both location and season. Therefore, a complete feasibility study for new renewable energy plant must consider whether the effect of climate change on future yield is significant.

In this paper, the focus is on solar power in Australia. One of the most relevant papers is by Burnett, Barbour and Harrison (2014) who analyse the effect of climate change on solar intensity in the UK, finding that it is likely to increase the solar intensity in the currently higher solar resource locations in the south and south west and slightly reduce the solar intensity in the currently lower solar resource locations. The net effect of climate change is to exacerbate the geographic variation in yield.

Furthermore, higher solar intensities are usually associated with higher temperatures. Higher temperatures reduce the yield from solar PV but increase the yield from concentrated solar power (CSP). The UK has moderate temperatures that are close to the standard temperature used in modelling solar power. Therefore, Burnett, Barbour and Harrison (2014), ignoring the effect of temperature on yield, use change in solar intensity as a proxy for change in yield and argue that this is appropriate for the UK. In contrast, Australia has much higher average temperatures. Therefore, this proxy is less appropriate and, therefore, an explicit model of yield that incorporates temperature is required.

Crook et al. (2011) globally analyse the effect of climate change on generic CSP yield, focusing on seven regions. However, providing technological analysis of this kind requires both forsaking the ability to select the most appropriate 'global climate model' (GCM) for a specific location and a yield model for a specific CSP technology. In this paper, we calculate the change in yield induced by climate change using GCMs for a specific location in Australia and a yield model for Compact Linear Fresnel reflector (LFR) CSP technology. We also compare our results with those of Crook et al. (2011).

The proposed Novatec Solar LFR plant at Collinsville in Queensland provides an ideal case study. Novatec Solar supplements the US National Renewable Energy Laboratory's (NREL 2012) Systems Advisor Model (SAM 2014) with templates to model yield from their LFR (Wagner 2012; Wagner & Zhu 2012). SAM (2014) calculates the kilowatts (kW) generated each hour using four environment variables or drivers for yield.

- Direct normal irradiance (DNI)
- Temperature (Dry bulb)
- Humidity
- Pressure

Thus, these four drivers form the nucleus of the "complete meteorological dataset" in the following discussion. Other environment variables also affect the amount of electricity produced but the main drivers of yield are these four variables.

Section 2 discusses the data used in the sensitivity analysis necessary to address the research question. Section 3 discusses the SAM (2014) calculations in more detail. Section 4 presents the yield sensitivity analysis results and compares the results with other studies.

2 Material and methods

A sensitivity analysis provides the methodology to determine the effect of climate change on yield. Section 2.1 selects Global Climate Models (GCM) for the coolest, most likely and hottest cases to find the change in the four drivers from 1990 to 2040. Section 2.2 determines 1990 values for the four drivers.

2.1 Climate change effect on four drivers from 1990 to 2040

We discuss the effect of climate change on the four drivers for yield. Weather affects the four drivers cyclically. In contrast, climate change produces a gradual change in the long-term means of the four drivers and affects the plant's yield permanently over its expected lifetime.

Climate change is a global phenomenon whose focus is on the average rise in global temperatures but the main driver for concentrated solar power (CSP) plants is direct normal irradiance (DNI). Nevertheless, studying temperature change and the associate changes in other variables provides a useful background to the issue. Additionally, climate change studies generally focus on global temperature change but local effects can run counter to the global effect, as seen in the case of the El Niño Sothern Oscillation (ENSO). A rise in temperature in one area can cause disruptions to normal weather patterns whose effects can be uneven.

Consequently, there requires some discretion in selecting Global Climate Models (GCM) that report the most likely, hottest or coolest cases for the geographic area of interest and provide the range of variables required for analysis. For this paper, there is a tension over the selection of the geographic area because selecting the Australian National Electricity Market (NEM) as the geographic area will best reflect the demand and price for the electricity produced but selecting GCMs specifically for Collinsville will best reflect the yield. Foster et al. (2013) have already conducted an analysis for the NEM for five variables, including three of the four drivers, but their focus is temperature rather than DNI. Their choice of the carbon emission scenario is SRES A1FI, which best reflects the high carbon emissions trajectory currently occurring around the world. Clarke and Webb (2011) select three from 23 GCMs reflecting two extremes and an average case for Foster et al. (2013):

- Most likely case – MRI-CGCM2.3.2
- Hottest case – CSIRO-Mk3.5
- Coolest case – MIROC3.2

For the five environment variables:

- solar radiation
- temperature
- relative humidity
- wind speed
- rainfall

The hottest case is the worst case scenario from a climate change perspective but it could be the best case from an LFR perspective because higher temperatures help provide more yield and increase electricity demand in Queensland from higher residential and commercial air-conditioning and refrigeration use.

Table 1 provides the expected change in solar radiation, mean temperature, and relative humidity from 1990 to 2040 for the three GCM's. The fourth driver, pressure, is omitted from the table because ozClim (CSIRO 2011; Page & Jones 2001) lacks pressure projections. Therefore, in this paper we assume no change in atmospheric pressure from 1990 to 2040.

