Climate Change Effects on Electricity Generation from Hydropower, Wind, Solar and Thermal Power Plants

by

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ABSTRACT

Climate change is affecting power generation globally. Increase in the ambient air temperature due to the emission of greenhouse gases, caused mainly by burning of fossil fuels, is the most prominent reason for this effect. This increase in the temperature along with the changing precipitation levels has led to the melting of the snow packs and increase in the evaporation levels, thus affecting hydropower. The hydropower in the United States might increase by 8%-60% due to Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 scenarios respectively by 2050. Wind power generation is mainly affected by the change in the wind speed and solar power generation is mainly affected by the increase in the ambient air temperature, changes in precipitation and solar radiation. Solar power output reduces by approximately a total of 2.5 billion kilowatt-hour (kWh) by 2050 for an increase in ambient air temperature of 1ºC. Increase in the ambient air and water temperature mainly affect the thermal power generation. An increase in the temperature as per the RCP 4.5 and RCP 8.5 climate change scenarios could decrease the total thermal power generation in the United States by an average of 26 billion kWh and a possible income loss of around 1.5 billion dollars. This thesis discusses the various effects of climate change on each of these four power plant types.

Dedicated to Daddy, Mamma, Pammu and Akka.

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TABLE OF CONTENTS

Page

CHAPTER

LIST OF FIGURES

Figure Page

LIST OF TABLES

Table Page

CHAPTER 1

Introduction

Climate change is a prevalent phenomenon occurring globally. Increase in the ambient air temperature is the primary reason for this change. Earth witnessed an increase in the temperatures from the early 1900s. During the 1960s, the emission of greenhouse gases such as carbon dioxide, methane, nitrous oxide and fluorinated gases was discovered as the main cause of global warming and their origin was attributed to the burning of fossil fuels which include coal, petroleum and natural gas. Fig. 1 depicts the sector-wise emission of greenhouse gases [1]. It can be seen from Fig. 1 that the greenhouse gas emissions from electrical power plants constitute a significant part of the overall emissions, thus making these plants one of the major contributors towards global warming.

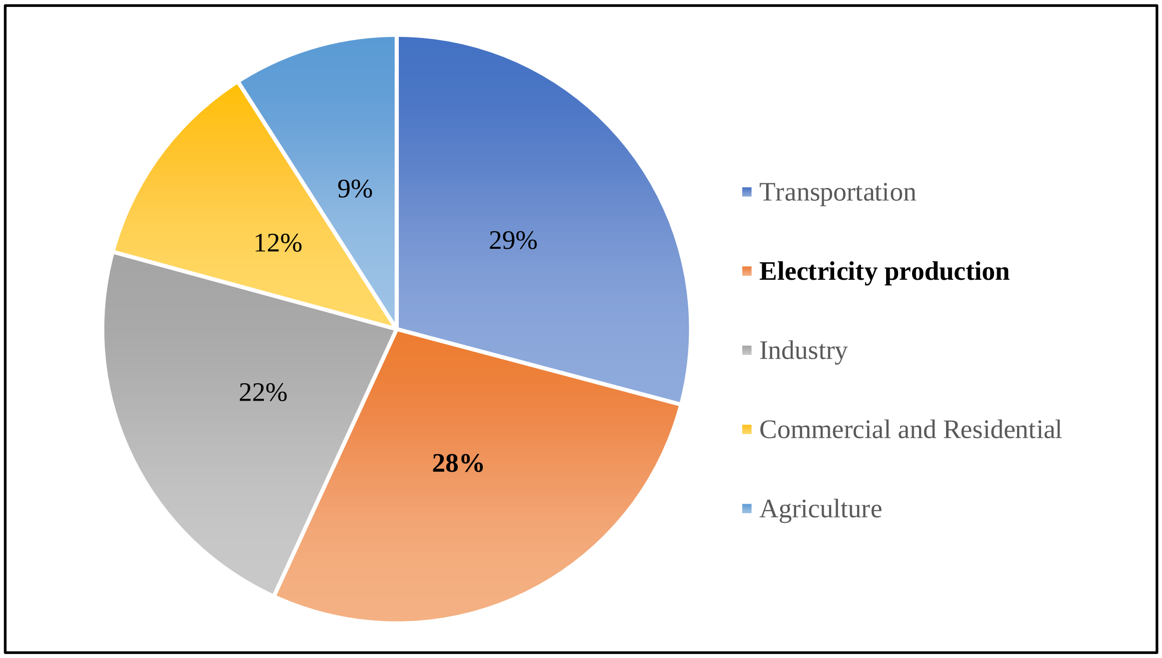

Fig. 1: Greenhouse gas emissions by sector (source: www.epa.gov [1]).

The commonly existing and widely accepted notion as seen above is that the power plants play a significant role in increasing the ambient air temperatures. But contrary to this view, is the abstruse notion that the increasing temperatures also affect the output from the power plants. This study focuses on the latter view and investigates the climate change effects on hydropower, solar power, wind power and thermal power plants.

In order to understand the impact of climate change on power plants, it is of primary importance to first identify the various effects of climate change that could affect each of the power plant types. Most common effects of climate change include increasing temperatures, changing snowpack levels, precipitation levels and the occurrence of extreme events such as floods, droughts, hurricanes and storms. A few of the effects pertain to only particular plants while others are common to all the plants.

Increase in the ambient temperatures affects all the plants directly or indirectly. The increase in the temperature worldwide has heightened the awareness to reduce the greenhouse gas emissions. This has encouraged the shift of power generation from combustion of fossil fuels to sustainable generation techniques from renewable sources of energy. These sources include solar, wind, hydro, geothermal energy and biofuels. Since the potential of these sources is a product of different environmental factors, change in climate will directly affect the power generation from these sources. Increase in the temperature reduces the efficiency of solar cells and also contributes towards the reduction in the snow levels which affects river flow, thus impacting hydropower generation. Change in wind speed affects wind power generation and the increased frequency of cyclones and hurricanes could damage the wind turbines.

The aspects of climate change mentioned above along with other factors such as change in precipitation, occurrence of extremes events such as droughts and storm surges, change in the solar radiation and air density are discussed in the upcoming chapters. Focusing on the dominant generation schemes, this thesis will analyze the extent to which the factors of climate change affect the power generation from hydro, wind, solar and thermal energy.

The effects which are going to be analyzed in the thesis for different plants are categorized in Table 1.

Table 1: Plant-wise Categorization of Different Climate Change Effects [2] [3] [4] [5]

Hydropower	**Wind Power**
- Change in the rainfall pattern - Change in snowpack levels - Evaporation - Timing of snow melts - Increased salinity - Extreme climate events	- Change in the wind speed - Increase in ambient air temperature - Gustiness - Extreme climate events
Solar Power	**Thermal Power**
- Cloud cover - Solar insolation (radiation) - Wind speed - Increase in the ambient temperature - Extreme climate events	- Water availability - Drought - Rise in the ambient temperature - Rise in the cooling water temperature - Increased salinity - Floods - Extreme climate events

Apart from analyzing the effects of climate change, this study also tries to forecast the changes in power generation for the U.S. by 2050 while taking climate change into consideration. The main metric used to project the power generation changes is the increasing ambient air temperature in U.S. by 2050 based on the different climate change scenarios maintained by the Intergovernmental Panel for Climate Change (IPCC).

The IPCC has forecasted different emission scenarios to predict the increase in temperatures in the future. The trajectories used in this thesis are representative concentration pathway (RCP) 4.5 and RCP 8.5. The RCP 4.5 scenario assumes that the emissions peak in 2040 and then decline whereas the RCP 8.5 scenario assumes that the emissions increase throughout the century. The global temperature is projected to rise over the 21st century and is likely to exceed 1.5°C by 2080-2100 in the RCP 4.5 scenario [6]. The RCP 8.5 scenario exhibits up to 2°C growth. The increase in temperatures is not uniform internationally. In the United States, the annual average temperature has increased by 0.7°C from the period 1901-1960 to 1986-2016 and by 1°C during 1895-2016. A rise of 1.4°C is predicted for the 2021-2050 period as per the RCP 4.5 scenario and by 1.6°C as per the RCP 8.5 scenario. For the period 2070-2100, an increase in the temperature by 1.6°C−4.1°C (RCP4.5) is projected and an increase of 3.2°C−6.6°C is forecast with the RCP 8.5 scenario [7].

The increase in temperature varies across regions. The northern regions experience greater increases in temperature due to the reduction in snow cover and albedo, with Alaska experiencing the highest rise in temperatures for the period 2070-2100 (RCP 8.5) as compared to the Northeast, Midwest, and Great Plains. There is a slight increase in the

Southeast due to the rise in evapotranspiration and the lowest increases are projected in Hawaii due to the effect of surrounding oceans with the remaining areas experiencing significant increases [7].

In summary, this thesis is going to analyze the effects of climate change on hydro, wind, solar and thermal power plants, and forecast the changes in national power generation per plant type respectively due to increasing temperatures of about 1.4ºC and 1.6ºC according to RCP 4.5 and RCP 8.5 for the U.S. in general by 2050. Some of the research on wind and hydroelectric power in this thesis was presented in [8].

CHAPTER 2

Climate Change Effects on Hydropower Generation

2.1 Introduction

Hydropower is the world's largest source of renewable electricity generation with an estimated production of about 16.4% of the total electricity generated globally. As of 2017, installed hydropower capacity was around 1114 GW which accounts for 50.8% of the overall renewable power capacity and the estimated electricity generated was around 4185 TWh [9]. Countries with highest hydropower generation are China, Brazil, Canada, United States, and Russia [10]. In the U.S, 7.5% of the net electricity generated was from conventional hydropower in 2017. This averaged to around 44% of the net electricity generated from the renewables, thus signifying the importance of hydropower [11].

Conventional hydropower, which is generated from either run-of-river dams or reservoir (storage) dams is calculated from

$$P = \rho\ \eta\ G\ h\ g \tag{1}$$

Where η is the turbine mechanical-electrical efficiency, ρ is the water density, G is the volumetric flow (function of volume and time), h is the effective head, and g is the acceleration due to gravity. From a practical viewpoint, a change in the volumetric flow G, tends to have the most noticeable impact on the electricity generated. Change in the rainfall, extreme events such as drought and floods, significant variation in the ambient temperature, change in snow cover and timing of snowmelts ultimately affect the volumetric flow [12]. Most of these variables have experienced changes in the last few years due to changing climate.

2.2 Shifts in Climate Change Variables

Several shifts due to climate change have occurred in the U.S. relevant to the variables discussed in Section 2.1. The national precipitation has increased over 4% with an increase of around 10% during the fall for the contiguous U.S. and over 2% during the winter whereas spring and summer exhibit an increase of 3.5% in different patterns during the 1901-2012 period. During the last century, regions of the Northeast, Midwest and Great Plains have had rainfall increases while parts of Southwest and Southeast have experienced decrease [13]. The average snow cover in North America has been decreasing at a rate of 8550 km_2 per year from 1972-2015 with the recent decade (2006-2016) having 4% decrease in the average snow area as compared to the first ten years (1972-1981) of measurement [14]. The summer and spring seasons have seen a decrease whereas the snow cover in the fall and winter has remained quite steady [14]. There is a recorded significant decrease in the snowfall days in the southern part and an increase in the northern part (1930-2007) with a projected reduction up to 40% in western regions [14]. These changes have mostly been attributed to the varying temperatures in the last century. When this change in temperature is extreme, events such as droughts and floods can occur. These changes directly affect the hydropower generation.

While the literature cannot exactly conclude a change in hydropower for a unit change in precipitation, snow fall or evaporation, information about the qualitative change in each of these variables in different regions could be useful. The information in [13] could provide an informatory guide to either check the prospects for the construction of new hydropower projects or maintaining the existing units.

2.3 Case Study – Colorado River Basin

Assessing the impacts of individual variables of climate change on hydropower generation is very complex because of the various regional differences [5]. While technology to predict the quantitative effects of changes in the variables for hydropower generation is still primitive, the different ways in which the variables come together to affect the stream flow, thus in turn affecting the power generation can be seen in the following case study [5].

History suggests that severe hydrological droughts occur in the western U.S. [13]. As a case in point, let us consider the southwestern U.S. Formed by Hoover Dam on the Colorado River linking the states of Nevada and Arizona, Lake Mead is the reservoir with the largest capacity in the U.S. The lake elevation had dropped to 329.75 m in 2010 and 326.63 m in 2016, which are the lowest recorded values as compared to 330.27 m in March 1956 during the peak of the 1950s drought as shown in Fig. 2.

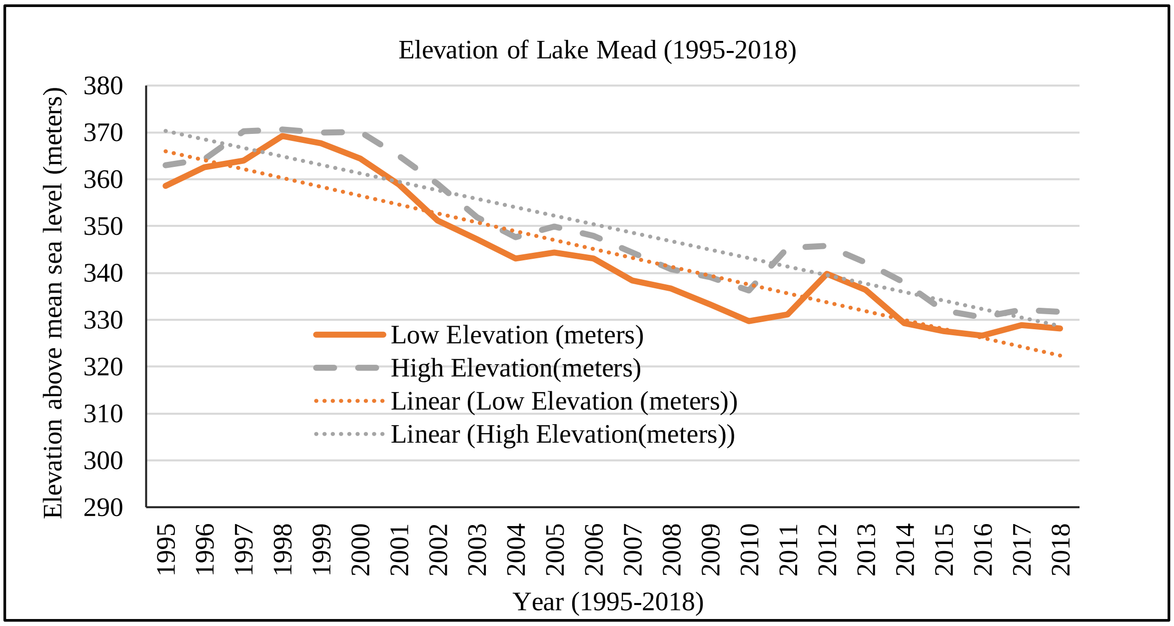

Fig. 2: Elevation of Lake Mead [15].

This has decreased the capacity of the dam from 2062 MW in 2002 to 2033 MW in 2016 with a suggested decrease to 1865 MW by 2050 [16]. The available energy from Hoover Dam has decreased close to 50 GWh/y (2.4%) from 2004-2016 with a suggested decrease up to 60 GWh/y (3%) from 2017-2050. The decrease starting in the 21st Century is mainly because of the drought in the West. The Palmer hydrological drought index (PHDI) is used to measure the effects of a drought. The annual PHDI depicted in Fig. 3 shows that the drought trend in the Upper Colorado Basin moving toward the drier period with the lowest values recorded in the summer of 2002 followed by very dry regimes throughout the early part of the century [15]. The drought has mainly occurred due to the combination of different factors such as increase in the temperature (Fig. 4), change in the precipitation levels, increase in evaporation rate, and decrease in the snow peak level.

