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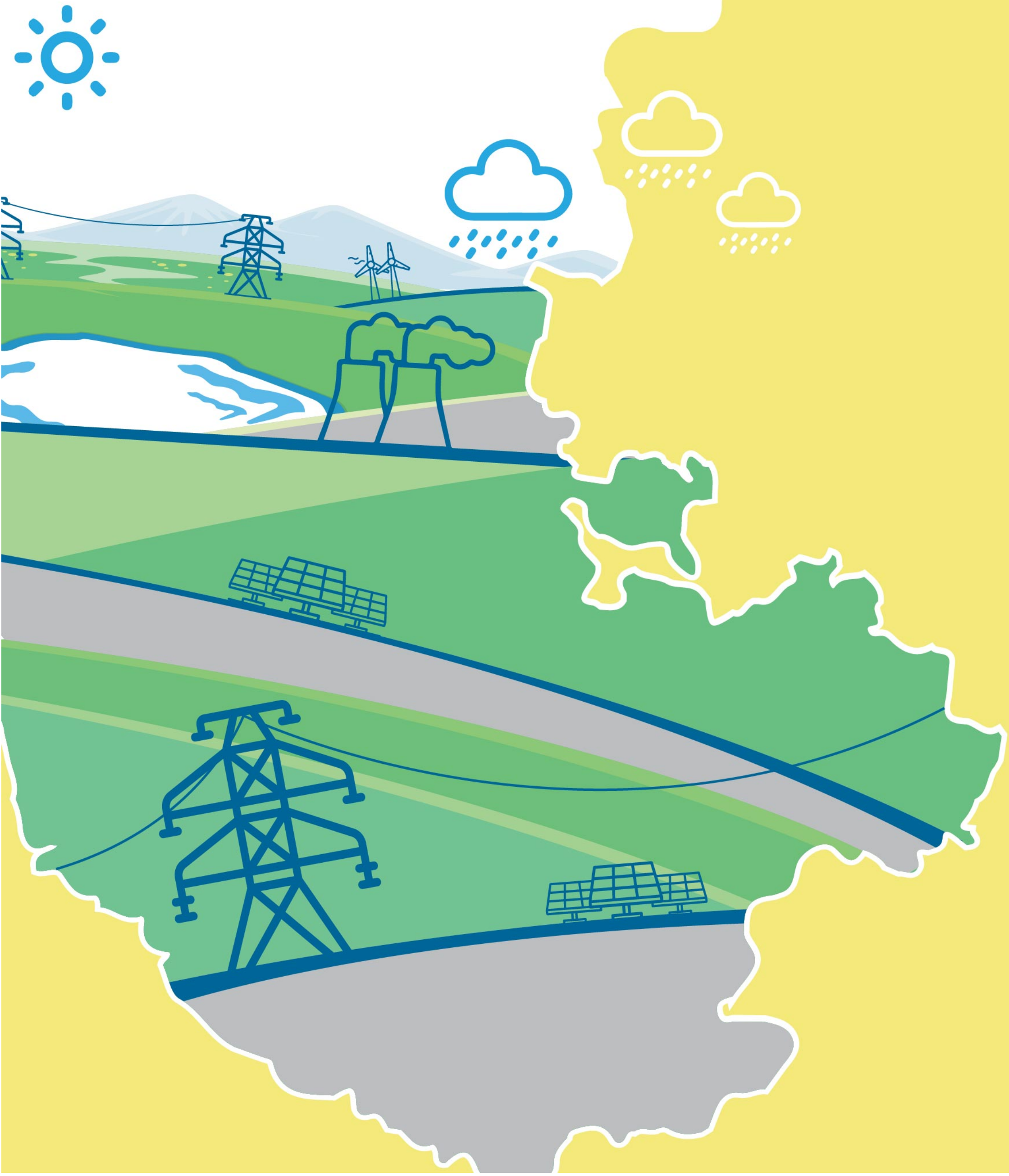
Climate Risk Profile for Power Sector in Karnataka



Climate Risk Profile for Power Sector in Karnataka

Center for Study of Science, Technology and Policy

March 2021

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Disclaimer

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(The author list provided assumes no particular order as every individual contributed to the successful execution of the project.)