Table 1: projected change in climate from 1990 to 2040 at Collinsville, Queensland, Australia

	Coolest case MIROC3.2-Medres	Most likely case MRI-CGCM2.3.2	Hottest case CSIRO-Mk3.5
Solar radiation (%)	-1	0.1	0.8
Temperature Mean (°C)	1.21	1.04	1.33
Relative humidity Mean (%)	0.8	-0.7	-0.9

(Source: CSIRO 2011; Page & Jones 2001)

We assume that percentage change in solar radiation in Table 1 provides a suitable proxy for the percentage change in DNI. However, the solar radiation in Table 1 is global horizontal irradiance (GHI). Equation 1 shows the instantaneous relationship between GHI, DNI and diffused horizontal irradiance (DHI).

Equation 1: Instantaneous relationship among three irradiances and zenith angle

$$DHI = GHI - DNI \cos(zenith)$$

Table 1 is concerned with total annual energy; therefore, if there is no percentage change in DHI, our assumption will hold, that is, a percentage change in GHI (solar radiation) can act a proxy for percentage change in DNI. There are countervailing climate changes trends that help maintain constant DHI, such as, the decrease in humidity and increase in bush fires and dust in the most likely and hottest cases.

We select the location at latitude and longitude (-20.5, 148) from the ozClim projection series (CSIRO 2011; Page & Jones 2001) because this location is the closest to the proposed plant at (-20.5344, 147.8072).

Notable is the magnitude of the projected mean temperature changes where the most likely case is smaller than both the coolest and hottest cases. As discussed earlier, the local effect can run counter to the global effect.

Additionally, the most likely expected percentage change in solar radiation, the main driver for yield, from 1990 to 2040 is 0.1 percent. The change in temperature is just over 1 °C and a decrease in humidity is 0.7 percent. These three changes taken together would increase yield.

2.2 Values for the four drives in the climate change base year 1990

In Table 2, we derive mean values for 1990 for temperature and relative humidity from BoM (2014) climate statistics for the Collinsville Post Office for the periods 1971-2000 and 1981-

2010 by averaging the 9 am and 3 pm values. The averaging between the 9 am and 3 pm values provides representative dry temperature and relative humidity for when the plant is operating. Averaging between the periods 1971-2000 and 1981-2010 weights the averages in the period 1981-2000 to more heavily reflect conditions a decade either side of 1990 the baseline year for the GCMs.

Table 2: Collinsville average temperature and humidly for 1971-2000 and 1981-2010

Driver	1971-2000		1981-2010		mean
	9 am	3 pm	9 am	3 pm	
Dry temperature (°C)	23.1	28.8	23.3	29.3	26.1
Relative humidity (%)	67	44	66	43	55

(Source: BoM 2014)

As noted, the BoM (2014) lacks atmospheric pressure data for Collinsville. Therefore, we use the average atmospheric pressure supplied by Allen (2013) for the period 12 December 2012 to 11 February 2014 that is 989.5 hPa or 98.95 kPa. Collinsville's average atmospheric pressure is slightly less than the pressure defined in both the 'standard temperature pressure' and 'standard ambient temperature and pressure' that use 100 kPa (1 bar). We expect lower pressure at Collinsville, given its 197 m altitude whereas both the 'standard temperature pressure' and 'standard ambient temperature and pressure' definitions assume the atmospheric pressure at sea level.

The BoM (2013) states that typical values for DNI are up to around 1,000 W/m2. We calculate an effective to satellite DNI ratio of 0.767. Therefore, we use a DNI value of 767 W/m^2 for 1990 for the sensitivity analysis. Table 3 calculates the effective to satellite DNI ratio for Collinsville by summing hourly terrestrially measured DNI (W/m^2) from Allen (2013) and satellite DNI from BoM (2013). However, Allen (2013) only has 343 complete days of DNI data for 2013.

Table 3: Collinsville's effective versus satellite DNI energy per area for 343 days and ratio for 2013

	343 days
Effective DNI from Allen (2013) (MWh/m^2)	1.916
Satellite DNI from BoM (2013) (MWh/m^2)	2.500
Effective-satellite DNI ratio	0.767

3 Theory/calculation

SAM (2014) calculates the hourly yield for LFR given hourly values for the four drivers in TMY format (Wagner 2012; Wagner & Zhu 2012). We use SAM version 2014.1.14 in this paper. It was planned that Novatec Solar would supply the LFR technology for Collinsville and it provided a sample template of default settings for this technology for the SAM (2014) titled "Linear Fresnel Novatec Solar Boiler". This file contains all the default parameters for a standard Novatec Solar installation. Table 3 shows the changes from the default setting advised by Novatec Solar for Collinsville.

