CL665: Stage II report

Analysing the impact of climate change on Solar power generation

Group 7

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1. Background and motivation:

Climate change is one of the most pressing challenges of our time. The Earth's climate is already changing due to human-caused greenhouse gas emissions, and these changes are expected to become more severe in the future. As seen multiple times across different studies, climate change has non-trivial impacts on a variety of industries. Studying the impact of climate change on energy production is important as it allows us to understand which methods of energy generation will be the most feasible in the future. Along with this, the adverse effects of climate change will have to be taken into account by governments around the world while planning future development.

Solar power is one of the most effective methods of renewable energy generation and has the potential to help mitigate climate change. The use of Solar power is increasing rapidly in India. This makes solar energy generation a prime candidate for investigation. However, solar power plants are also vulnerable to the impacts of climate change.

Climate change is expected to impact solar power plants in a number of ways, including:

- **Change in insolation:** Climate change is expected to lead to increased cloud cover in some regions. This could reduce the amount of sunlight available to solar panels and therefore reduce the amount of electricity generated.
- **Higher temperatures**: Climate change is also expected to lead to higher temperatures. This could reduce the efficiency of solar panels, as they operate less efficiently at higher temperatures.
- **More extreme weather events:** Climate change is expected to increase the frequency and intensity of extreme weather events, such as hurricanes, floods, and wildfires. These events could damage solar panels and other infrastructure and disrupt electricity generation.
- **Wind flow patterns and speed:** Climate change will affect the temperature distribution across the globe, leading to changes in wind speeds and wind flow patterns. Winds directly affect the humidity and temperature of the panels and hence impact energy generation.

Considering all these, it is prudent to investigate the impact of climate change on solar power generation to observe where we expect to incur losses and what we can do to mitigate them. It is, however, difficult to analyze the future patterns of dust degeneration, humidity and extreme weather conditions. Hence we restrict our scope to **insolation** and **temperatures**.

2. Specific objectives and approach:

<u>Problem definition:</u>

To access the impact of

1. Solar irradiation
2. Surface temperature

On annual solar power generation (PV) in 2023, 2050, and 2100. The changes in these two parameters are as captured by the climate model and scenario that we have considered.

<u>Specific Objectives:</u>

1. Understanding the impacts of the above-mentioned factors on solar power generation
2. Analyse the data and select the model based on the requirements
3. Predicting patterns and changes in the efficiency of solar power generation
4. Repeating this analysis for selective regions across India to find the most deployable place for solar
5. Comment on the feasibility of solar power generation as an energy production avenue in the future in each climate change scenario (SSP2-4.5 and SSP5-8.5).

3. Literature review

<u>Paper Title</u>**:** Climate change impacts on future photovoltaic and concentrated solar power energy output

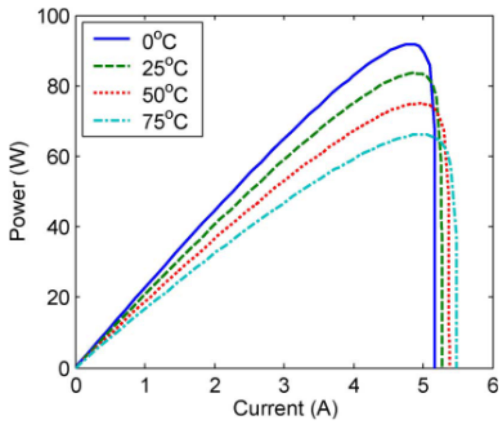
<u>Paper Finding, Summary, and Relevance to our Project:</u>

This paper is mainly referred by our group for its matethamtical equations and relations that connected temperature and insolation(irradiance) to the efficiency and energy output of solar panels. We have followed a methodology similar to the one given in the paper.