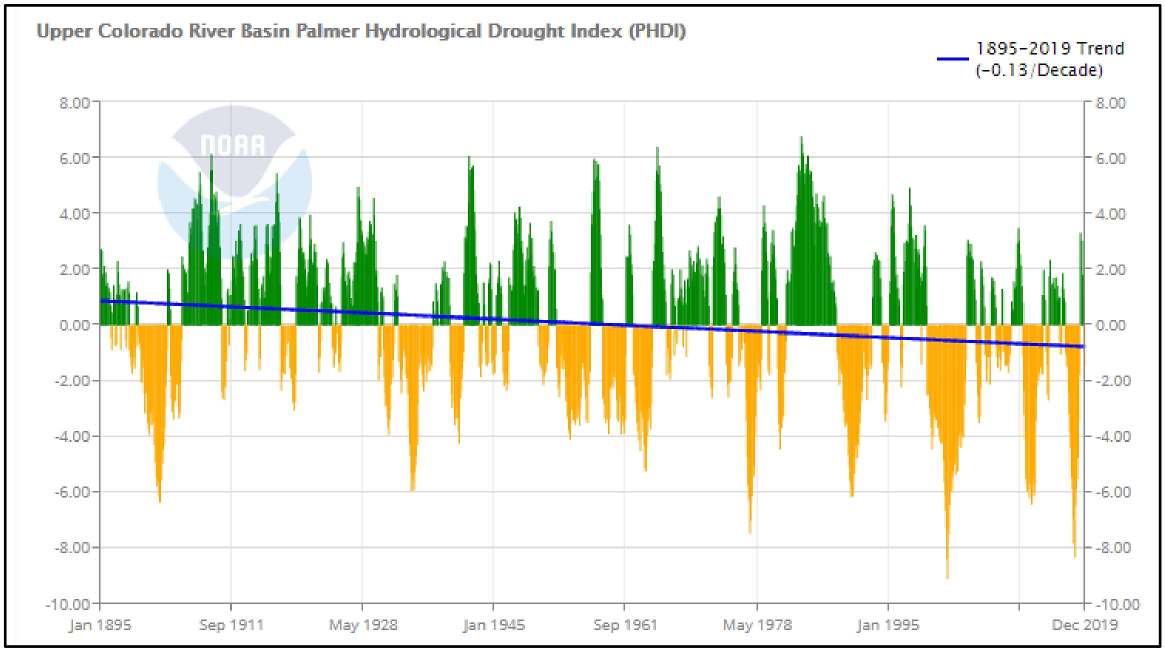

Fig. 3: PHDI trend line - Upper Colorado River Basin [15].

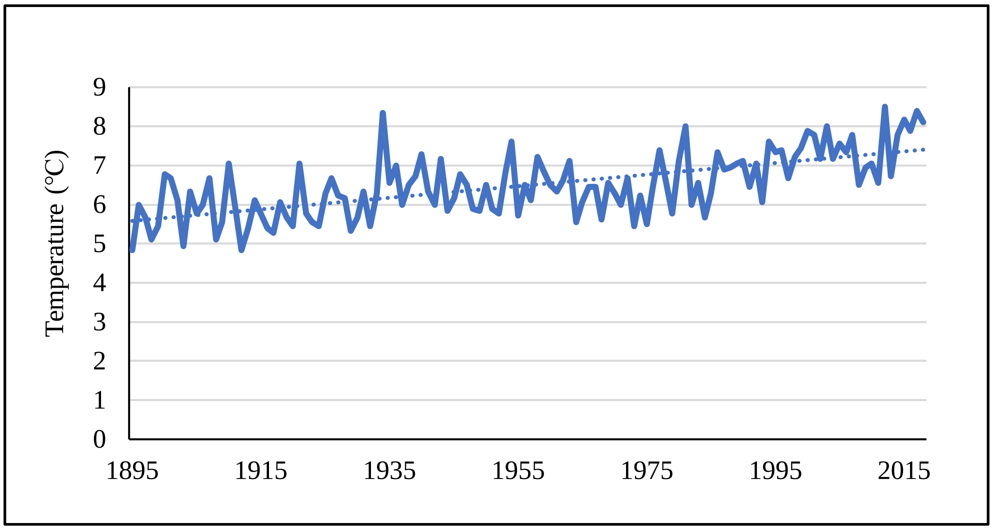

Fig. 4: Average air temperature in the Colorado River Basin [17].

The runoff into the Colorado River is either due to precipitation or melting of the snow packs. In general, rainfall seeps underground or evaporates or flows through a dam. Ref. [17] shows that although there has been a declining trend in precipitation from the 1960s, there is no significant change in the average precipitation level over the last century as shown in Fig. 5.

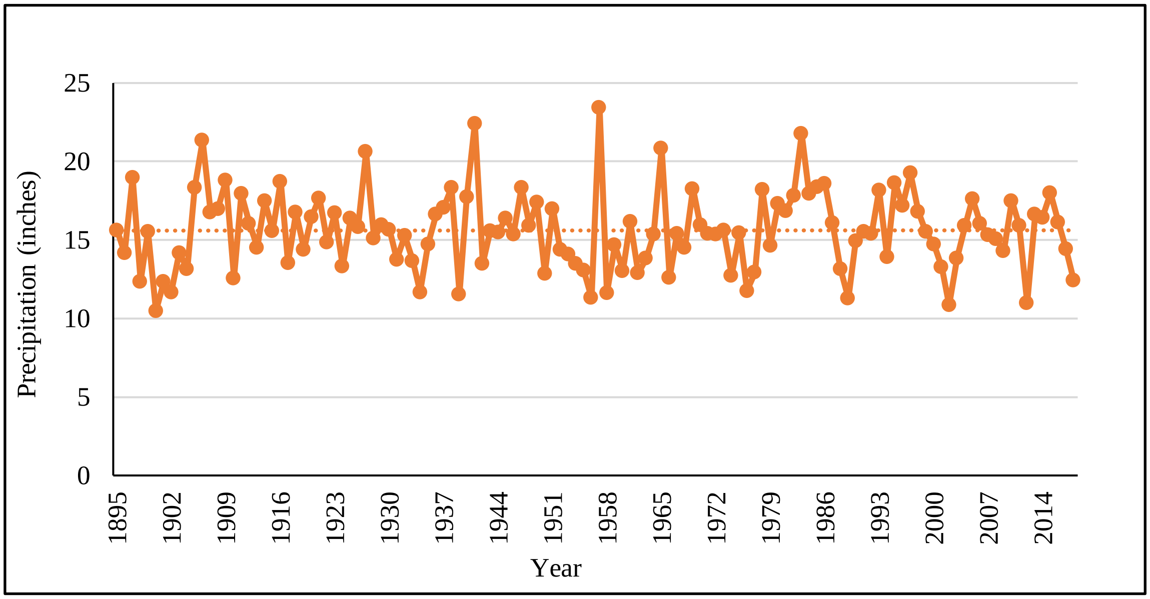

Fig. 5: Precipitation in Colorado River Basin [17].

So, one of reasons for the significant decrease in the river flow as shown in Fig. 6 can be attributed to an increase in the evaporation rate. Over the simulations performed in [18], the long term (1916-2016) change in the annual evapotranspiration (ET) is +4.7% and when the factor of temperature is removed, there is just an increase by +2.6%. This suggests that 45% of the annual ET increase is attributable to the warming temperatures. The remaining 55% could be attributed to the change in the wind speeds and wind resource variability. There has been a substantial 30% increase in the ET rate during winter but relatively small changes during summer. This clearly demonstrates the effect of increasing temperatures on the ET rate [18].

Another reason for the decrease in the river flow is the reduction in the snowpack levels or the change in the timing of snowmelts. Apart from the rainfall, the Colorado River receives 70% of its annual runoff from the snowpack of the Rocky Mountains [19]. The warming temperatures affect the snow levels in the region. Ref. [20] shows that there has been a decrease of 10%-20% in annual amount of water from snow during the 1980s and 2000s, and also projects a further loss up to 60% in the next 30 years. This decrease in the Snow Water Equivalent (SWE) and the snow pack levels are also supported by other research work [19], [21]. These changes in climate in terms of the above factors have reduced the river flow which in turn has reduced the power generation in the Colorado River Basin as shown in Fig. 6.

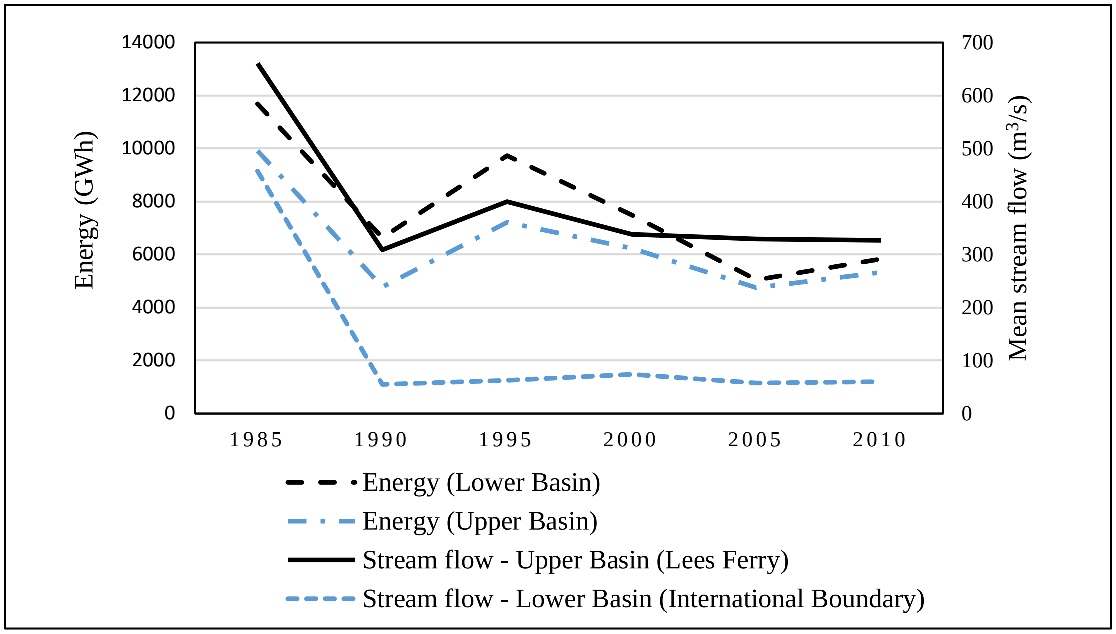

Fig. 6: Electricity generation and annual river flow in the Upper and the Lower Colorado River Basins [22].

2.4 Extreme Events and Other Factors

Apart from the factors such as precipitation, snowmelt and evaporation which effect the hydropower generation in the form of decreased runoff, there are other factors such as increased salinity, floods, storm surges and cyclones which could also potentially affect the hydropower generation adversely by damaging the equipment and machinery [5] [2] [3].

Changing climate has caused the sea levels to rise. This poses a problem in countries like Bangladesh in which the sea levels are rising and eventually effecting the fresh water. Rising sea levels increase the saline content in the fresh water which in due course is used by the hydropower or thermal plants to produce electricity. High saline content exacerbates the corrosion process of the pipes, valves and other such equipment at the plant [2].

The plant equipment is only intended to operate within the design limits. Extreme events such as floods and increased precipitation due to changing climate can increase the runoff rapidly. In the case of a storage type dam, this effect may not affect the turbines. But in the case of a run-of-river dam, the turbine could lack the capacity to incorporate the sudden increase in the runoff beyond its design ability. This could render the turbine unavailable to extract the extra potential thus affecting the power generation [23].

Water scarcity, which is becoming a prevailing problem due to the climate change, could lead to increased tensions for water demand between communities for agriculture purposes. This could lead to a diversion in the river flow thus reducing the water available for power generation [23].

2.5 Forecasted Changes in the Hydropower Generation based on Literature

The studies performed globally have been listed in [5]. There have been studies in literature which try to forecast the changes in the hydropower generation for the future in the U.S. due to climate change. A few studies project an increase in the national hydropower generation while the others forecast a decrease. Among these studies, there are very few which try to quantitatively predict the change in hydropower production in the future for the U.S.

Ref. [24] takes a very intense approach by using temperature and precipitation projections from integration of various climate change models to analyze the climate change effects for around 500 hydropower units in 2119 river basins spread throughout the contiguous U.S. The changes in hydropower generation in various locations due to climate change under different emission scenarios by 2025 and 2050 are discussed in [24]. The impact on hydropower is more prominent region-wise as different regions are affected in different ways depending on the corresponding geography. In summary, the average generation across the contiguous U.S. was projected to increase by 6.5 TWh/y and 1.3 TWh/y by 2050 under the REF and POL 4.5 scenarios respectively. Ref. [24] [25] [26] give a detailed outline of various projection scenarios available and help to approximate REF and POL 4.5 to RCP 8.5 and RCP 4.5 scenarios, respectively. The annual increase in the generation is primarily due to the increase in the mean annual runoff due to increased snowmelt, rising temperatures and precipitation in the Pacific Northwest which accounts for over 40% of the U.S. annual hydropower generation as shown in [24] and with a projected increase of 8.0 TWh/y by 2050. It is counter balanced by a decrease in the southern central regions by 1.2 TWh/y by 2050.

We can see the projected electricity generation from renewable sources of energy up to 2050 in Fig. 7 and the changes in the hydropower generation due to the RCP 4.5 and RCP 8.5 scenarios by 2050 solely based on [24] are compared to values forecasted by Energy Information Administration (EIA) in Fig. 8. Ref. [24] is used in this study to project future hydropower changes by 2050 because it is a recent exhaustive study which investigates the quantitative effects of climate change on hydropower carried out in the U.S. at the time of the current research and it pertains to the climate change scenarios such as RCP 4.5 and RCP 8.5 used this thesis. Ref. [24] takes into consideration many factors which have previously not been taken into account such as the turbine capacity and the operational limits at the facility-level for around 30 years up to 2050 and that study integrates around 54 climate models to account for the changes in the forecasted runoff at each of the facilities.

When there is an increase in the runoff, the turbine and the designed equipment might not have the capacity to accommodate the increase. So, an increased runoff can only increase the hydropower generation only up to a particular extent. While the previous studies do not particularly confirm the details of this aspect while making forecasts, Ref. [24] takes an unprecedented approach by incorporating turbine capacity and other design and operational characteristics at each concerned facility while forecasting the projected changes in the hydropower generation.

Based on the results in [24], we can see that the projected changes in the hydropower generation is almost equal in the case of RCP 4.5 and the EIA case but it increases by a significant margin in the RCP 8.5 scenario. This could be expected because RCP 8.5 is the extreme scenario which projects high temperature increases.