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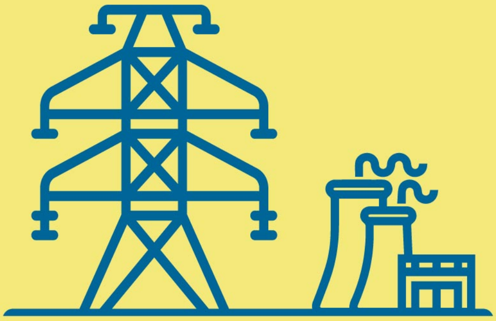

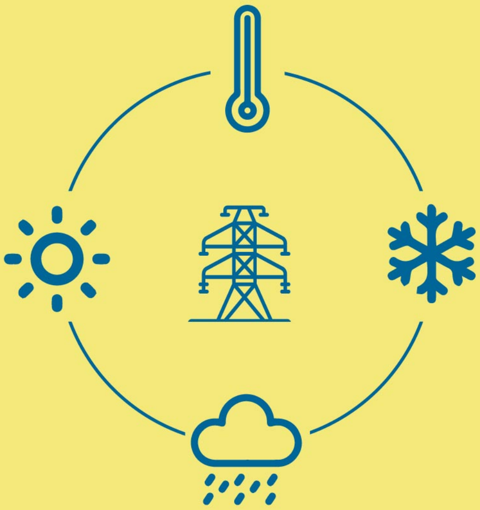

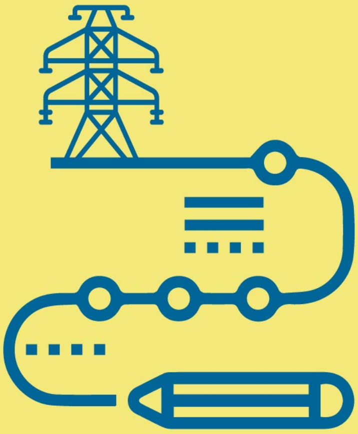

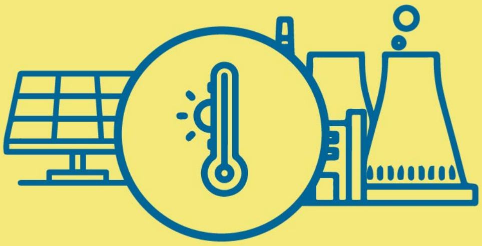

Executive Summary

Power infrastructure, which includes assets for generation, transmission, and distribution of power, is vulnerable to manifestations of climate change. Data from the International Disasters Database shows that during 1998–2017, India experienced an average of 16 extreme weather events resulting in a total economic loss of USD 45 billion, compared to an average of 10 events during 1978–97 with USD 20 billion in losses. Extreme weather events in the last two decades have resulted in loss of lives, decreased agricultural productivity, and infrastructure damage. Given infrastructure investments are large and long term, there is a need to identify climate risks and build resilience in power infrastructure assets.

This study aims to (i) develop a climate hazard map at the district level for Karnataka, (ii) assess climate risks and their implications for thermal, solar, and wind infrastructure assets, and (iii) recommend strategies for building infrastructure resilience.

The methodology adopted for the study is threefold:

(i) Climate hazard mapping: Climate hazard maps are developed by assessing projected changes in mean maximum temperature and rainfall, and heavy rainfall events for all the districts of Karnataka. Climate projections have been made using an ensemble of 15 CMIP5 climate models for the period 2021–2050 (2030s henceforth) under a high-emission representative concentration pathway (RCP) 8.5 scenario (a scenario of the Intergovernmental Panel on Climate Change [IPCC]).

(ii) Climate risk assessment: Risk is defined as the potential for loss, damage, or destruction that results from exposure to a hazard. Climate risk assessment adopts a scoring criteria for the extent and likelihood of occurrence of a hazard and the extent of vulnerability of an infrastructure asset, and then computes the overall risk score for an infrastructure segment in a district.

(iii) Literature survey: Projected changes in summer maximum temperature, rainfall, and heavy rainfall events have both direct and indirect impacts. The adaptation strategies for coping with projected changes in climate parameters are suggested on the basis of published literature.

Findings: Climate analysis at the district level for Karnataka shows there is no one dominant hazard, and the magnitude of various hazards is varied across the districts.

- Summer maximum temperature is projected to increase by 1.4–2.4°C in the districts with thermal power plants, and 1.7–2.4°C in districts with solar power plants.

- Mean annual rainfall is projected to increase by 11–22% in the districts with power infrastructure.
- Heavy rainfall events are projected to increase by 2–6 events in districts with thermal power plants and 1–2 events in some of the districts with solar power plants. Notably, in Bagalkot and Chitradurga districts with solar power plants, such events have not been recorded in the past.