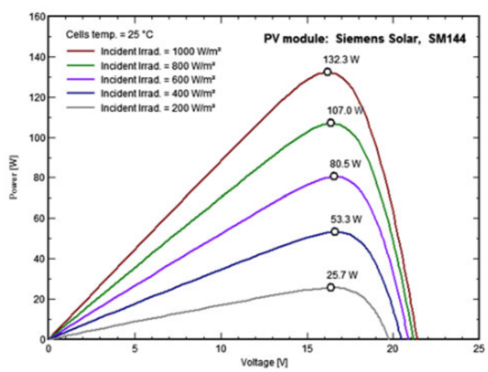
The paper examines how the changes in temperature and insolation will affect photovoltaic (PV) and concentrated solar power (CSP) output for a variety of locations like Europe, USA, China, Algeria, Australia and Saudi Arabia. The relevant climate data is obtained from the coupled ocean-atmosphere climate models HadGEM1 and HadCM3 under the IPCC SRES A1B scenario (rapid economic growth with a balanced use of renewable and fossil fuel power generation). They also observed that for PV there is considerable variation in relative contribution from temperature and insolation depending on location whereas for CSP the contribution from changes in insolation is always dominant.

Effects of the study parameters:

1. Temperature: Temperature effect on the relationship of power and current of a standard (MSX-83) solar panel with a constant insolation equal to 1000 W/m2 is shown in the figure. [1]



2. Irradiation: The effect of solar irradiation on the PV power output of a typical module. [2]



Paper Title : The near future availability of photovoltaic energy in Europe and Africa in climate-aerosol modeling experiments

Paper Finding, Summary, and Relevance to our Project: The near future change in the productivity of photovoltaic energy (PVE) in Europe and Africa is assessed by using the climate variables simulated by the ECHAM5-HAM aerosol-climate model and a model for the performance of photovoltaic systems. The analysis indicates that reductions in aerosol emissions in the near future will result in an increase of global warming and a significant response in surface solar radiation and associated PVE productivity. A statistically significant reduction in PVE productivity up to 7% is observed in Eastern Europe and northern Africa, while a significant increase up to 10% is observed in Western Europe and Eastern Mediterranean.

[1] Weidong Xiao, et.al., Topology Study of Photovoltaic Interface for Maximum Power Point Tracking, IEEE Transactions on Industrial Electronics 54(3):1696 - 1704, July 2007

[2] M.A. Darwish et.al, PV and CSP solar technologies &desalination: economic analysis, Desalination and Water Treatment, DOI: 10.1080/19443994.2015.1084533

The main significance of this paper is that it demonstrates that climate modeling is a valuable tool for investigating future changes in PVE productivity and obtains results that are consistent with other papers' findings.

Paper Title: Recent developments of solar energy in India: Perspectives, strategies, and future goals

Paper Finding, Summary, and Relevance to our Project: The idea of using solar as an energy source in India's perspective is highlighted in this paper.It is used to increase power generation and expand energy reliability while considering the social and financial beneficial properties. The energy reliability factor becomes quite relevant to our project.
Solar energy is generally produced by using the techniques of solar photovoltaic (SPV) or concentrated solar power (CSP). As per the forecast of 'The International Energy Agency' , within the year 2050, CSP and SPV will commit about 11% and 16% of the total electricity consumption respectively in the world. This paper highlights the difference between SPV and CSP systems. Solar power plants transform the energy of sunlight into the electrical energy, by using either SPV or CSP. CSP system consists of lenses and tracking systems to concentrate on the sunlight of a large area into a small beam. Photovoltaic effects are used for converting the energy of sunlight to electrical energy in case of SPV.
This paper also illustrates a technique for the allocation of wasteland for solar power generation by considering some factors, including availability of wasteland, direct normal irradiance, and sustainability of waste-land for generation of wind power etc.