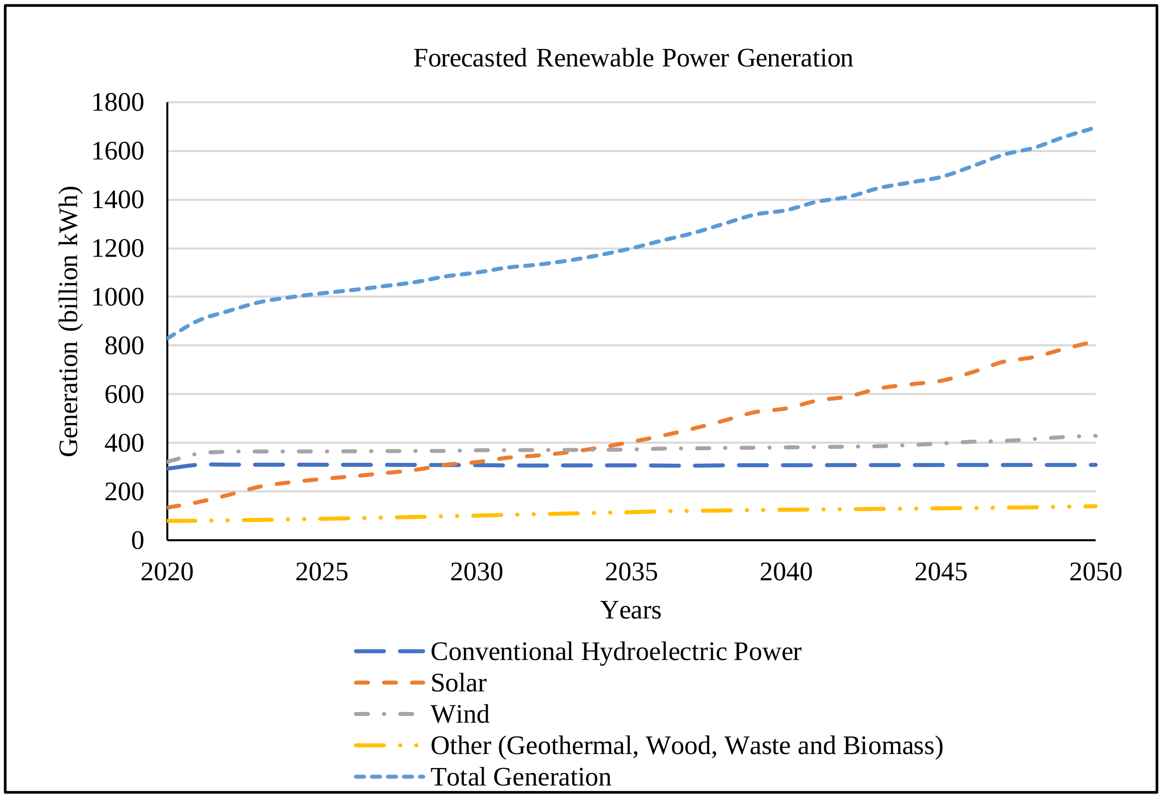

Fig. 7: Forecasted renewable power generation up to 2050 [27].

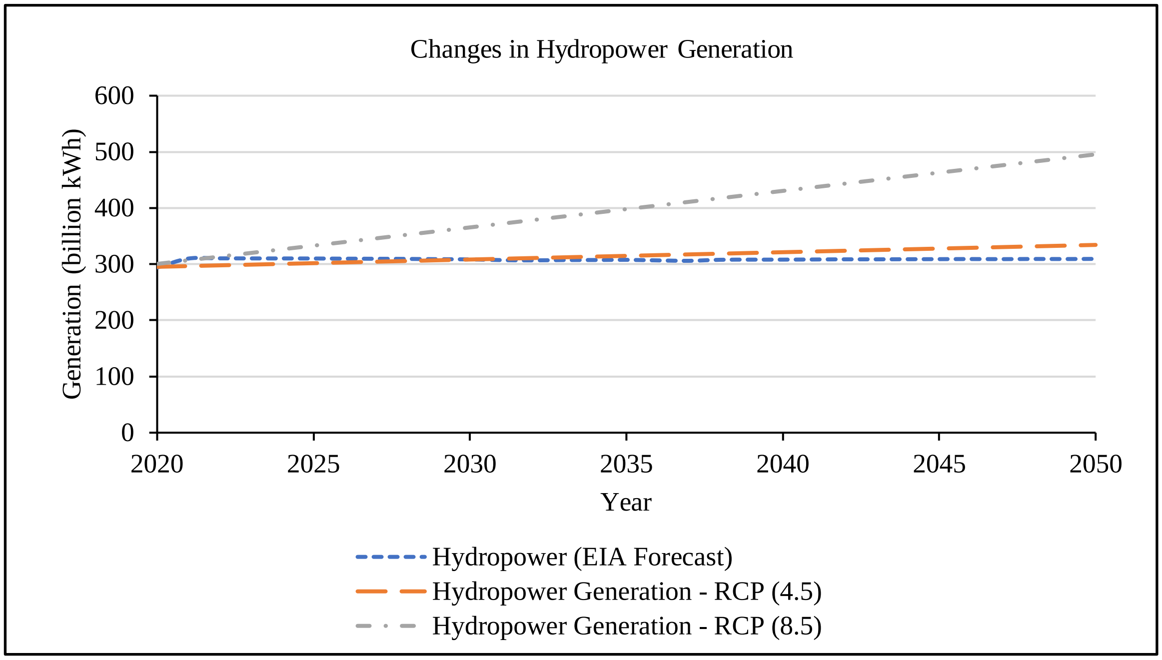

Fig. 8: Comparison in hydropower generation projected by EIA [27] and ref. [24].

From Fig. 8, we can see that in the case of the RCP 8.5 scenario, there is a lot of potential for electricity generation from the hydropower plants in the Pacific Northwest. Most of the potential can be harnessed if the hydropower plants in the northwest region consist of reservoir dams rather than run-of-river dams. The reservoir dams generally have larger storage facilities that might help reach the extra potential as these facilities can act as buffer to facilitate the increase in the runoff.

Another study has also quantitatively forecasted the federal hydropower production up to 2050 [28]. While [28] also agrees with an annual increase in the hydropower power generation by 2050, this study takes into account only 36 GW of hydropower capacity in the U.S. as compared to approximately 100 GW overall capacity. So, Ref. [24] is given more preferrence in predicting the future hydropower production in U.S. while taking climate change into consideration.

2.6 Adaptation Measures

As the climate is changing, the models which are used to predict the climate change are also evolving. The advances in the methodology used to forecast the changes in climate should be harnessed and regular studies should be made to understand the effects of climate change on a timely basis. Further, sharing these studies among various organizations would be highly beneficial in understanding this transient phenomenon and its effects on electricity production [28]. Also, the daily characteristics of precipitation, increasing temperatures, snowmelts, etc. could be monitored and if there is a deviation from the normal records, the planning, equipment and operations could be updated to adapt to the changing parameters [28].

2.7 Conclusion

Hydropower in the Colorado River Basin is mainly affected by the increase in the temperature and evaporation and decrease in the snow levels. Hydropower generation is projected to increase nationwide, but more emphasis should be placed on the regional effects. Based on the results in Fig. 8, the hydropower might increase by 8%-60% due to RCP 4.5 and RCP 8.5 scenarios respectively.

Hydropower capacity is being increased in the developing countries as it could be a possible solution to meet the demand as it is cheaper to maintain, and it helps balance out the fluctuating power generated by solar and wind power plants. Effects of climate change should be considered in the plans to build future hydropower plants.

CHAPTER 3

Climate Change Effects on Wind Power Generation

3.1 Introduction

Wind power is the world's second largest source of renewable electricity generation with an estimated production of 5.6% of electricity generated globally. As of 2017, the installed wind power capacity was 539 GW which accounts for 24.5% of the overall renewable power generation capacity [10]. Countries with highest wind power capacity are China, United States, Germany, India, and Spain. In the U.S., 6.5% of the net electricity generated was from wind power in 2017, which is around 38.9% of the net electricity generated by the power sector from renewable sources of energy [11].

The amount of power generated by a wind turbine is

$$P_{wind} = \frac{16}{27}\,\eta\,\rho\,A\,v^3/2 \tag{2}$$

Where η is the turbine mechanical-to-electrical efficiency, ρ is the air density, A is the area swept by the blades and v is the wind velocity. Climate change does not modify the area swept by the blades, but could alter the efficiency, air density and the wind speed, thus affecting the power generated.

3.2 Efficiency

Icing affects the availability and the efficiency of the turbines in high elevations and latitudes. Studies in Finland show that the areas which reported icing have experienced reduction in the turbine availability by 1.3 % in a year [29]. There is also a loss in turbine efficiency during icing events. But, rising temperatures help in melting the ice on the turbines, hence aiding in improving the efficiency. Ref. [4] suggests that most of the wind turbines are likely to experience a rise in the availability due to increased temperatures in Scandinavia. In the U.S., since the temperatures are rising throughout the country, the areas with icing events could benefit. Rising temperatures facilitate higher availability, hence higher power in icing affected areas. But the degree of benefit of rising temperatures on the turbine efficiency in U.S requires further research.

3.2 Air density

The rise in temperature (T) decreases the air density ($\rho \propto T^{-1}$) which in turn reduces the power generation. Table 2 displays the maximum percentage decrease possible in the wind power produced in the U.S considering only the effect of temperature. The predicted changes in temperature by the mid-century period and the late-century period from RCP4.5 and RCP8.5 scenarios are used. The change in temperature is gathered from the data in [13] and the decrease in percentage of power generated is calculated from Eq. (2).

There is a small difference in temperature which should be accounted here. Although the Introduction says that the overall predicted national temperature change is around 1.4ºC–1.6ºC as per the RCP 4.5 and RCP 8.5 respectively by 2050, Table 2 seems to have different values as it gives regional temperature ranges. Another reason could also be that initial temperature values used in Table 2 were taken from [17] and these values could vary from the values used in [13]. Except for Table 2, the temperature values mentioned in the Introduction are used elsewhere.

Table 2. Reduction in the Power Generation due to Air Density Decrease with Increasing Air Temperatures

Region	**RCP4.5 (2036-2065) – (2071-2100)**	**Power decrease (%)**	**RCP8.5 (2036-2065) – (2071-2100)**	**Power decrease (%)**
Northeast	2.21ºC-2.93ºC	0.8-1.0	2.83ºC-5.06ºC	1.0-1.8
Southeast	1.89ºC-2.46ºC	0.6-0.8	2.39ºC-4.29ºC	0.8-1.5
Midwest	2.33ºC-3.09ºC	0.8-1.1	2.94ºC-5.27ºC	1.0-1.9
North Plains	2.25ºC-3.02ºC	0.8-1.1	2.83ºC-5.21ºC	1.0-1.8
South Plains	2.01ºC-2.66ºC	0.7-0.9	2.56ºC-4.69ºC	0.9-1.6
Southwest	2.07ºC-2.74ºC	0.7-1.0	2.66ºC-4.81ºC	0.9-1.7
Northwest	2.03ºC-2.77ºC	0.7-1.0	2.59ºC-4.73ºC	0.9-1.7

3.3 Wind Speed

Change in wind speed is the major factor influencing wind power generation as power is directly proportional to the cube of wind velocity. If the wind speed changes by 1%, the power generated by the turbine will change by 3% and a change in 10% would change the power generated by 33%. Ref. [4] mentions that a wind speed of 3 m/s could generate 16 W/m$_2$ wind power, whereas a wind speed of 12 m/s can generate 1305 W/m$_2$ of wind power. This highlights the extent to which changes in the wind speed impact power generation. The prediction of the extent of change in the wind speed in U.S is limited as most of the research is exploratory rather than conclusive. It is also limited by the availability of the resources to forecast accurate predictions.

Table 3 highlights the results from various research papers regarding the changes forecasted in the wind speed, power, resource and energy density.

Table 3: Wind Speed Potential and Energy Research Outcomes

Research Outcomes	**Ref. (date)**
Kansas, Texas and Oklahoma have the greatest increase in the wind speed and are expected to gain over 2% wind energy availability. Highest average energy density is predicted in the Midwest, with Wyoming having the maximum. Northwest and Northeast regions are expected to experience decrease in the average wind speeds.	[30] (2006)
Seasonal wind power patterns in most of the U.S. would experience 0-30% decrease and in a few areas 0-30% increase while the annual patterns would be affected by ±10%. The central High Plains and the coastal Northwest are slightly affected. The Texas-Oklahoma regions are expected to have an increase in the wind power. A decline in wind power was depicted in north-central U.S and mountain areas of northwestern U.S.	[31] (2001)
The wind power resource in the Northwest U.S. is projected to decrease up to 40% in the spring and summer months.	[32] (2008)
The results from two different models (the Hadley Model and the Canadian Model) suggest that the wind speeds in the U.S. would reduce by 1%-3.2% in next 50 years and 1.4%-4.5% in the next 100 years. Although both the models agree on results at the national level, the results from these two models at the regional level showed very few similarities.	[33] (2002)
The regions of Texas, Kansas, Oklahoma, Missouri, Arkansas and Louisiana are predicted to have a 5-10% increase in the mean wind speeds.	[34] (2011) [30]
Fairly stable or slightly increased wind resources are projected in states of Texas, Kansas and Oklahoma.	[35] (2011)

From Table 3, we can see that research consistently predicts an increase in the wind speed in Texas, Oklahoma and Kansas. This wind speed is changing mostly because of the difference in the temperature gradient between the poles and the regions of interest.

These states already have considerable wind power installations. Increased wind speeds should lead to a boost in power generation. But huge changes in the wind speed could hinder the availability of the turbine. Sudden bursts of wind or extreme wind speeds, which are being recorded more frequently and are predicted to be more common in the future as a result of changing climate, will also affect power generation [2] [29]**.** Wind turbines can operate only within a particular range of velocities. So, an increase in wind speed beyond the cut-out speed could actually decrease the average output from the turbine [4] as shown in Fig. 9. We can see that in the presence of sudden bursts of extreme wind speeds [29], there is a probability that the wind speed could exceed the cut-out speed, potentially damaging the wind turbine or curtailing the power output to zero more frequently thus reducing the energy generated from the wind turbine.

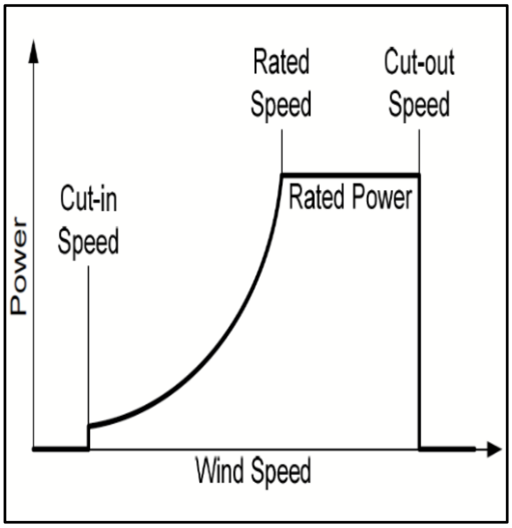

Fig. 9: Wind speed and power generated.

3.4 Extreme Events and Other Factors

Other factors such as permafrost and sea-ice hinder the operation of wind farms. Change in the permafrost conditions due to climate change has profound impact on the construction and maintenance of the wind farms at high latitudes. As the Alaska Electric Cooperation reported "*Warming trends are effecting the level of permafrost which makes it difficult in the design of wind farms"* [29].

Extreme events of climate change in terms of storm surges, cyclones could also affect the wind power generation as they could potentially destroy the facility itself. Thus, it is very important that climate change be considered while building wind turbines in the future.

3.5 Conclusion

The increase in the local temperature does not significantly alter the wind power generation, rather change in the wind speed is the most important factor. Studies are consistent with predicting increased wind speeds increase in Texas, Kansas and Oklahoma.

The uncertainty in the occurrence of climatic events leads to a greater uncertainty in forecasting the precise quantitative extent to which the climate change is taking place, and this leads to even greater uncertainty in predicting the climate change on wind power generation.

CHAPTER 4

Climate Change Effects on Solar Power Generation

4.1 Introduction

Electricity can be generated from solar power through the use of photovoltaics or through heliothermal processes (i.e. concentrated solar power (CSP)). In 2017, solar power generated through photovoltaics (PV) had the highest percentage increase in the installed capacity globally. Specifically, there was an increase in the installed PV capacity of approximately 33% from 303 GW to 402 GW. Countries with the highest PV capacity are China, U.S, India, Japan and Turkey. The CSP capacity increased from 4.8 GW to 4.9 GW. Countries with the highest CSP capacity are Spain, U.S., South Africa, India, and Morocco [36]. CSP had a lower percentage increase and contributes a very small portion of the overall solar generation and its properties are similar to those of thermal power plants. Due to these reasons, this chapter emphasizes only on the photovoltaic cells. In the U.S., the net electricity generated from solar power across all sectors is shown in Fig. 10.