Climate risk is a function of the type, extent, and likelihood of a hazard, and vulnerability. In the case of thermal power plants, while increase in temperature poses 'high' risk to Raichur and Bijapur plants and 'medium' risk to the Bellary plant, increase in heavy rainfall events poses 'very high' risk to Bellary and Bijapur plants and 'high' risk to the Raichur plant. Similarly, in the case of solar power plants, temperature increase in seven of the eight districts poses 'high' to 'very high' risk, and increase in heavy rainfall events poses predominantly 'medium' risk.

However, a composite scoring method that takes into account changes in both maximum temperature and heavy rainfall events, along with the vulnerability criteria, indicates the following:

- Thermal power plants in Bijapur are at 'medium-high' risk; Raichur and Bellary plants, 'medium' risk, and the Udupi plant, 'very low' risk.
- Solar power plants in all the eight districts fall in the 'low-medium' risk category.

Implications: While rise in maximum temperature, dry spells, and shortage of water are key risks to thermal power plants, heavy rainfall events causing material damage are risks to solar and wind power plants.

The implications of increase in temperature and shortage of water are

- 0.3–0.5% reduction in solar efficiency and material damage
- 0.4–0.7% reduction in thermal efficiency and reduced transmission efficiency because of additional resistance and increased conductor sag

The implications of increase in heavy rainfall events are

- 30% reduction in solar efficiency due to dark rain clouds, and material damage
- Reduced boiler efficiency because of increased moisture content of coal and delay in coal supply as Karnataka thermal plants rely on interstate coal supply

Recommendations: Power infrastructure in Karnataka, at risk from projected changes in climate, needs strategies to help anticipate, absorb, accommodate, and recover from climate shocks. All power infrastructure segments require these measures, but they are costly. Alternatively, resilience in existing infrastructure with likely high exposure to climate hazards could be achieved by tweaking the design, operation, and maintenance. Broadly, adaptation strategies could be

- **Technological**—promoting better designs, improved standards, and deployment of new technologies,
- **Planning-related**—mapping climate hazards and risks to help formulate strategies for exposure reduction and facilitate decisions on investing in resilient infrastructure and increasing share of renewables, and
- **Policy-related**—promoting informed and transparent decisions on power infrastructure development that are cognizant of climate risks, investment decisions that prioritise projects and designs that are adaptable to future climate conditions, and budgetary allocation for periodic review, repair, and upgradation to reduce climate vulnerability.

Specific recommendations include

- Development of a Resilience Index with a Minimum Acceptable Standard for periodic review of existing infrastructure
- Drafting of a retrofit code and imposition of legal liability to adhere to standards
- Construction of legislations for adoption of green infrastructure or a hybrid approach incorporating grey and green infrastructure
- Development of a compendium of resilient technologies through the creation of a technological consortium for research, development, and innovation
- Development of a climate-risk-data generation and dissemination network for overcoming information paucity and promoting climate-resilient planning.