Data on Solar Resources in India: The average solar insolation received in India is approximately200 MW/km-square wit h an average 250–300 sunny day in a year. The solar radiation varies geographically. Annual radiation of solar energy is highest in northern region, especially in Ladakh and least in the North-Eastern Region. The solar insolation level in India is more than 5000 trillion kW h per year, whereas daily solar insolation changes from 4 to 7 kW h/m2 , depending on the location. The annual global solar insolation varies from 1600 to 2200 kW h/m2.

Some areas of Gujarat, Rajasthan,Madhya Pradesh, Andhra Pradesh and Maharashtra also receive a large amount of solar radiation as compared to other areas of India.The solar radiation level is lowest in some parts of Arunachal Pradesh and Sikkim.

The paper states that the changing behavior of solar irradiance has affected the generation of solar power. Solar power generation is varied with the change in season in India, due which energy storage technologies are required for maintaining the power supply from solar power plants throughout the year.

Paper Title: Impacts of Climate Change on energy systems in global and Regional Scenarios

Paper Finding, Summary, and Relevance to our Project: This paper drives home the point that the energy sector not only contributes to climate change but is also vulnerable to climate change. These impacts can be related to different aspects of energy systems, including energy supply and demand, but also to cost and transport of energy.

Climate change and climate extremes can also affect the resilience of energy systems and the reliability of energy supply, via impacts on transmission systems or infrastructure
Climate change influences both the demand and supply of energy . It changes energy demand by affecting the duration and magnitude of diurnal and seasonal heating and cooling requirements.

This paper goes on to talk about the various adaptations that energy systems can use to get past vulnerability including reducing energy demand, reducing water demands for cooling operations through alternative cooling technologies, increasing energy generation capacity and energystorage and using the mix of electricity generation technologies.

Novelty: We have selected and are specifically focusing on locations of current and upcoming solar power plants in India. Assuming certain climate scenarios, we are projecting the solar power generation potential of India by 2070 and checking if solar can actually be the most efficient renewable energy source for India's power plan. We will also be commenting on locations in India that should be utilized for solar projects, if any.

4. Methodology

We use the publically available data from the HadGEM3-GC31-LL model in CMIP6 (https://cds.climate.copernicus.eu/cdsapp#!/dataset/projections-cmip6?tab=form). We look at 4 quantities: air temperature at the surface, total radiation above cloud cover, total radiation at the surface, and fractional cloud cover. We then use this data to obtain the efficiency using the empirical formulae used in 10.1039/c1ee01495a.

We have conducted all these calculations for Rajasthan and Gujarat, representative states that we chose as major projects already exist in Rajasthan and Gujarat.

The data was downloaded to a local ,laptop and all analysis was carried out by us.

Terms used:

CMIP6 : Coupled Model Intercomparison Project Phase 6 (Latest Phase)

SSP5-8.5 : Shared Socio-economic pathways with 8.5W/m^{2} GHG radiative forcing in the fossil fuel intensive future

SSP2-4.5 : Shared Socio-economic pathways with 4.5W/m^{2} GHG radiative forcing in the middle road future

Modeling Equations:

The climate model data obtained consists of monthly means of near-surface temperature (T), fractional cloud cover (Cf), total insolation for the actual cloud cover (Gtot), and clear-sky total insolation for if there were no clouds present (Gc).

For concentrating technologies, direct insolation is required. The paper we refer to uses annual global means of the output from the Edwards-Slingo radiative transfer model; we used the empirical relationship between the direct insolation (Gdir) and Gcs which was:

Gdir=0.75*Gcs*(1-Cf).