Table 4: Advised default setting changes to SAM's 'Linear Fresnel Novatec Solar Boiler'

Field groupings	Input fieldnames	Advised value	Default value
Solar Field parameters	Field aperture:	174,624 m^2	862,848
	Number of modules in boiler section:	11	12
	Number of modules in superheater section:	6	6
	Collector azimuth angle:	-10°	0
Steam Conditions at design	Field outlet temperature:	500 °C	500
	Turbine inlet pressure:	120 bar	90
Plant Design	Design turbine gross output:	30.07 MWe	49.998
	Rated cycle efficiency	0.407	0.3941

To allow the LFR plant to maximise the collection field within the land space available, Novatec reduced the number of modules in the boiler section from 12 to 11 and changed the collector azimuth angle from *0°to -10°,* that is, from true north to a 10° inclination to the west. Then, it optimised the field aperture size to minimise the levelised cost of electricity (LCOE). The increase in the default 'design turbine gross output' is consistent with the increase in '… turbine gross output'.

4 Results

Table 4 shows the expected values for the four drivers in the year 2040 for the three GCMs. Table 4 calculates these values by combining Section 2.2's values for the four drivers for yield for the 1990 baseline year and Table 1 the change for the drivers from 1990 to 2040 for three GCMs.

Table 5: Values representing the four drivers for the base year 1990 and sensitivities for Collinsville

Driver	1990 baseline	Coolest case MIROC3.2-Medres	Most likely case MRI-CGCM2.3.2	Hottest case CSIRO-Mk3.5
DNI (W/m^2)	767	759	768	773
Dry temperature (°C)	26.1	27.3	27.2	27.5
Relative humidity (%)	55	55.4	54.6	54.5
Pressure (hPa)	989.5	989.5	989.5	989.5

Table 5 shows SAM's (2014) annual gross yield calculations using the values for the four drivers in Table 4. Table 5 also shows the percentage change in annual yield induced by climate change from 1990 to 2040 in the three GCMs. In the most likely and hottest cases, the increase in yield is less than 0.3% and 1.2% respectively and in the coolest cases, the decrease is less than 1.2%. The thirty-year lifetime of the proposed plant (2017 to 2047) is less than the sensitivity analysis period (1990 to 2040). Therefore, the magnitude of the percentage change in gross yield will be less

Table 6: Climate change induced percentage change in yield from 1990 to 2040 for Collinsville

	1990 baseline	Coolest case MIROC3.2-Medres	Most likely case MRI-CGCM2.3.2	Hottest case CSIRO-Mk3.5
Gross Yield (GWh)	82.80	81.81	83.06	83.82
Change in yield (%)	0.0%	-1.2%	0.3%	1.2%

5 Discussion

In both this study and that of Crook et al. (2011), the same baseline year 1990 is used but, in contrast, this study ends 2040 and the latter in 2100. So, we interpolate Figure 3 in Crook et al. (2011) to find a 1% change in CSP yield for Australia for 2040. In agreement, this result falls within this paper's hottest case scenario shown in Table 5 of 1.2% change in yield.

However, this paper only presents the change in gross yield and a PPA analysis requires evaluating the effect of climate change on electricity demand and wholesale electricity prices. Bell and Wild (2013) calculate the effect of climate change on the NEM's demand from 2009 to 2030. They find a 1.57% increase in total net demand and a 2.23% increase in peak demand for the Collinsville node, which would have an upward pressure on electricity wholesale spot prices. However, the August 2014 Electrical Statement of Opportunities (AEMO 2014) calculates the regional reserve deficit timings and expects surplus generation capacity in the whole of the NEM beyond 2023-24. This excess capacity would moderate the effect of any increase in demand on wholesale spot prices. However, between 2024 and 2047, many coal and gas generation plant begin to reach their 'end of use' dates and would need significant refurbishment, replacement or closure, thus potentially impacting upon any assessment of surplus generation capacity. The effect of climate change on wholesale spot prices at Collinsville provides the opportunity for further research.

The modelling of Electricity Markets becomes complex very quickly, so it is essential to focus on cores issue such as gaining a PPA. Incorporating climate change into the modelling of both yield and wholesale spot prices would impose a great deal of complexity concerning a small effect in this the case study. However, an assessment of climate change effects on yield and demand may be useful for projects in other locations. In Section 1 we discussed other global and national studies into the effect of climate on yield. These studies provide a good indication as to whether it is worthwhile to incorporate climate change effects into feasibility studies for a particular plant or location. In this regard, Crook et al. (2011) proved to be a useful guide for this study.

Furthermore, both the GCMs and the BoM lack atmospheric pressure data, which presents an impediment to accurately calculating yield. In Section 2.1 we discussed the fact that the most likely effects of climate change are to reduce humidity and increase temperature and DNI. This scenario is similar to what happens in the *El Niño* phase of the ENSO cycle. Therefore, the *El Niño* phase and climate change have similar implications for the LFR in the Collinsville case with regard to increasing yield and electricity demand. This similarity also suggests that there would be an increase in atmospheric pressure.

6 Conclusions

In this CSP case study, we found that the effect of climate change on yield is likely to be quite small. Therefore, any feasibility study of a similar CSP plant can ignore the climate change effect. However, the effect of climate change in increasing electricity demand requires consideration but, again in most conditions, the effect on wholesale spot prices is likely to be small. This is particularly true in Australia given the generation overcapacity that is likely to prevail for some years to come in the National Electricity Market.

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8 Glossary

Please supply, as a separate list, the definitions of field-specific terms used in your article.

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