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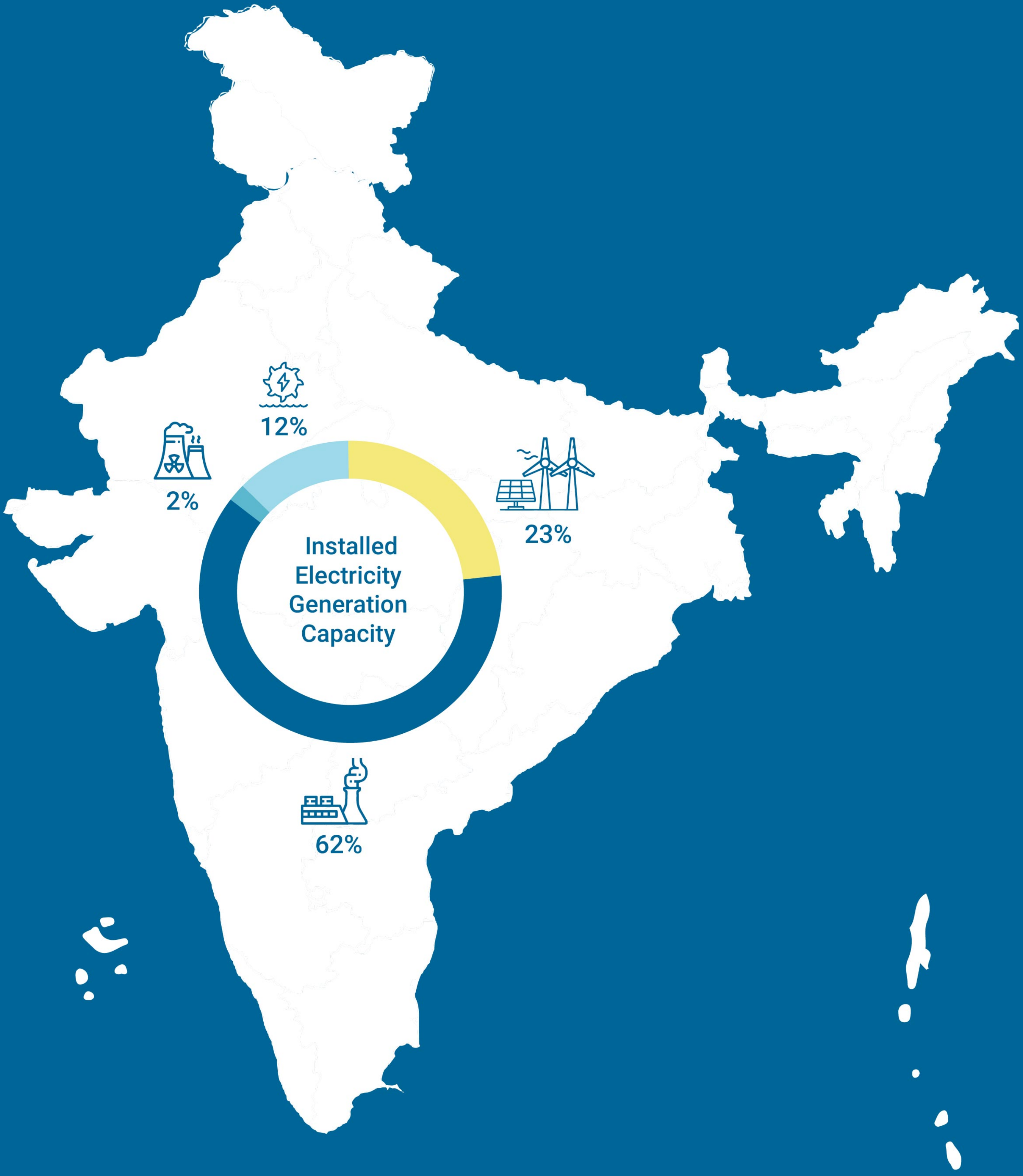

87.26 GW — RE Target → **175 GW** - - - → **500 GW**

2020 2022 2030

1. Introduction

Public infrastructure is the backbone of any economy. Several studies have highlighted the positive relationship between high-quality public infrastructure and economic productivity in the long run (Berg et al., 2012; Calderon and Serven, 2014; Ghazanchyan and Stotsky, 2013). Infrastructure investment can help in promoting inclusive development and fighting income inequality, as these factors depend on the type, extent, and quality of infrastructure that supports key services, namely, food, energy, water supply, safe and resilient cities, and sustainable industrialisation (Bhattacharya et al., 2016).

Infrastructure assets typically include buildings and facilities that enable power delivery, transportation, water, and telecommunications services. Power infrastructure includes assets put together for generation, transmission, and distribution of energy, as well as those linking these asset blocks to each other.

1.1. Overview of Power Infrastructure in India

India is not just the third largest producer of electricity in the world but also the third largest consumer—behind China and the USA—with a total electricity consumption of 1.54 trillion kWh, which is expected to reach 4 trillion units by 2030[1]. In terms of installed capacity too, India ranks third in the world, with a capacity (utilities and non-utilities) of 371.98 GW as of July 2020[2].

The power sector infrastructure in India has grown manifold in the last seven decades—the capacity has increased from 1.36 GW in 1947 to 371.98 GW in 2020 (Figure 1). The gross electricity generation in India from utilities has increased from 7,99,851 GWh during 2009–10 to 13,71,779 GWh during 2018–19. In other words, the gross electricity generated increased by a compound annual growth rate (CAGR) of 5.49% during the period 2009–10 to 2018–19[3].