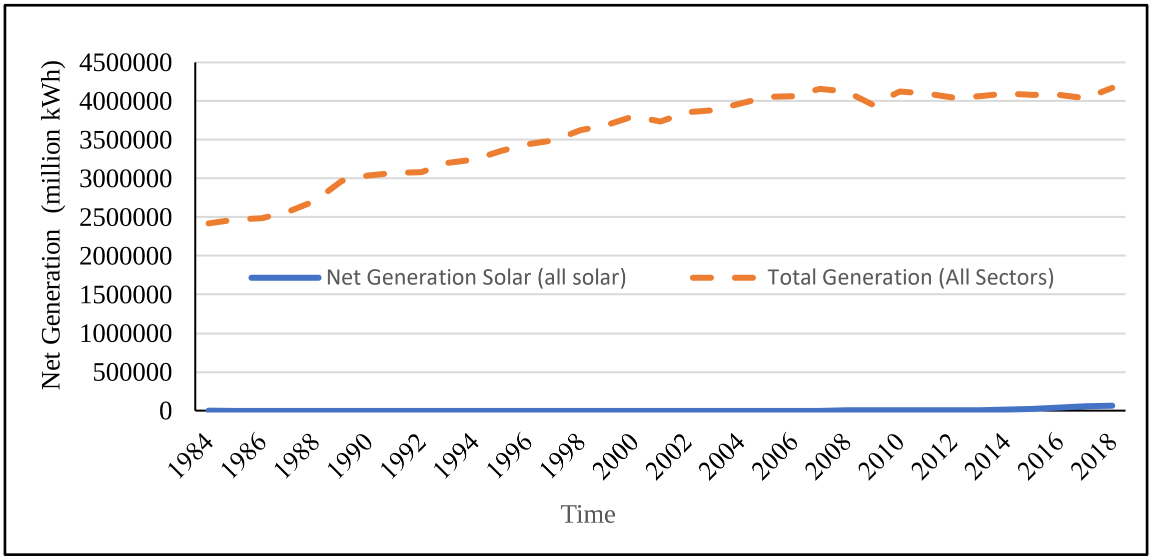

Fig. 10: Net electricity generation [37].

From Fig. 10, it can be seen that the generation from solar power sums up to approximately only 1.5% of the overall net generation. Although it represents a very small percentage of the entire generation, it should be noted that the power from solar energy has increased significantly in the last decade (2008-2018) from 864 million kWh to 63825 million kWh by around a staggering 7300%. This increase could be mainly because of the widespread awareness to reduce greenhouse gas emissions, favorable government policies (e.g., tax incentives), decreasing prices of the solar module installations and increase in the efficiencies of the various technologies used. Various environmental, societal, economical, governmental factors can affect the power generated from a solar power unit. But the main factor of importance in this work is the climate change in terms of increase in the ambient air temperatures, changes in the precipitation and solar radiation.

The annual total solar electricity generation can be given by

$$E = Q\ T_{daylight} A\ \varepsilon\ t \tag{3}$$

Where A is the active solar panel area, ε is the efficiency, t is the time over which electricity is calculated, Q is the solar radiation, and $T_{daylight}$ is number of sunshine hours. From the factors mentioned, those affected due to the climate in terms of increasing temperatures, wind speed, precipitation and solar irradiation are mainly the change in the efficiency and incoming solar energy which eventually affect the power generated from a solar unit. This chapter analyzes the effects of climate change in terms of increasing temperatures on solar power generation by 2050 and tries to qualitative analyze the effects of precipitation, wind speed, extreme events and solar irradiation on solar power generation.

4.2 Solar Power Generation and Climate Change

4.2.1 Solar Radiation

Solar insolation is the amount of light energy reaching the surface of the Earth. The total solar insolation at the Earth's atmosphere is around 1366 W/m^2 [38]. This solar radiation gets converted to electrical energy by the solar panels. So, a change in incoming solar radiation directly affects solar power generation and is the major factor of concern regarding the effect of climate change on solar power production [5].

The main reason for the change in solar irradiation is because of the aerosol content in the atmosphere [39]. Aerosols are particles from pollution, volcanic eruptions, forest fires and from the burning of coal and oil such as sulfur, nitrogen, chlorine particles, etc. which are suspended in the air. When these particles accumulate to form larger particles, they scatter or absorb light. Unlike greenhouse gases which cause warming of the atmosphere, the aerosols actually cool the atmosphere by scattering or absorbing the incoming solar radiation [40]. In this manner, the incoming solar radiation is reduced, thus affecting the solar energy reaching the solar modules and hence decreasing the power output from the solar cell [39]. The technical details regarding the aerosol compositions are beyond the scope of this study but their detailed effects are included in studies mentioned in [5] [40] [39]. The combined effects of warming atmosphere due to greenhouse gases and cooling atmosphere due to aerosols in the same regions is very hard to understand even qualitatively mainly because of the primitive state of the reliable climate models [40]. But the qualitative effects of change in the solar radiation on solar power are addressed in the literature [5] as discussed below.

The direct solar radiation is projected to decrease globally by 5% by 2039 but the changes vary regionally [41]. The solar radiation is projected to increase in Europe, most parts of the U.K. and decrease in Africa. The power output is projected to increase in European countries such as Spain, Germany and decrease in North-West China and India with no significant effects in Algeria and Australia [5]. While most of the research presented includes studies investigating the effect of solar radiation on solar power production, it does not quantify the extent to which the solar power output gets affected per unit change in solar radiation. So, the current study is limited only to the qualitative effect of solar radiation. This means that an increase in the solar radiation increases the solar power output and vice versa [5].

There is very little research performed on the changes of solar radiation in the U.S. Ref. [42] projects up to ±10% change in the direct solar radiation in different regions of the U.S. by 2040-2069 as highlighted in Table 4.

Table 4: Projected Solar Irradiation Changes in the U.S by 2040-2069

Winter		Summer	
Increase	Decrease	Increase	Decrease
Great Lakes northeast U.S. Western Montana - Washington	southern U.S. Texas southern Arizona	Most of the U.S. (maximum in Pacific Northwest and northeast U.S.)	southern California Arizona (very small) Colorado/Utah
Spring		Fall	
Increase	Decrease	Increase	Decrease
Pacific Coast northeast U.S. Arizona Louisiana-Alabama	Rest of the U.S. (Mainly in north Texas and western Montana)	southwest U.S. southern Texas Florida northeast U.S.	Mississippi/Alabama Midwest U.S. Central Great Plains northwest U.S.

Changes in the solar irradiation due to climate change is one of the most important effects of climate change on solar power production [43] [5] [39]. Since the information present in Table 4 might not be sufficient to quantitatively predict the effect of changes in solar radiation, it still might be useful in evaluating locations for the installation of new solar units in the near future.

4.2.2 Wind Speed

A variation in the wind speed may affect the temperature near the solar cell, thus effecting the efficiency and power from the cell [5]. An increase in the wind speed could decrease the temperature near the surface of the solar cell due to convective cooling, which is the phenomenon of transferring heat from a body to the fluid surrounding the body [44]. Based on the relationship between the temperature and efficiency in Eq. (4), this increase in the wind speed might cool the solar cells, hence increasing the efficiency and power generation from the cells [5]. Since this study is mainly based on the work from the literature, the effect of wind speed on solar power generation can only be validated on a conceptual and qualitative basis since there is very little authoritative work published regarding this effect [5].

Ref. [5] lists the various research activities performed taking into account the wind speed on solar power while trying to study the climate change impacts. A study on the climate change impacts on solar power in Europe acknowledges that the effect of wind speed on solar power is existent but it offers no highly conclusive connection on how wind speed affects solar power [45]. Another study performed to find the future impact of climate change on the solar potential in the Canary Islands considers wind speed in its simulations, but it does not show derivative results regarding the effect of climate change on wind speeds [46]. Apart from the above studies which consider the wind speed in more of a qualitative sense, there are two studies performed in India which try to quantify the relationship between the module temperature, efficiency and wind speed [47] [48]. The results indicate the correlation coefficient between the efficiency of the solar cell and wind speed is 0.68 [47]. Ref. [48] tries to form an equation which considers both ambient temperature (T) in degrees Celsius and wind velocity (v) in meters per second while establishing a relationship with output efficiency (η).

$$\eta = 14.9852 - 0.08666\, T + 0.017647\, v \tag{4}$$

The study successfully verifies the credibility of Eq. (4) by comparing the values obtained with the actual recorded values. This equation could be used once more research has been conducted into the projections of future wind speeds.

As the effects of wind speed on solar power production have very minute amount of work in the literature, this thesis does not consider the effects of wind speed while trying to project the future climate changes by 2050 in Section 4.2.4.2.

4.2.3 Change in Precipitation

Another reason for a change in incident solar radiation is because of change in the rainfall pattern. According to the study conducted in [49], it was found that increase in the precipitation events leads to a decrease in the sunshine hours as the amount of annual precipitation increases [49]. The sunshine hours are depended on the clearness of the sky. This reduction in the sunshine hours can decrease the amount power from a solar unit.

Precipitation is also directly related to the cloud cover which could also inhibit the solar radiation from the reaching the surface of the module. More the cloud cover, lesser the solar power output and vice versa [5] [39] [43].

4.2.4. Increase in Ambient Air Temperature

4.2.4.1 Increase in the Ambient Air Temperature and Power Generation

An increase in the air temperature affects the efficiency of solar cells. The relationship between the efficiency and the temperature of a solar cell [50] is given by

$$\eta = \eta_{ref}(1 - \beta_{ref}\,(T - T_{ref})) \qquad (5)$$

Where η is cell efficiency at temperature T, η_{ref} is the cell efficiency at the reference temperature T_{ref}, β_{ref} is the temperature coefficient (generally 0.004/K) and is given by $(T_0 - T_{ref})^{-1}$, T_0 is the highest temperature at which efficiency is zero. T_0 is 270ºC for silicon cells [50]. Generally, the η_{ref} value is found at the ambient temperature which is around 20ºC in most of the testing environments. Variation of the theoretical efficiency with an increase in the ambient temperature is shown in Fig. 11.

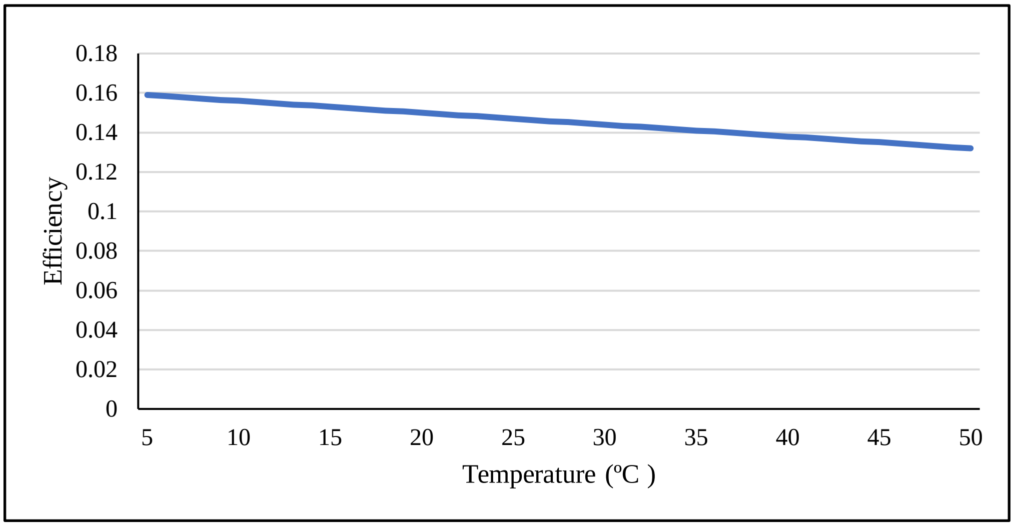

Fig. 11: Change in silicon solar cell efficiency with increasing temperature.

Since the power is directly related to the efficiency, the maximum output power of the cell is reduced with increasing temperatures [50] [51]. For a cell with a reference efficiency of 15%, an increase in the temperature of 1ºC decreases the theoretical power about 0.4% as per Eq. (5). This is also supported by a study performed in the Canary Islands which predicts the output power to reduce by 0.4% for an increase in the ambient air temperature by 1ºC [45] and another study also shows the similar decrease in the output efficiency by 0.5% for an increase in the ambient air temperature by 1ºC [43].

The corresponding change in the power output of the cell also depends on the type of the module used. Fig. 12 highlights the prominent module technologies which are available in the market and their respective losses in the percentage of output power for an increase in the ambient air temperature.

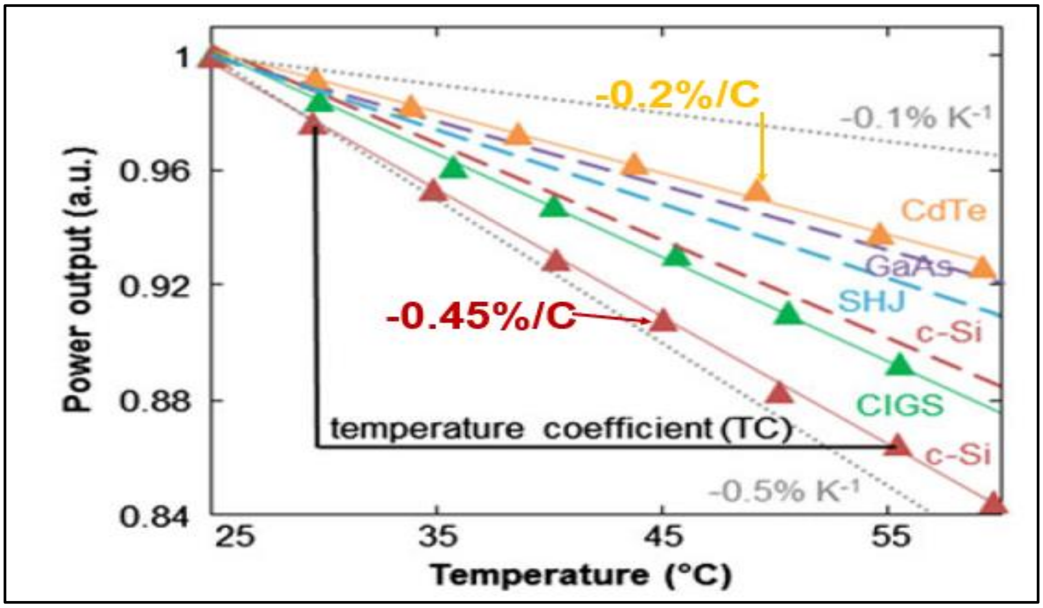

Fig. 12: Solar cell output power variation with increasing temperatures [52].

From the data in Fig. 12, we can clearly see that the range of power variation across different modules is around 0.1-0.5% for an increase in the ambient temperature of about 1ºC. This is also supported by [45] [43] [5]. Using these values, we can try to forecast the effected generation by 2050.

4.2.4.2 Forecasts Related to Generation Loss by 2050 due to Temperature Increase

Based on the data regarding decrease in the power output for a degree increase in the ambient air temperature, we have tried to forecast the loss in the power generation by 2050. From Chapter 1, the ambient temperature is going to increase by 1.4 ºC and 1.6 ºC by 2050 according to the RCP 4.5 and RCP 8.5 scenarios. But since these are just projections, we are going to calculate for an increase in the range of temperatures from 1ºC to 4ºC.