A factor of 0.75 is required because the scattering of sunlight by air molecules and aerosols occurs even under clear-sky conditions.

$$G_{\mathrm{dir}} = 0.75 G_{\mathrm{cs}}(1 - C_{\mathrm{f}}).$$

To adjust to daytime monthly mean temperature (*T*day), the paper assumes that the temperature varies roughly sinusoidally over the day with an amplitude of *DTR*/2, where *DTR* is the diurnal temperature range (temperature difference between maximum and minimum daily temperatures), and a mean value of *T*, so that *T*day can be approximated as the following equation:

$$T_{\mathrm{day}} = \overline{T} + \frac{\overline{DTR}}{4}$$

The established negative gradient linear relationship for the efficiency of a PV cell as a function of cell temperature is depicted with the following equation:

$$\frac{\eta_{\mathrm{cell}}}{\eta_{\mathrm{ref}}} = 1 - \beta\left(T_{\mathrm{cell}} - T_{\mathrm{ref}}\right) + \gamma \log_{10} G_{\mathrm{tot}}$$

η ref is the reference efficiency, *β* and γ are respectively the temperature and irradiance coefficients set by the cell material and structure, and *T*cell and *T*ref are respectively the cell and reference temperatures. Similar to the calculations in the articles, we use *β* = 0.0045 and γ = 0.1, which is typical for monocrystalline silicon cells, and *T*ref = 298 K.

$$T_{\mathrm{cell}} = \mathrm{c}_1 + \mathrm{c}_2 T + \mathrm{c}_3 G_{\mathrm{tot}}$$

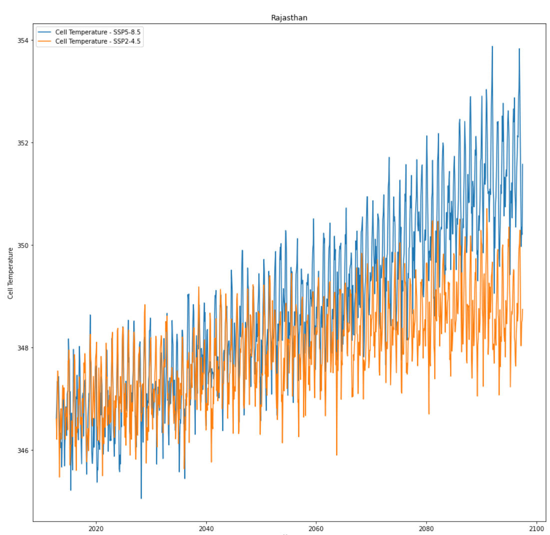
Following the work of several authors, a general empirical expression for the cell temperature is used for T_{cell}. T is the ambient temperature in °C. Coefficients used for the calculations are taken from Lasiner and Ang for a monocrystalline silicon cell: $c_1 = -3.75$ °C, $c_2 = 1.14$, $c_3 = 0.0175$ °C m^2W^{-1}.

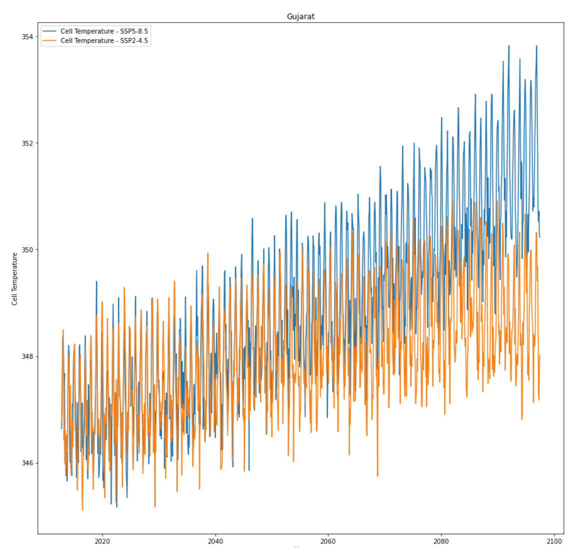
5. Results and discussion

Following is the printout of the code: https://drive.google.com/file/d/1LIG3eDFZv4fhl5EWtPNwG8iT3XFQS4ny/view?usp=drivelink