India ranks fourth in the world in wind power, fifth in solar power and hydropower, and fifth in total renewable power installed capacity. As of March 31, 2020, India's installed RE capacity stood at 87.26 GW, of which solar and wind comprised 34.81 GW and 37.74 GW, respectively, while biomass and small hydropower constituted 9.86 GW and 4.68 GW,

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[1] https://economictimes.indiatimes.com/industry/energy/power/indias-electricity-consumption-to-touch-4-trillion-units-by-2030/articleshow/52221341.cms?from=mdr

[2] http://cea.nic.in/reports/monthly/installedcapacity/2020/installed_capacity-07.pdf

[3] http://www.mospi.gov.in/sites/default/files/publication_reports/ES_2020_240420m.pdf

respectively. Installed RE capacity has posted a CAGR of 17.33% between 2016 and 2020 (CEA, 2020). The Government of India (GoI) has set an ambitious target of achieving 175 GW of RE capacity by 2022 and 500 GW by 2030[4] as part of the Paris Agreement commitments.

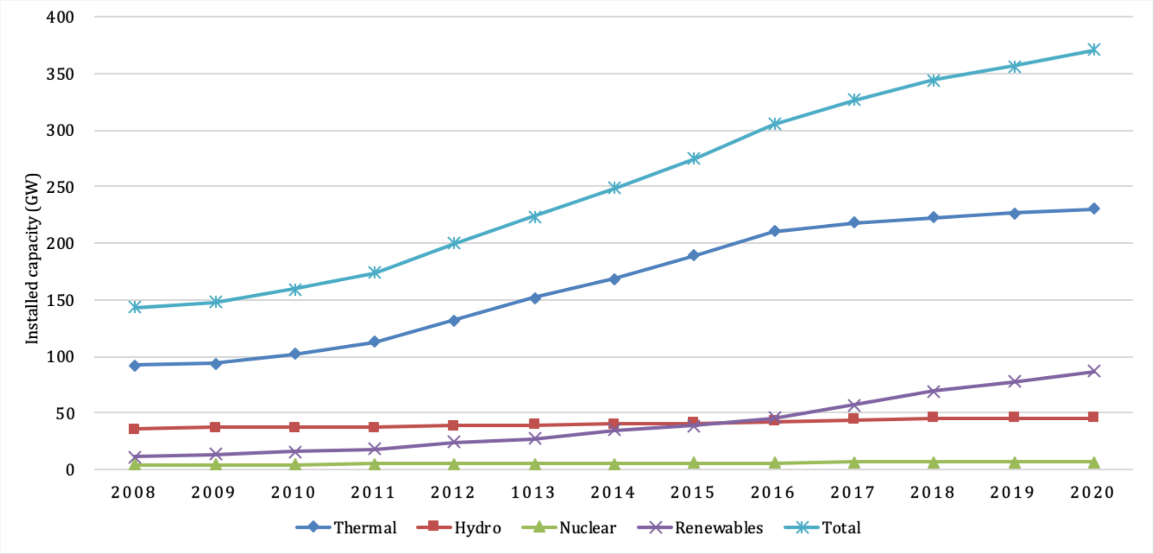

Figure 1: Installed power generation capacity in India from 2007–08 to 2019–20

(Source: http://www.cea.nic.in/monthlyinstalledcapacity.html)

In 2020, the percentage share of total installed thermal power capacity in India was 62.22%, followed by RE at 23.45%, hydro at 12.4%, and nuclear at 1.88%.

1.2. Overview of Power Infrastructure in Karnataka

The total installed electricity capacity in Karnataka stood at 28,789.99 MW as of March 2019, making it the seventh largest state in India in terms of generation capacity. Karnataka accounts for almost 18% of the total installed RE capacity in India. Within the state, RE constituted 54% of the total installed capacity at 13.83 GW in 2019 and 27% of the generated electricity in 2018.

The shares of thermal, nuclear, and hydro in installed capacity and generation in 2019 and 2018 are presented in Figure 2 and Figure 3, respectively.