Fig. 13 depicts the forecasts in the power generation by 2050. We can clearly see that renewable generation sums up to around 31% of the projected generation by 2050.

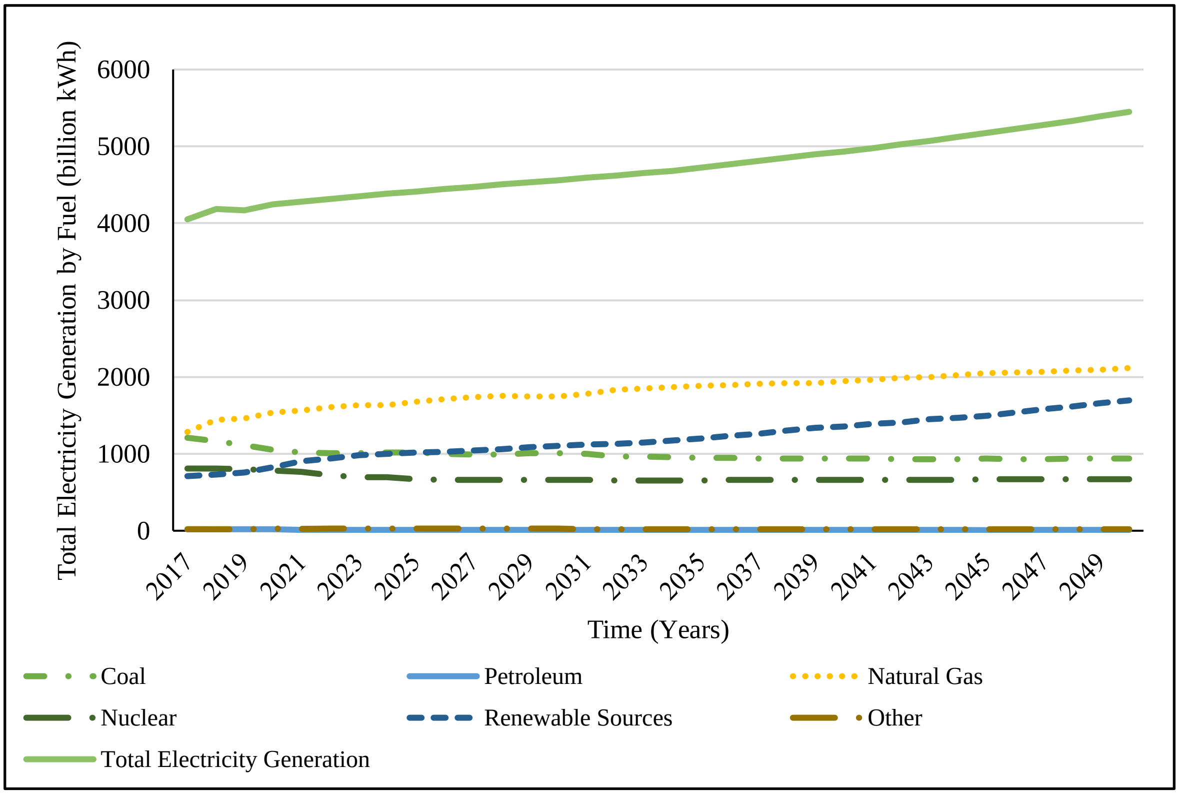

Fig. 13: Future electricity generation by 2050 [27].

Fig. 14 depicts the split of the 31% of the renewable energy present in Fig. 13. We can see that the around 48% of the renewable energy is from solar energy, i.e., 818 billion kWh. This once again highlights the importance of the solar power generation in the future.

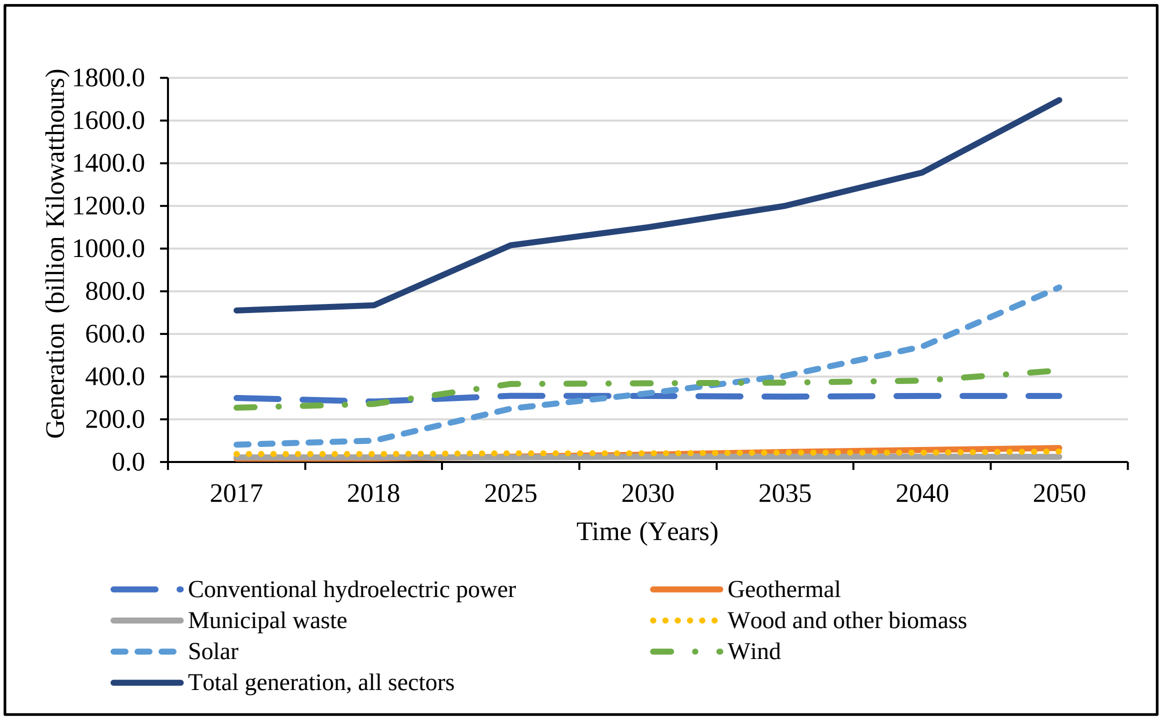

Fig. 14: Electricity generation (renewables) by 2050 [27].

Since we know the percentage power reduction per degree increase in the ambient air temperature, the future power generation and the future increase in the temperature, we can now forecast the losses in the power generation in the future by 2050.

Fig. 15 forecasts the losses in the power generation by 2050 and highlights the RCP 4.5 and 8.5 scenarios. The forecasts are done by using the following formula,

Power Loss $_{\text{by 2050}}$ = Predicted generation (billion kWh) * Temperature Change * Decrease in power output (%/ºC) (6)

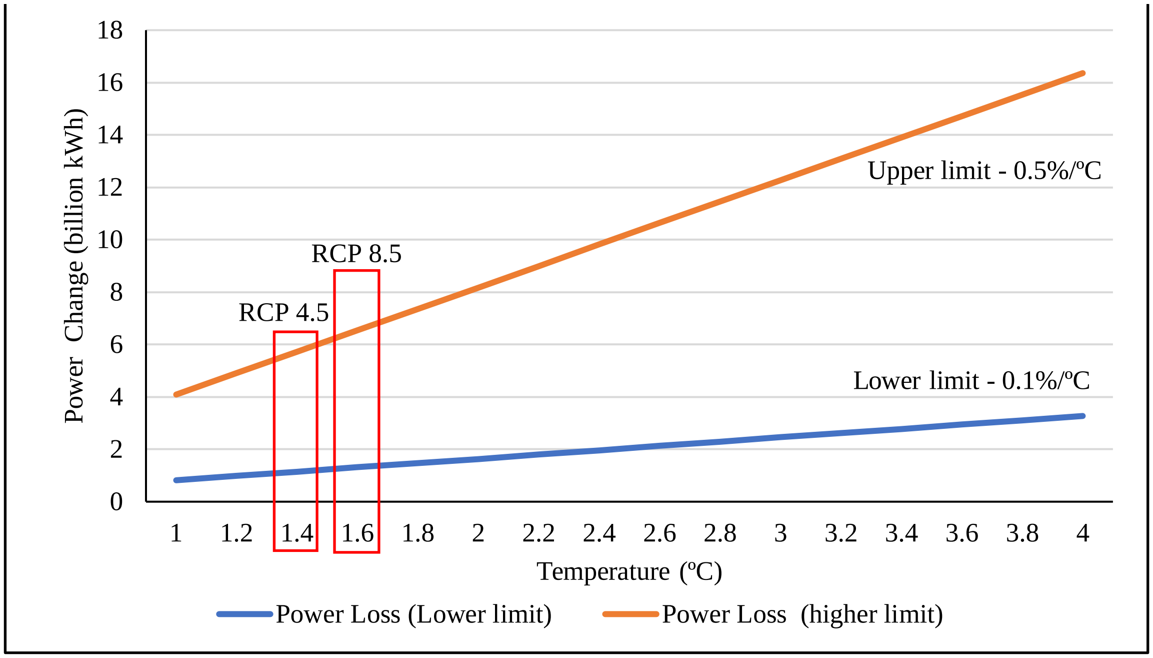

Fig. 15: Predicted loss in the power generation by 2050.

From Fig. 15, we can see that a loss of around 1 to 6 billion kWh could be experienced due to an increase in the temperature by 1.4ºC (RCP 4.5) and a loss of 1.3 to 7 billion kWh could be experienced due to an increase in the temperature by 1.6ºC (RCP 8.5). On an average we can see that around 2.5 billion kWh is lost per increase in the ambient air temperature by 1ºC. This equals the reduction in the entire solar power generation in 2050 by approximately 0.05% due to the increase in the ambient temperature of 1ºC.

Hence the increase in temperature is not the main factor of concern regarding the climate change on solar power production. This effect can also be mollified by the increasing advancements in the solar modules which support a wider range of operating temperatures.

4.2.5 Extreme Events

Apart from the conventional aspects of climate change, effects involving solar irradiance, wind speed, precipitation, cloud cover and air temperature, extreme events which are in the recent times linked to climate change also affect the power generated from solar energy [5]. These extreme events could cause damage to solar cells and other infrastructure. Extreme winds also lead to sand depositions on panels which block the incoming solar irradiance from reaching the solar panel, thus reducing the efficiency and output power from the solar modules [43] [5]. Extreme events also lead to events such as heat waves which increase the temperatures, thus reducing the efficiency of the cells.

4.3 Conclusion

Solar power generation is mainly affected by increasing temperatures, changes in the precipitation and solar radiation. The solar power output reduces by approximately 2.5 billion kWh by 2050 for an increase in ambient air temperature of 1ºC. The power output increases for a decrease in precipitation and vice versa. This same line of thought applies for the effect of solar radiation on power generation also. But the solar power output increases for an increase in the solar radiation and vice versa. Overall, the effect of temperature on solar power was quantified and the qualitative effects of precipitation, wind speed and solar radiation were analyzed.

CHAPTER 5

Climate Change Effects on Thermal Power Plants

5.1 Introduction

Thermal power plants are the most dominant sources of power generation internationally. These include power from coal, natural gas, nuclear, oil, solar thermal, biofuel and geothermal units. Out of these sources, nuclear, natural gas and coal fired power plants are of primary importance in this work as they currently account for around 80% of the power generation around the globe. This significance of the thermal power plants can be seen clearly from Fig. 16. Although the percentage of thermal power generation may vary across countries, the thermal power plants continue to remain the most important sources in almost all the countries. Leading countries with the highest thermal power generation are China and the U.S. Fig. 17 depicts the importance of electricity generated from thermal power plants in the U.S.

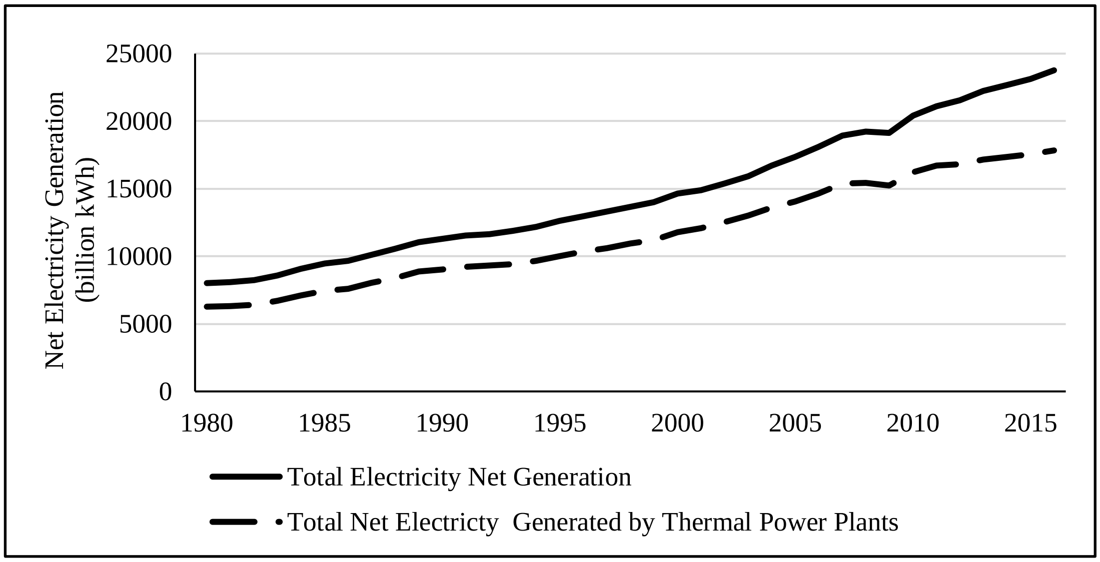

Fig. 16: Net electricity generation, world [53].

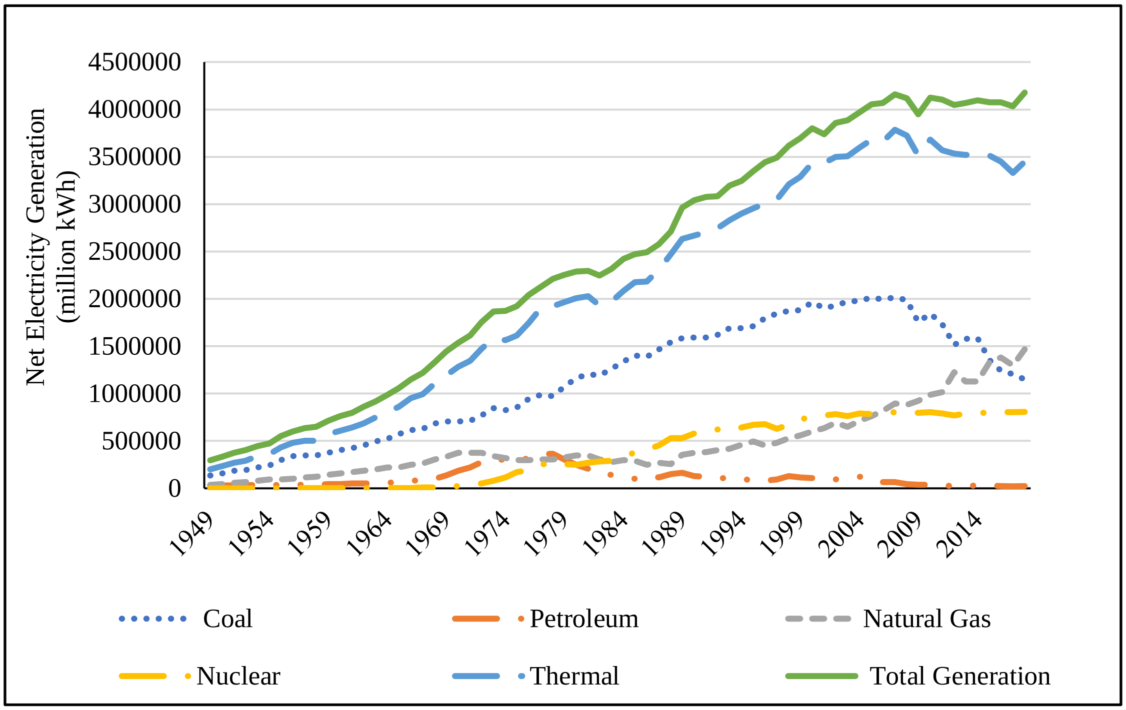

Fig. 17: Net electricity generation, U.S. [54].