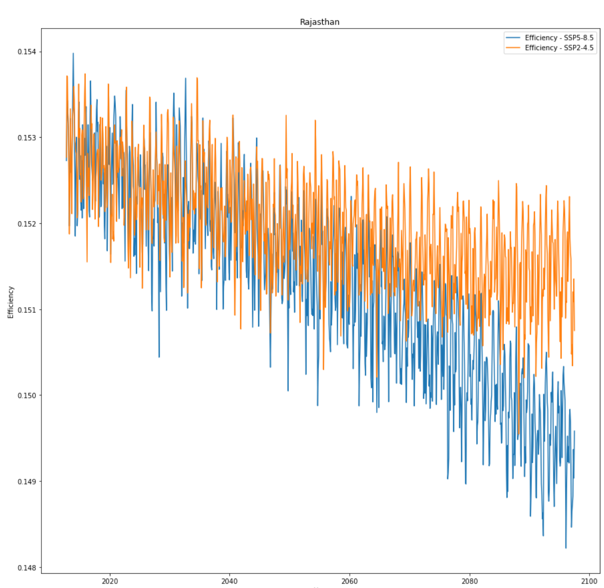
We find the following trends based on the model predictions:

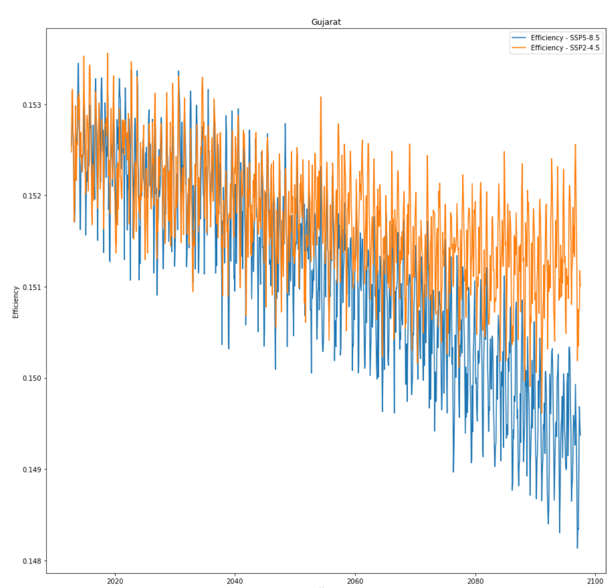
1) Cell Temperature:



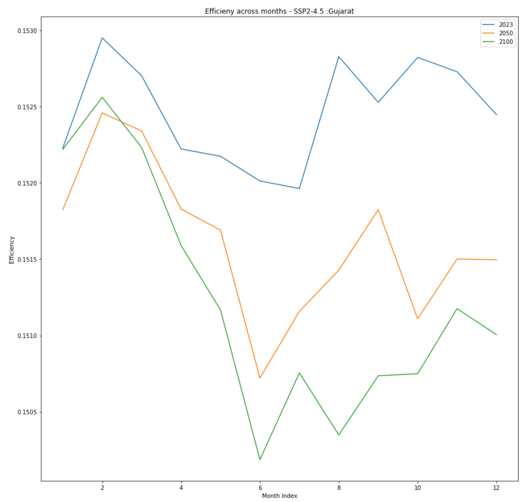


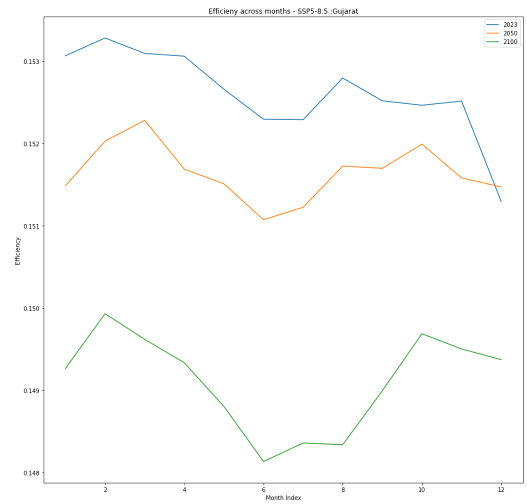
2) Efficiency:

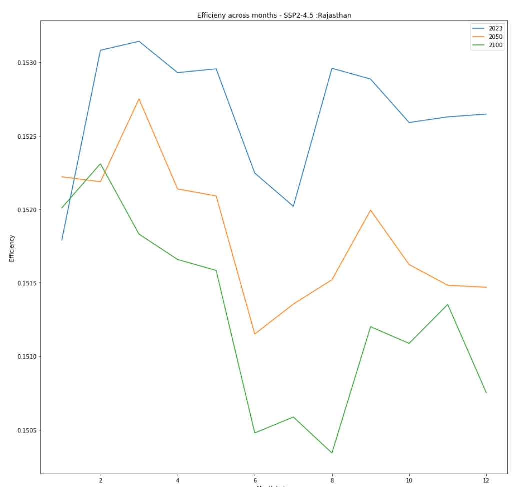


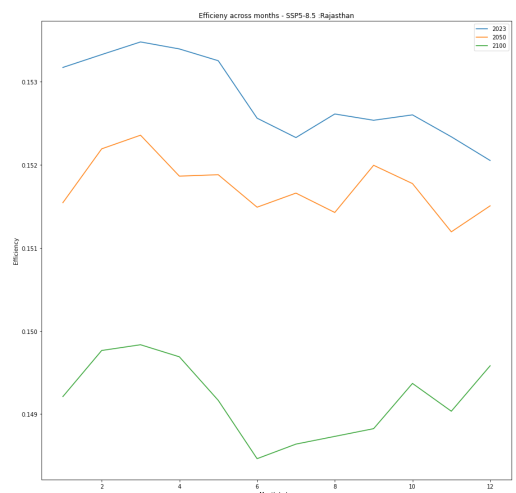


Across sample years:

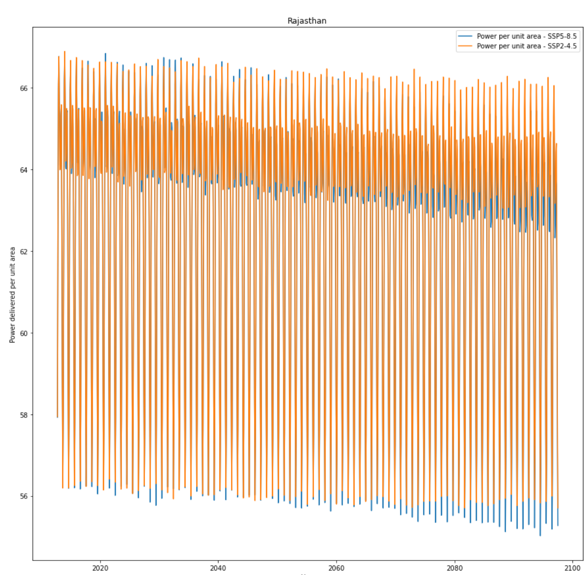


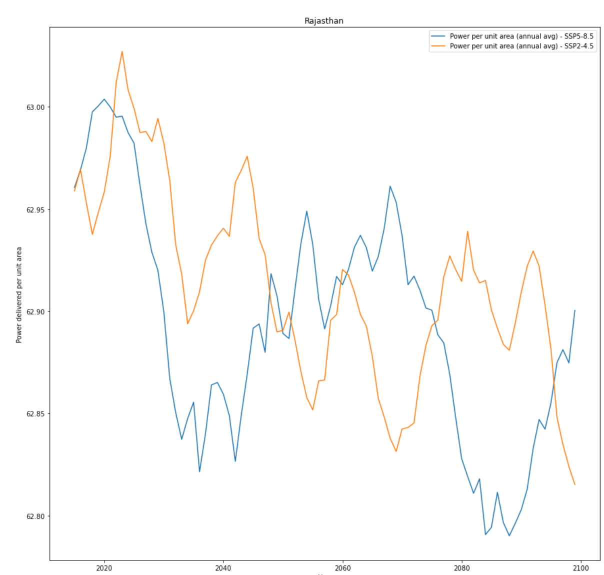




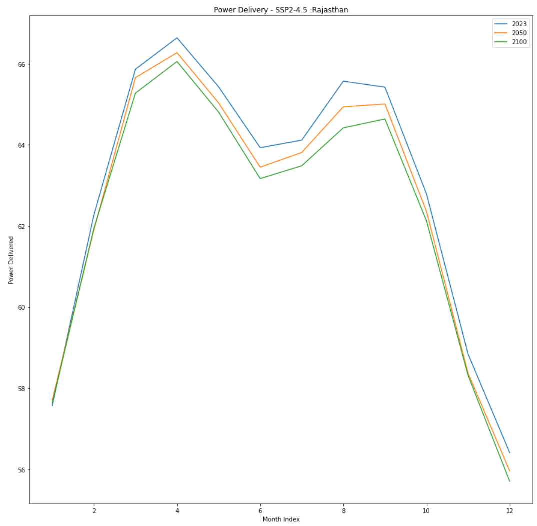


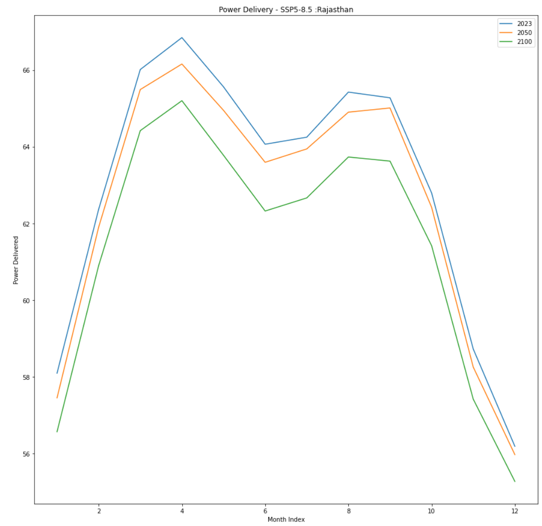
3) Power delivered per unit area:

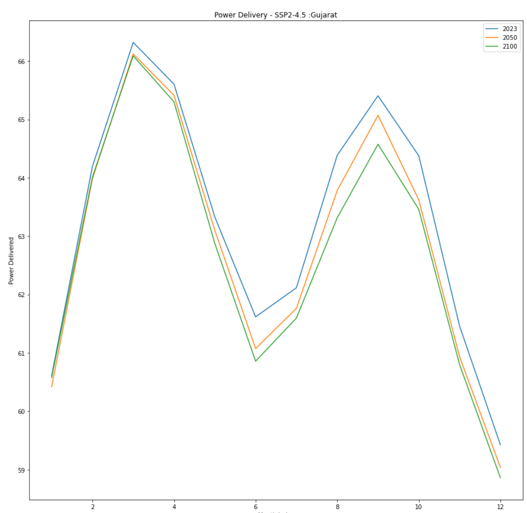


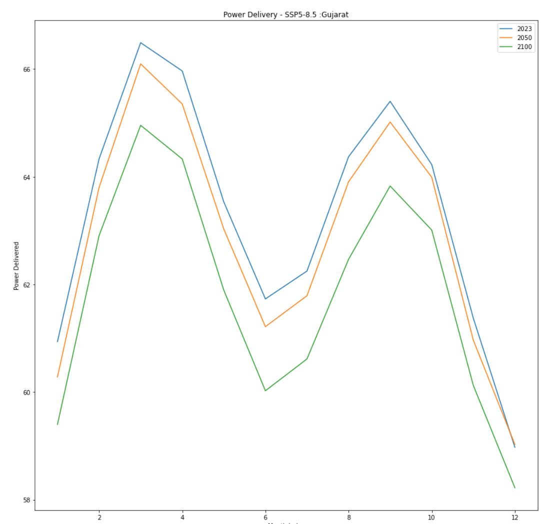


Across sample years :