As of 2018, coal fired plants generate around 28% of the net electricity produced in the U.S. as compared to 2007, when the net electricity generated from coal was almost equal to 49% of the total electricity generated. A few of the reasons for this decrease include the increasing popularity for the use of renewables, widespread awareness to aid the decrease of the emission of the greenhouse gases, and cheaper natural gas prices. Electricity generation from natural gas has been increasing and amounts to around 35% of the total net electricity generated nationally in 2018, whereas the net electricity generated from the nuclear sources has remained rather stable over the last 20 years with around 19% of the total generation as of 2018. We can see that around 80% of the power generated is from coal, nuclear and natural gas in 2018. This information highlights the importance of the thermal power plants in electricity generation in the U.S.

Many factors could affect the power produced from these sources such as government policies, increase in the prices of the natural gas, coal or uranium, availability of the material, societal factors, environmental factors, etc., but the factor of prime importance in this work is climate change.

The emission of greenhouse gases from the power plants (mostly coal fired) is one of the main reasons for climate change. At the same time the increase in the ambient air and water temperatures is also affecting the power generation adversely. This chapter deals with the effects of climate change on thermal power plants.

5.2 Thermal Power Plants, Cooling Systems and Climate Change

5.2.1 Thermal Power Plants and Climate Change

Thermal power plants are electricity generating units which convert heat energy to electrical energy. In each of the thermal plants considered in this work, heat energy is produced either from burning of coal, combustion of gas or from nuclear processes. This heat energy produced is used to rotate the turbine thus converting the thermal energy to mechanical energy which is then used to rotate the shaft of the generator. The generator then converts this mechanical energy to electrical energy which is dispatched to meet the electricity demand.

The conversion from the thermal energy to electrical energy happens in thermodynamic cycles. The thermodynamic cycles in a power plant are either Rankine cycle in coal fired plants and nuclear plants, Brayton cycle in natural gas plants or a combination of both the cycles in a combined cycle natural gas plant. The Rankine and the Brayton cycles are depicted in Fig. 18 and Fig. 19, respectively.

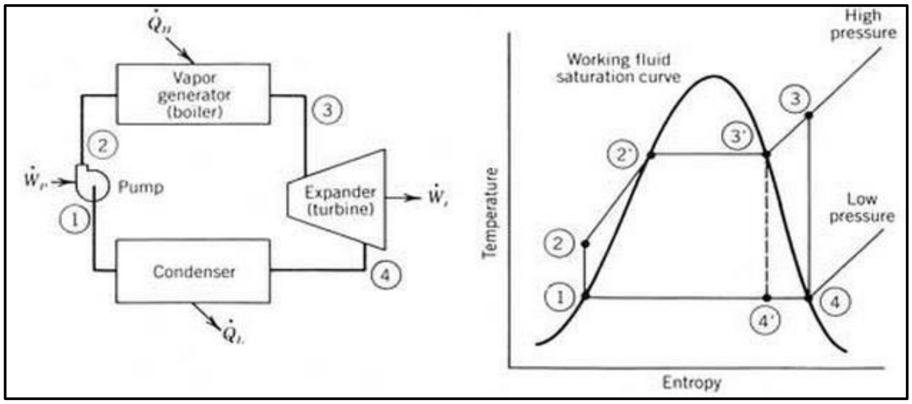

Fig. 18: Rankine cycle and associated T-s diagram (Source: Ref. [55]).

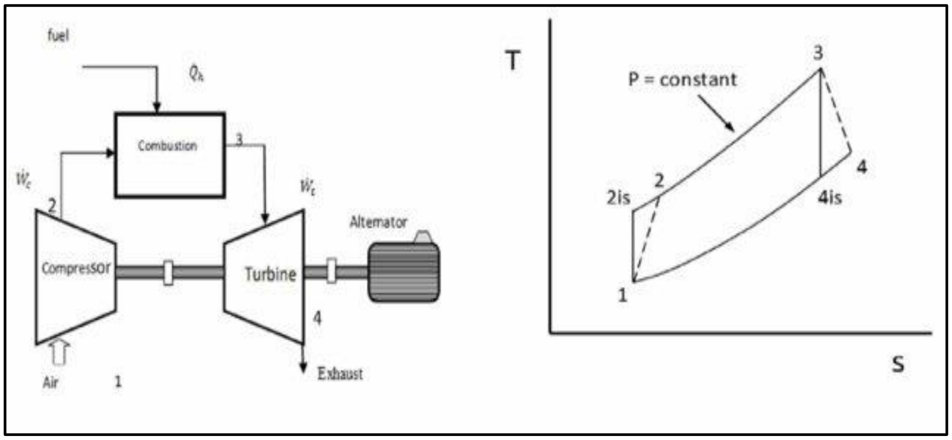

Fig. 19: Brayton cycle and associated T-s diagram (Source: Ref. [56]).

An important technical factor of concern regarding the functioning of power plants is the efficiency of these cycles. The thermal power plant efficiency depends on internal factors such as the properties of component design involving the boiler and condenser limits and the inherent properties of pumps, pipes, turbines, compressor, etc., and the external factors such as the flow of coolant water available, ambient air temperature and pressure and coolant water temperature. A change in any of the above factors influences the efficiency, hence the power output from these cycles. Since this work deals only with climate change, we are going to limit our studies only to the external factors such as changes in the ambient air and water temperatures and the available water flow and their effect on the power plants. We do not consider the effect of changes due to the internal factors because they are mainly affected by principle design involving mechanical and structural properties rather than by climate change.

5.2.1.1 Rankine Cycle and Climate Change

The Rankine cycle is mainly employed in coal fired and nuclear power plants. The main difference between a Rankine cycle in a coal fired or a nuclear plant is the source of heat generation in the boiler. In a coal fired plant, the heat is generated in the boiler due to the combustion of coal, whereas in the nuclear plant the heat energy comes mainly from the nuclear fission processes occurring in the reactor.

From Fig. 18, we can see that the Rankine cycle basically consists of a pump, boiler, turbine and a condenser. The places that climate change can have an effect on the plant with a Rankine cycle are at the boiler (place of combustion) and condenser in a coal fired plant, but mainly the condenser in a nuclear plant as the reactor (similar to the function of a boiler furnace) is not exposed to ambient air, as the boiler in a coal plant. The change in the ambient air temperature could affect the combustion process of coal in the boiler which in turn effects the boiler efficiency thus influencing the power output. The increase in the condenser temperature, T_{low} or T_1, decreases the efficiencies of both coal and nuclear plants while keeping the temperature at which heat is added, T_{high} or T_3, constant. This can be concluded from the Carnot efficiency shown in Eq. (7).

$$\eta_{carnot}=1-\frac{T_{low}}{T_{high}}=1-\frac{T_1}{T_3} \tag{7}$$

The condenser temperature changes mainly based on the coolant water temperature and the cooling system type. The effect of this coolant temperature based on the type of cooling system is discussed in Section 5.2.2.

5.2.1.2 Brayton Cycle and Climate Change

The Brayton cycle is primarily used in natural gas plants. From Fig. 19, we can see that the main components of natural gas plants include a compressor, combustion chamber and a turbine.

The place climate change can affect the plant with a Brayton cycle is at the compressor inlet. Increase in the ambient temperature of air, T_{low} or T_1, going inside the compressor decreases the efficiency of the cycle and hence the power output while keeping the temperature at which heat is added, T_{high} or T_3, constant. This can be concluded from the Carnot efficiency shown in Eq. (7).

5.2.1.3 Combined Cycle and Climate Change

Combined cycle plants are typically fueled with natural gas. These plants are a combination of both the Brayton and the Rankine cycles. In addition to all the components of both Rankine and Brayton cycle as seen in Fig. 18 and Fig. 19, combined cycle units can also include a supplemental heat unit. But it is of no importance in this work as climate change does not affect this unit directly.

The combined cycle plants could also use cooling systems to cool the working coolant at the condenser. In these cases, the effects of change in the coolant temperatures depend on the type of cooling used which is going to be discussed in Section 5.2.2.

This implies that the effects of climate change which apply to the Rankine and Brayton cycles also apply to the plants which use a combined cycle.

5.2.2 Cooling Systems and Climate Change

One of the main components of most of the power plants is the condenser. It is used to achieve a closed cycle by cooling the working fluid. To carry out this task, various types of cooling systems are used to transfer the waste heat.

5.2.2.1 Once Through Cooling Systems (OT)

In the once through cooling systems, the power plant draws water from a nearby source such as a river, lake or a sea and passes it through the condenser of the plant. The heat is then transferred to the coolant extracted from the environment which is later discharged back into the environment at a higher temperature. The transfer of heat from the working fluid to the external coolant is mainly dependent on the temperature of the coolant. When the temperature of the coolant increases, comparatively lesser heat is transferred to the coolant thus eventually keeping the condenser at a higher temperature, T ($T > T_{low}$) than its design specifications. From Eq. (7), we can see that this decreases the efficiency of the system and hence reduces the output from the power plant [57].

Increase in the intake coolant water temperature also leads to an increase in the discharge water temperature [58]. There are maximum temperature limits set on the discharge cooling water. When the ambient water temperature is already near the limits, the plant must shut down or curtail its operation to avoid discharge violations. This reduces the availability of the thermal power plant [59]. These discharge violations are more to do with the protection of the aquatic life at the place of discharge [58]. In U.S., the discharge regulations are developed by U.S. Environmental Protection Agency under the Clean Water Act [60] [61]. To overcome this problem recirculation type cooling systems and dry cooling systems were developed.

5.2.2.2 Recirculation Type Systems (RT)

In this type of cooling system, there are cooling towers present which evaporate part of the discharge transferring the heat of the water into the air. The discharge coolant water which is now at lower temperature is introduced back into the condenser. When there is an increase in the ambient air temperature, the discharge from the cooling towers is introduced back into the condenser now at higher temperatures [57]. As per Eq. (7), it can be seen that this increase in the air temperatures in the cooling towers leads to an increase in the water temperature which is re-inserted back as the coolant into the plant. This eventually increases condenser temperature which further leads to a reduction in the efficiency and hence the power output of the plant [57]. Thus, an increase in the air temperature reduces the efficiency of the power plants which employ recirculation type cooling systems and hence the power output. While there is a factor of humidity also present, its effects on this type of cooling system is not considered in this study because of insufficient research in the literature.

5.2.2.3 Dry Cooling Systems (DC)

Another cooling system in which the air temperature can change the output of the plant is when dry cooling is used, where air is used as the coolant. When the temperature of the air increases, the rate of heat transfer is once again limited, similar to what happened in the once through system thus reducing the efficiency [57], but in this case it is air instead of water as the coolant fluid.

This section outlines the different ways in which different plants using different thermodynamic cycles and cooling systems can be influenced by the increasing temperatures. These effects are going to be clearly analyzed for coal, natural gas and nuclear power plants in the upcoming subsections. The effect of water availability on power plants will be discussed later in Section 5.4.

5.3 Climate Change Effects on Different Types of Thermal Power Plants

5.3.1 Climate Change Effects on Coal Fired Power Plants

Coal fired power plants use coal as the primary fuel and generally have an efficiency of about 40%. These kinds of plants generally use the Rankine cycle as shown in Fig. 18 which has an efficiency of around 20% and could have efficiencies up to 30% - 40% with superheating [57]. From Section 5.2.1.1, the two main locations in a coal fired power plant that could be affected by climate change are the boiler and the condenser.

At the boiler, oxygen is needed for the combustion of coal to provide heat energy. Since the main function of the boiler is to use energy to increase the temperature for complete combustion to occur, the air entering the combustion chamber at 20°C needs relatively lesser energy to increase it to the combustion temperature rather than the air entering at 15°C [59]. Thus, an increase in the ambient temperature of air going into the boiler increases the boiler efficiency and hence the power output of the system. While the studies from the literature have not evaluated this kind of increase in the boiler efficiency on the power output, a few of them have confirmed the increase in the boiler efficiency with higher air temperatures. Ref. [62] states that an increase in the air temperature of 1°C could increase the boiler efficiency by approximately 0.045%.

At the condenser, an increase in the condenser temperature decreases the efficiency of the system and hence reduces the power output. This increase in the condenser temperature is mainly because of the increase in the coolant water temperature and the cooling systems used as discussed in Section 5.2.2. Although the temperature of the condenser is not the same as that of the coolant, the change in temperature of the coolant produces almost the same change at the condenser. For example, if the coolant water temperature is 20°C, the condenser temperature is not the same. But a change of about 1°C in the coolant is reflected directly on the condenser. So, the change in the coolant temperature and the condenser temperature is assumed to be the same in this study.

In summary, an increase in the air temperature decreases the power output of coal fired plants with the recirculation cooling and direct cooling systems and increase in the water temperature decreases the output of the plants with once through cooling systems. Ref. [63] state that the power output of a coal fired power plant decreases by 0.6% for an increase in the ambient temperature by 1°C.

5.3.2 Climate Change Effects on Nuclear Power Plants

Nuclear power plants produce thermal energy from the nuclear fission process. There are two types of nuclear plants: pressurized water reactors (PWRs) and boiling water reactors (BWRs). Both of these plants use the Rankine cycle and have an efficiency of approximately 33%. Currently there are 96 licensed nuclear power plants in the U.S. These consist of 64 PWRs and 32 BWRs [64]. These power plants are similar to the working of the coal fired power plants except for the fuel used. One more change is that they use a reactor instead of a boiler. So, the effect of air temperature as on a combustion chamber does not apply here because the reactors are air sealed. So, the main place the climate change can have an effect on the nuclear plant is at the condenser.

Since the nuclear power plants are similar to the working of the coal fired power plants, the change in the air and water temperature affect the condenser based on the cooling systems used. An increase in the air and water temperatures reduces output from the nuclear plant with cooling towers (recirculation type systems) and once through systems respectively. There has been valuable research done in this area.

In the plants with wet cooling towers, a study in Europe states that an increase in the air temperature of 1°C in the cooling tower causes the coolant water to increase by 0.4°C to 0.5°C thus reducing the power output by 0.3%-0.4% at the temperatures below 20°C. For the higher temperatures, the power output reduces by 2.2%-2.5%. This is because of the reduction in the load at higher temperatures due to the maximum discharge temperature limits and water unavailability due to the possibility of droughts [65]. In the same study, another simulation model also concludes that power output reduces by 0.7% and 2.3% at low and high temperatures respectively for an increase in the air temperature by 1°C. This means that thermal plants in places with higher temperatures like Arizona, Texas and Nevada could be more affected than the places at relatively lower temperatures.

Studies also indicate that for the plants with once through cooling systems, the power output decreases by 0.39%-0.45% for an increase in the ambient water temperature by 1°C [66] [67]. The knowledge about the effect of decrease in the efficiency also helps in siting the power plant. This information could be considered while building a new nuclear plant. Studies in Turkey show that siting a nuclear plant near the Black Sea is much better compared to the Mediterranean Sea because temperatures in the Black Sea are 7°C colder thus leading to increase in the efficiency by 0.78%-0.84% [66]. The literature present in this area clearly agrees with the fact that the increase in the inlet water temperatures will decrease the efficiency of the power generation.