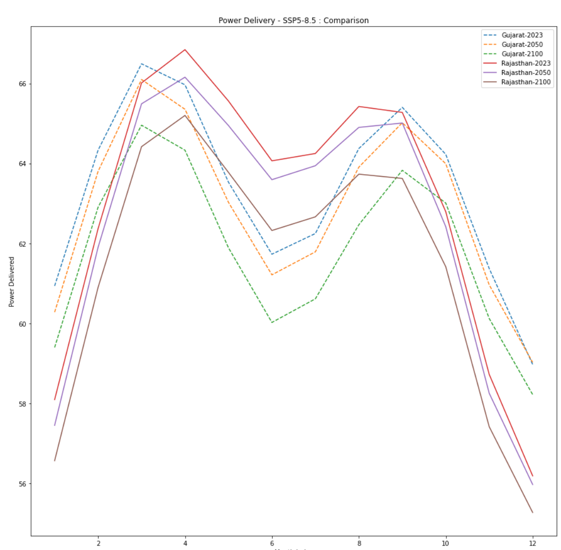


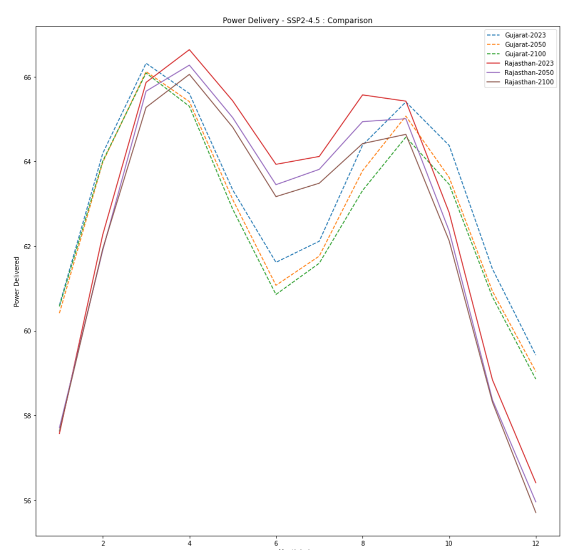






4) Comparison of Rajasthan and Gujarat:





6. Conclusion and Future plan

Based on our obtained results, we make the following conclusions:

- ☐ Gujarat shows resilience to the overall effect of climate change, the efficiency of solar panels in that region do not change as much as Rajasthan giving us a narrower range of efficiency. Rajasthan shows variable efficiency - high during summer months and low during winter months, which is expected due to a similar underlying climatic pattern. Based on this,we recommend Gujarat as the state for future solar power projects as it is less susceptible to climate change
- ☐ We observe that on the efficiency of solar panels decreases with passage of time for both scenarios SSP2-4.5 and SSP5-8.5. It descreases drastically for SSP5-8.5 , given that the effects of climate change are more drastic in that scenario.
- ☐ Gujarat is a better choice for future projects as it shows more resilience to climate change. The short term loss we see by choosing Gujarat over Rajasthan will be overcome in the future by Gujarat's resilience.

Future Work:

- ☐ We can incorporate more factors such as wind speed to get a better prediction.
- ☐ Taking a cross-model average will allow us to look beyond limitations of a single model run.
- ☐ More locations can be incorporated to make a better recommendation.

7. Work distribution

	Sanya	Anurag	Arya
Model scoping	50	30	20
Data collection	10	90	0
Software work	20	80	0
Analysis	60	20	20
Report writing	50	10	40

References

1) **https://doi.org/10.24406/publica-fhg-356329**

2) https://doi.org/10.1039/c1ee01495a
3) https://cds.climate.copernicus.eu/cdsapp#!/dataset/projections-cmip6?tab=form