The water temperatures are predicted to increase by 2050 and the largest increases are predicted in eastern North America, Europe, Asia and South Africa of about 1.3°F – 2.2°F. This increase in the water temperature could lead to a decrease in the efficiency [58]. An increase in the temperature of the intake water temperature by 1°C could lead to a decrease in the power output by 0.15%-0.5% for the U.S in general [68]. The summary of the studies is presented in Table 5 and Table 6.

Table 5: Literature Survey – Nuclear Power Plants (Effect of Air Temperature)

Ref	Details of the study	Plant Type (Cooling type)	Δ T	Δ Eff.	Δ power
[65]	Regression analysis was done on two European datasets to determine the effect of temperature change on the nuclear power supply for the difference in the power output at low and high temperatures.				
	- A plant specific data set with a BWR and wet cooling tower was analyzed. For a temperature range of -7°C to 20°C and 21°C-35°C, the power output decreases by 0.3%-04% and 2.2% -2.5% respectively, for an increase in the ambient air temperature of 1°C.	BWR (recirculation type)	1°C	-	0.3-0.4% (low temp.) 2.2-2.5% (high temp.)
	- A panel data set which take seven European countries into consideration and analyzes the nuclear supply in each of the countries. An increase in the ambient air temperature by 1°C decreases the power output by 0.7% and 2.2% for an increase in the temperature by 0°C-1°C and 20°C-21°C respectively.	Combination of various cooling technologies in NPPs.	1°C	-	0.7% (low temp.) 2.3% (high temp.)

The coal and nuclear plants could potentially have dry cooling systems also. But in the U.S., since there are very few of this type of cooling system associated with coal plants and none associated with nuclear plants at present or in the near future [69], we do not consider them in our study.

Table 6: Literature Survey – Nuclear Power Plants (Effect of Water Temperature)

Ref.	Details of the study	Plant Type (cooling type)	Conclusions		
			Δ T	**Δ Eff.**	**Δ power**
[66]	First law energy analysis was performed on a conceptual PWR NPP to find the variation in the thermal efficiency and power output due to a change in the coolant medium temperature. - Efficiency decreases by 1.2% for ΔT (change in coolant temperature) of 10°C. - Net power output decreases by 8.9% for ΔT (change in coolant temperature) of 20°C. Linear relationship was seen between increase in the coolant medium temperature and decrease in the efficiency and net power output to reach the conclusion.	PWR (once through cooling type)	1°C	0.12%	0.45%
[67]	This study develops a model for condenser heat balance to evaluate the impact of the change in the coolant medium temperature on the efficiency and the net power output of the plant. (The work in this study depicts linear relationship between change in the coolant temperature, efficiency and net output power.)	PWR (once through)	1°C	0.16%	0.39%

5.3.3 Climate Change Effects on Natural Gas Power Plants

Gas turbine power plants use natural gas as the primary fuel and generally have an efficiency of less than 30% [57]. These kinds of plants use the Brayton cycle as shown in Fig. 19. A conventional combustion turbine using the Brayton cycle mainly experiences the effects from Section 5.2.1.2. We can see that the main areas where climate change can affect the power plant is because of the increase in the air temperature at the compressor and at the combustion chamber. Another type of natural gas plant is a steam turbine plant which uses the Rankine cycle. These types of plants experience similar effects at the condenser as that of coal fired plants. Since we do not have any literature for these kinds of plants, we exclude them from our study.

When the incoming ambient air temperature increases at the compressor there is a decrease in the efficiency and hence the power output of the plant. The increase in the temperature causes the gas to expand thus resulting in a reduction in the density. This will reduce the amount of oxygen supplied for combustion in turn reducing the efficiency of the plant, hence the power output [59].

While the increase in the air temperature at the compressor reduces the efficiency, the increase in the air temperature at the combustion chamber (boiler) increases the efficiency. This effect is similar to what was discussed for the effect of air temperature on the combustion chamber in the coal plants in Section 5.3.1. In this case, it is the combustion of natural gas instead of coal.

Many people have come up with various research on this topic. Studies in Ref. [70] state that the increase in the ambient air temperature of 10°F would decrease the efficiency of the gas turbine by 0.5% and the power output by 3%-4% and an increase of

air temperature by 60°F would reduce the gas turbine efficiency by 1%-2% point reduction and the power output by 20%-25%. The latter case is analyzed for a change in the seasons near desert areas, which is the reason for the large temperature difference. From the above values, a doubt may arise about the linearity of the temperature correspondence on the efficiency and the power output. One possible reason for the higher power and efficiency loss at higher temperatures is the impact of reduced load [65]. The turbine efficiency of the natural gas plant is more sensitive to the increase in the ambient air temperature [59]. Studies in the UAE showed that an increase in the ambient air temperature by 1°C led to a decrease in the efficiency by 0.1% and a 1.47 MW power output based on the observations from 160 MW and 265 MW plants [71].
The studies are summarized in Table 7.

Although there are studies agreeing on similar efficiency change due to increase in the temperature, the following study has shown a deviation. An increase in air temperature by 1°C decreases the plant efficiency by 0.007 and 0.004 percentage points for coal and natural gas plants, respectively, for open cooling systems, and 0.004 and 0.009 percentage points for plants with recirculation cooling systems [59]. This could be mainly because of the difference of the data used in the various studies [59]. That master’s thesis study is considered as an outlier and is therefore given lower importance in this study.

Table 7: Literature Survey – Natural Gas Power Plants (Effect of Air Temperature)

Ref	Details of the study	Plant Type	ΔT	Δ Eff.	Δ power
[71]	The performance of two specific gas turbines: SGT 94.2 and SGT 94.3 was evaluated for changes in the ambient temperature. The study was carried out in Dubai. - The efficiency and output power reduce by 0.1% and 1.47 MW respectively for every K degree rise in the ambient air temperature. (This study suggests linear relationship between the change in the ambient air temperature, efficiency and power output.)	Gas turbine PP (natural gas or diesel) Recirculation type	1°C	0.1%	0.55% (inferred)
[72] [70] [65]	The values obtained here are not from the actual source but are from the papers which have analyzed the actual source [72] because of the unavailability of the original source. - Ref. [65] says that the change in the efficiency and power would be 0.09-0.24% and 0.6-0.72% respectively for 1°C change in the ambient air temperature. - Studies in Ref. [70] state that the increase in the ambient air temperature of 10°F would decrease the efficiency of the gas turbine by 0.5% and the power output by 3%-4% and an increase of air temperature by 60°F would reduce the gas turbine efficiency by 1%-2% point reduction and the power output by 20%-25%. Both of these have assumed linear relationship between the output power and change in the ambient temperature.	Gas turbine in desert area. Cooling type unknown	1°C	0.09-0.24 %	0.6-0.72%
[63]	The change in the ambient temperature of 1°C changes the output of the natural gas plant by 0.6%.	Natural gas (unspecified cooling system)	1°C		0.6%

5.3.4 Climate Change Effects on Combined Cycle Power Plants

Combined cycle power plants use a combination of both the Brayton and Rankine cycles and usually have an efficiency up to 60% [57]. The studies regarding the effect of increasing air temperatures on combined cycle plants are shown in Table 8.

Table 8: Literature Survey – Combined Cycle Natural Gas Power Plants

Ref	Details of the study	Plant Type	ΔT	Δ Eff.	Δ power
[73]	A combined cycle power plant in Taiwan was selected and the net output power and the net heat rate were evaluated at various loading, condenser pressure by a testing team. The output power was 505.484 MW. - For a change in the condenser temperature of 1°C, the power output decreases by 1.28 MW - For an increase in the ambient air temperature of 1°C, the efficiency and power output increase by 0.1% and 0.6% respectively. (This study and [74] suggest linear relationship between change in the air temperature efficiency and net power output.)	CCPP (Dry cooling) Uses Ambient air as the cooling medium	1°C (condenser temp.) 1°C (air)	 0.1%	0.25% (Inferred) 0.6%
[74]	The effect of ambient air temperature on a combined-cycle power plant with a capacity of 600 MW is evaluated for a change of ambient air temperature from 0°C-35°C and gas temperature after supplemental heating from 525°C-675°C. - An additional net power of 70 MW could be generated with supplementary heating with the plant 642 MW at highest conditions. - Efficiency lies between 52%-55.4% for the temperature range. - Net power lies in the range of 540-640 MW for the temperature change of 35°C.	CCPP (wet cooling tower) Recirculation Type	1°C (air)	0.18 % (Inferred)	0.45% (Inferred)

5.4 Effects of Water Flow on Thermal Power Generation

Water flow and availability are vital to thermal power generation. The freshwater withdrawals by the power sector accrue to around 41% of the national withdrawals in the U.S. [58]. The importance of the water can be noted by the fact that approximately 25 gallons of water are required to produce one kWh of electricity via a steam cycle [70]. This shows that a decrease in the availability of water could decrease the power plant availability. Thus, the production of energy from the fossil fuels is directly linked to the availability of water [70].

Ref. [75] anticipates that thermal plants would see a reduction in their capacity from 4%-16% between 2031 and 2060 because of reduced water availability due to heat and drought. Sometimes if the water availability decreases by a huge margin due to droughts or heat waves, there is a very high chance of the power plants shutting down. Ref. [63] reports that a few of the utilities in Europe had to shut down or reduce output power due to the low water levels during the heat wave in 2006. The various plants which had to curtail operation in U.S. due to water unavailability are listed in [58].

5.5 Extreme Climate Change Effects on Thermal Power Plants

Climate change can lead to extreme weather conditions thus increasing the possibilities of major storms and hurricanes. This has affected the operations of many power plants and has also resulted in the loss of the plant infrastructure. Studies in the past have shown that the occurrence of extreme events has increased and they are also predicted to increase in the future on the basis of climate change while recent studies link the extreme events to the climate change [76].

Extreme events could also affect the operating fuel of the power plant. An occurrence of a heat wave or high temperature could lead to the combustion of the coal stock or very cold temperature could lead to freezing of the cold stock. Increase in the heavy precipitation could also lead to the drenching of coal piles which could increase the moisture content [76]. An increase in the moisture content of coal of about 10% reduces the boiler efficiency of the coal fired power plant by 1% [76].

Increase in the occurrence of storms and hurricanes has affected the plant infrastructure by breaking away of the pipes, roof, tiles of the cooling tower, etc. which could cause the power plant to be shut down in extreme cases. For example, Hurricane Katrina caused almost 15$ billion losses to the entire energy industry in general and rendered most of the plants out of operation. One such example is the Yscloskey Gas Processing Plant which was out of operation for 6 months. This actually reduced the amount of material available for the production thus causing problems to the power plants which depend on it.

Most of the coal is transported either using railways or waterways. Rail tracks could be distorted due to extreme temperature and both railways and water ways could be affected due to heavy floods and storms, thus leading to a decrease in the power due to the shortage of available materials.

Offshore impacts due to storms could be quite significant destroying platforms and pipelines thus creating a problem for power generation [70].

5.6 Forecasted loss in power and income by 2050

The previous subsections have addressed the different ways in which thermal power plants are affected by a change in the ambient air and water temperatures. Most of the studies reviewed previously in this work have reported a decrease in the power output and efficiency by 0.3%-2.3% and 0.09%-0.24% respectively for an increase in the ambient temperature of 1°C depending on the type of the plant and location. In the first look, these percentage change values might seem very minute and can even lead us to dismissing the importance of the effect of increasing temperatures on thermal power generation. But we should not do so. The main point to be noted at this juncture is not just the small percentage changes, but the amount of power represented by those percentage change values. Since thermal power plants in the U.S. accounted for around 80% of the electricity generated in 2018 [53] and are forecasted to make up around 70% of the total generation in 2050 [27], even a small percentage decrease such as 0.5%-1% in efficiency or power output could mean loss of a couple of billion kilowatt-hours of generation and millions of generation income. Ref. [63] states that a decrease in 1% efficiency could lead to an output power loss of 25 billion kWh. These reasons give rise to a strong necessity to know how much power generation is going to be affected in the future (by 2050 is considered in this work) in the U.S due to climate change.

This section is going take various studies from the literature and try to forecast the losses in power generation and the generation income related to the coal fired, natural gas, combined cycle and nuclear plants by 2050 due to increasing temperatures. Because of the various combinations of power plants and the cooling systems used, followed by the unavailability of enough published information regarding the effect of air and water temperature increase on each type of power plant and corresponding cooling system, the number of combinations of power plants and cooling systems are going to be narrowed down based on the dominant types of cooling systems used in the U.S. and the available information in the literature.

Based on 4 different power plants and 3 different cooling systems, there are twelve possible combinations of power plants and cooling systems relevant to this study, i.e., each of the three cooling systems could be possibly combined with each of the four power plants considered in this study. But in the U.S., not all combinations of power plants and cooling systems are used. The division of cooling systems in the U.S. by energy source at the end of 2017 are depicted in Fig. 20.

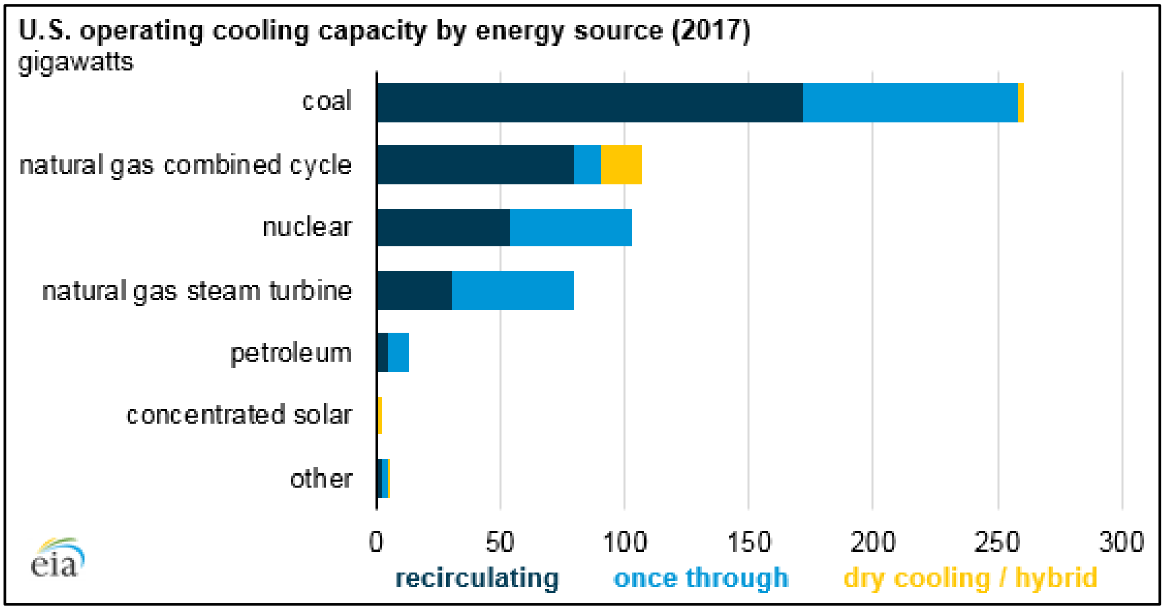

Fig. 20: Cooling system capacity in the U.S. (source: Ref. [69]).

From Fig. 20, we can see that the coal fired power plants present in the U.S. use once through and recirculation type cooling techniques dominantly and only around 1% use dry/hybrid cooling methods. Since this percentage is very small, the dry/hybrid cooled coal fired plants are not considered in this study. Likewise, nuclear plants and natural gas steam turbine plants use only once through and recirculation cooling methods. So dry cooled nuclear and natural gas steam turbine plants are not considered in this study. Only the combined cycle natural gas plants use significant amount of dry cooling units along with once through and recirculation types.

Although the number of combinations has been narrowed based on the dominant cooling systems, another metric used to determine the various thermal plants and the cooling systems used in this work are the related studies present in the literature. Literature studies used in this section form the basis of forecasting the generation and income losses by 2050. Tables in Section 5.3 summarize the studies present in the literature related to the effects on power plants due to the change in the air and water temperature.

The studies in the literature take into account the direct change in the output of the power plant for a change in the air temperature of 1°C in most of the cases. But a few of these perform the analysis for a given range or difference of temperatures. They do not directly evaluate the power output for a change in the air temperature of about 1°C, but they suggest linear relationship between the change in the temperatures and the efficiency and power output. In those studies, a linear relationship is assumed and the change in the power output for a change in 1°C is inferred from the material present. There are very few studies that evaluate the direct relationship between the change in the water temperature and the power output.

Based on the different cooling systems used dominantly and the studies available in the literature, the following is a summary of the different plant and cooling systems and the plants marked in *italic* are the ones which have studies present in the literature and they employ dominant cooling types (CT).

Coal Fired Power Plant (CFPP)

- **Change in the air temperature affects**
  - *Coal Plants with cooling towers (RT)*
  - Coal Plants with dry cooling (DC) (excluded from the study as coal plants in U.S. hardly use dry cooling as seen in Fig. 20)
- **Change in the coolant water temperature affects**
  - Coal Plants with once through (OT) cooling systems (no data available).

Natural Gas Power Plant (NGPP)

- **Change in the air temperature affects**
  - *Natural Gas Plants with cooling towers (Steam Turbine)*
  - Natural Gas Plants with dry cooling (excluded from the study as gas plants in U.S. hardly use dry cooling as seen in Fig. 20)
- **Change in the coolant water temperature affects**
  - Natural Gas Plants with once through cooling systems (no data available).

Nuclear Power Plant (NPP)

- **Change in the air temperature affects**
  - *Nuclear Plants with cooling towers*
  - Nuclear Plants with dry cooling (excluded from the study as coal plants in U.S. do not use dry cooling as seen in Fig. 20)
- **Change in the coolant water temperature affects**
  - *Nuclear Plants with once through cooling systems*

Combined Cycle Power Plant (CCPP)

- **Change in the air temperature affects**
  - *CCPPs with cooling towers*
  - *CCPPs with dry cooling*
- **Change in the coolant water temperature affects**
  - CCPPs with once through cooling systems (is excluded because very few plants use once through cooling system and even fewer are forecasted to use in future as seen in Fig. 20).

Based on the above relevant plants and the data available, the summary of all studies related to the decrease in the power output for an increase in the air temperature by 1°C are projected in Table 9. The direct change in the power plant output for an increase in the water temperature is available only for the nuclear plants which lose 0.39%-0.45% of the power output for an increase in the external coolant temperature by 1°C [66].

We now have the range of values the power output is going to decrease for an increase in the air temperature of 1°C. From Table 9, coal fired power plants are going to decrease by 0.6%, nuclear power plant is going to decrease from 0.3%-0.7%, natural gas plants could decrease from 0.55%-0.72% and combined cycle plants could experience a decrease in the power output by 0.25%-0.45% across all the types of cooling systems.

Table 9: Decrease in the Power for a Change in the Air Temperature by 1°C

Plant Type	**CT**	**Δ Power**	**Ref.**
CFPP	-	0.60%	Mideska,2010 & Linnerud, 2011 [4]
NPP	RT	0.3-0.4%	Linnerud, 2011 [4] [65]
NPP	-	0.70%	Linnerud, 2011 [65]
NGPP	-	0.60%	Mideska,2010 & Linnerud, 2011 [4]
NGPP	-	0.6-0.72%	Bull, 2007 & Linnerud, 2011 [4]
NGPP	-	0.55%	Ashley Le, 2011 [71]
CCPP	DC	0.25%	Chuang and Sue, 2005 [73]
CCPP	DC	0.60%	Chuang and Sue, 2005 [73]
CCPP	RT	0.45%	Arrieta, 2005 [74]

In Chapter 1, we saw that the air temperature is projected to increase by 1.4°C and 1.6°C according the RCP 4.5 and RCP 8.5 scenarios respectively by 2050. Since these are just projections, temperature could change more or less. So, this study has calculated the loss of power and income for an increase of 1°C to 4°C.

The power generated by 2050 is forecasted at 5449 billion kWh [27]. The distribution per energy sources based on Ref. [27] predicts coal at 17%, nuclear at 12%, natural gas plants at 39% and remaining 31% by renewables [27] as shown in Fig. 13. Since 39% of natural gas is a combination of both the natural gas and combined cycle plants, their capacity factor has been used to split between combined cycle and conventional gas turbine. The combined cycle has a capacity factor of 94% and conventional gas plants have a capacity factor of 3%. The forecasted generation cost by 2050 is at 0.054 $/kWh [27] in general as the EIA does not provide values for each type of generation. Using these forecasted values and the values from Table 8, we have forecasted the loss of power and generation income in Fig. 21 and Fig. 22 respectively.

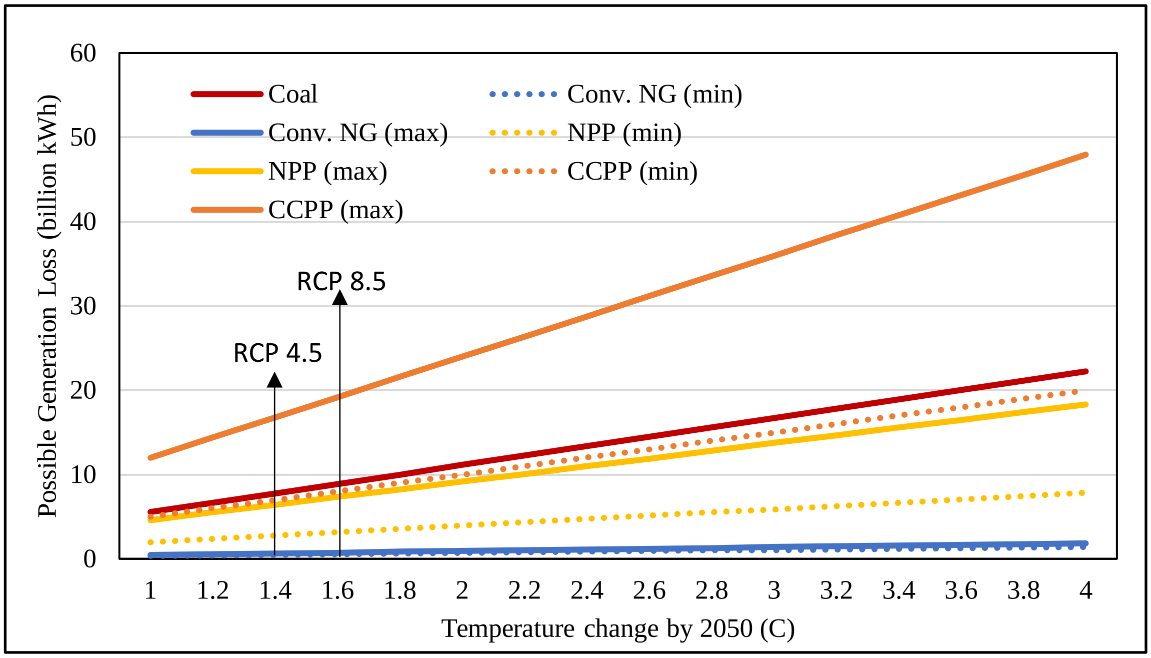

Fig. 21: Possible generation loss by 2050 [27].

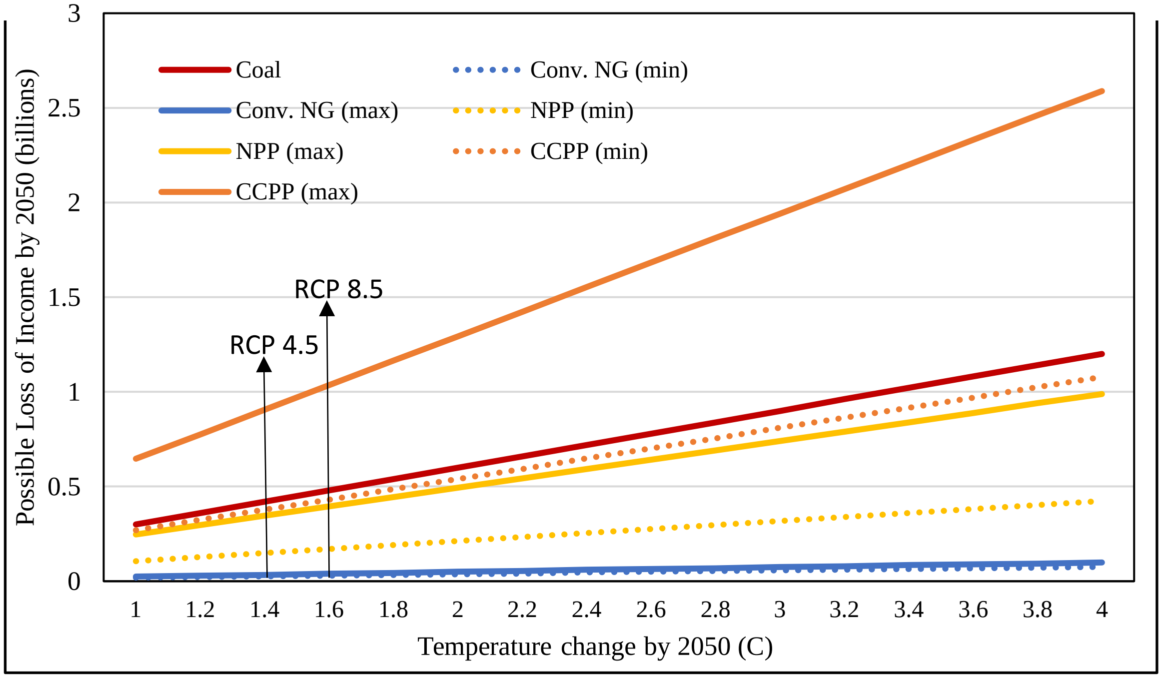

Fig. 22: Possible lost income by 2050 [27].

From Fig. 22, we can see that the possible loss from the from the coal, natural gas, nuclear and combined cycle plants averages to about 17 billion kWh for an increase in the ambient air temperatures by 1°C and about 24-28 billion kWh based on the RCP 4.5 and 8.5 scenarios. This loss could be equated to almost six 500 MW plants in terms of new power plants. In terms of renewable energy, an average loss of 26 billion kWh by 2050 based on the RCP 4.5 and RCP 8.5 scenarios could be equated to around 3% of the entire solar generation (48% of renewable generation), 6% of the wind generation (25%), 9% of the hydropower generation (18%) and nearly 38% of the entire geothermal production (4%). This shows that although the change might be small, the amount of power lost by that change is quite significant.

5.4 Adapting to Climate Change

Climate change scenarios have led to various studies that have investigated the different methods which can be used to mitigate the effects of climate change on thermal power plants. These methods include using higher capacity pumps, increasing the water intake, managing and planning the schedules of the power cycles of the plant (when the risk of load reductions is high), choosing the right location with regards to the climate, trying to use various alternative types of cooling such as the cooling towers and hybrid/dry cooling techniques as they are less vulnerable to the reduced water availability posed by the climate change as compared to the once-through systems or reducing the capacity of the plant [77] [78].

5.5 Conclusion

The decrease in efficiency and the power output could be small but could be quite significant in terms of the power generation being affected. A change in 1% could lead to a loss up to 25 billion kWh [63]. This is huge amount of energy to replace. The main area to focus here is the amount of income and power lost due to climate change. The decrease in the power generation may not be by a huge margin, but the loss of power and income will be significant. An increase in the temperature as per the RCP 4.5 and RCP 8.5 decrease the generation by an average of 26 billion kWh and a possible income loss of around 1.5 billion dollars. Many techniques are being developed and used to mitigate the effect of climate change on thermal power plants.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

Climate change is affecting the power generation globally. The impacts of climate change on solar, wind, thermal and hydropower have been analyzed and the extent of possible changes to the projections made by EIA [27] are summarized below.

The hydropower generation could significantly be impacted by the increase in the ambient air temperatures which leads to a decline in the snow packs and increase in the evaporation levels and by the change in the precipitation levels. This eventually leads to a change in the river flow, thus affecting the hydropower generation. Using the most relevant projections [24], the hydropower might increase by 8%-60% due to RCP 4.5 and RCP 8.5 scenarios by 2050 respectively.

The uncertainty in the occurrence of climatic events leads to a greater uncertainty in forecasting the precise quantitative extent to which the climate change is taking place, and this leads to even greater uncertainty in predicting the climate change on wind power generation. The increase in the temperature does not significantly alter the wind power generation, rather change in the wind speed is the most important factor. Studies are consistent with predicting increased wind speeds in Texas, Kansas and Oklahoma.

The effect of climate in terms of increasing temperatures, changes in the precipitation and solar radiation could mainly affect the solar power generation. It can be seen that a loss of around 1 to 6 billion kWh could be experienced due to an increase in the temperature by 1.4ºC (RCP 4.5) and a loss of 1.3 to 7 billion kWh could be experienced due to an increase in the temperature by 1.6ºC (RCP 8.5). On an average we can see that around 2.5 billion kWh is lost per increase in the ambient air temperature by 1ºC. This equals the reduction in the entire power generation in 2050 by approximately 0.05% due to the increase in the ambient temperature of 1ºC on the solar power generation.

The thermal power generation could mainly be affected by the increase in the ambient air and water temperatures. An increase in the air temperature as per the RCP 4.5 and RCP 8.5 decrease the generation by an average of 26 billion kWh and a possible income loss of around 1.5 billion dollars. It can be seen that the possible loss from the from the coal, natural gas, nuclear and combined cycle plants averages to about 17 billion kWh for an increase in the ambient air temperatures by 1°C and about 24-28 billion kWh based on the RCP 4.5 and 8.5 scenarios. This loss could be equated to almost six 500 MW plants in terms of new power plants. This shows that although the change might be small, the amount of power lost by that change is quite significant.

When considered individually, hydropower generation could benefit the most from climate change, specifically an electrical energy generation increase by 8%-60%. On a national basis, thermal power could be affected the most because of the generation mix in which electricity from thermal power plants accounts for almost 70% of the power generation nationally. Solar power is the least affected, and the extent to which wind power is affected can only be decided with more accurate and relevant studies in the future.

There are few techniques which can be used to adapt to the changing climate. Thermal plants could use higher capacity pumps, increase in the water intake, use various alternative types of cooling such as the cooling towers and hybrid/dry cooling techniques., and future plants must consider climate change effects when siting. Solar modules should be designed to withstand higher temperature ranges like the monocrystalline solar cells which can very efficiently tolerate changes in the temperatures. Some hydropower plants could benefit if the plant management took climate change into consideration and installed higher capacity turbines to accommodate the increased runoff.

6.2 Future Work

Upon the availability of climate change data for each of the regions in the U.S., nationwide forecasts could then be extended to region-wise forecasts. With the access to better simulation tools in future, the accuracy of each of the forecasts will be increased based on the power plant type. The data regarding the per unit cost of each generation type could also be included to increase the strength and accuracy of the forecasts. The future work could also include the impact of electrification of vehicles and homes; however, this is dependent on projections by the EIA in their future energy reports. Those findings could then be used to make the relevant forecasts.

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