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[4] https://www.livemint.com/news/india/india-plans-to-set-up-500gw-of-renewable-energy-capacity-by-2030-1561474737868.html

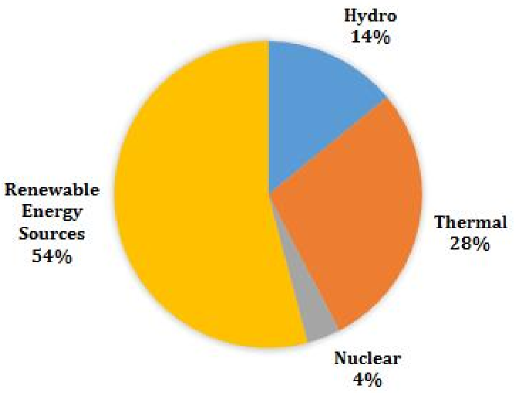

Figure 2: Shares of different power segments in installed capacity in Karnataka (2019)

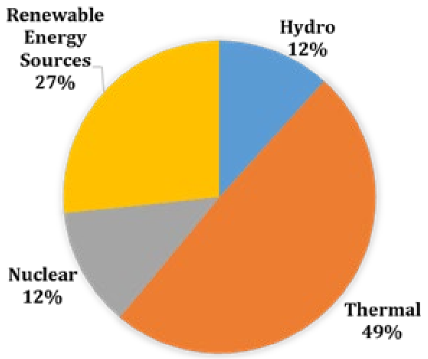

Figure 3: Shares of different power segments in generation in Karnataka (2018)

Thermal: Thermal power plants in Karnataka are mainly located in four districts—Raichur, Bellary, Bijapur, and Udupi (Figure 4). Karnataka has a total coal-based power capacity of 9.875 GW. Thermal plants in Raichur, Bellary, and Bijapur together account for 86% of the installed capacity. The two power stations (with a total of 10 units) in Raichur account for 34.46% of the total installed capacity. In-state coal capacity in Karnataka is absent, and coal is supplied to the state's thermal stations from other states via railways or imported through sea routes.

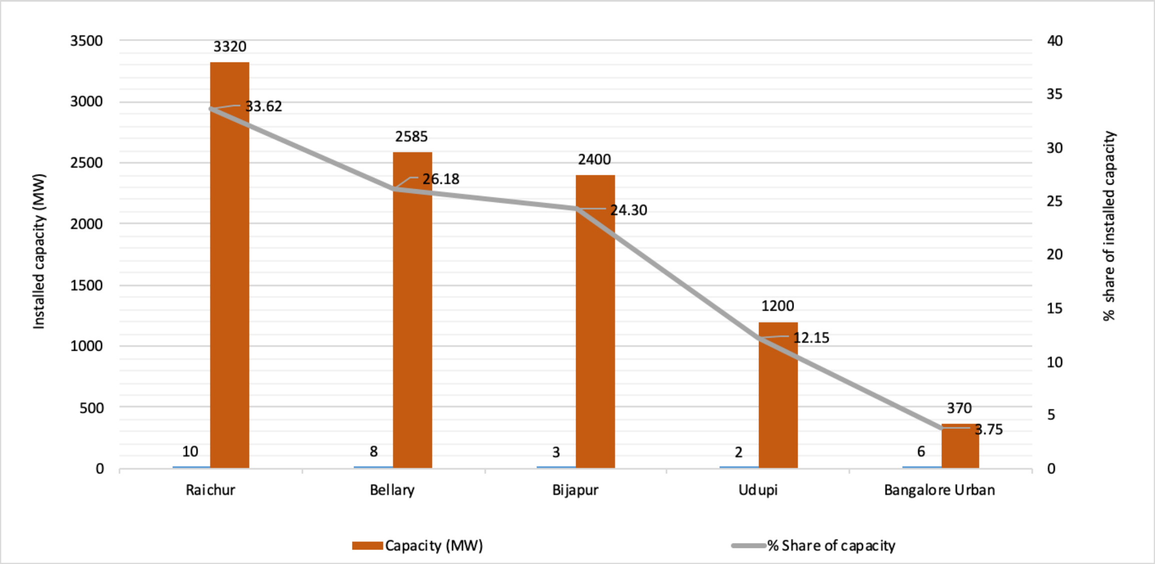

Figure 4: District-wise installed thermal power generation capacity in Karnataka

(Source: CEA Annual Report 2019–20)

Solar: Solar photovoltaic (PV) plants are spread across 24 districts in Karnataka, and 75% of the installed capacity is in eight districts, namely, Tumkur, Chitradurga, Bellary, Bidar, Belgaum, Gulbarga, Raichur, and Koppal[5]. In fact, Karnataka has the world's largest solar park of 2000 MW capacity at Pavagada in Tumkur. The district-wise share of commissioned solar PV capacity in Karnataka in 2019 is presented in Figure 5. In addition to the solar plants already commissioned, plans are underway to install substantial additional solar capacity in many districts of Karnataka by 2021, bringing the state's solar PV potential to an estimated 24.7 GW[6].

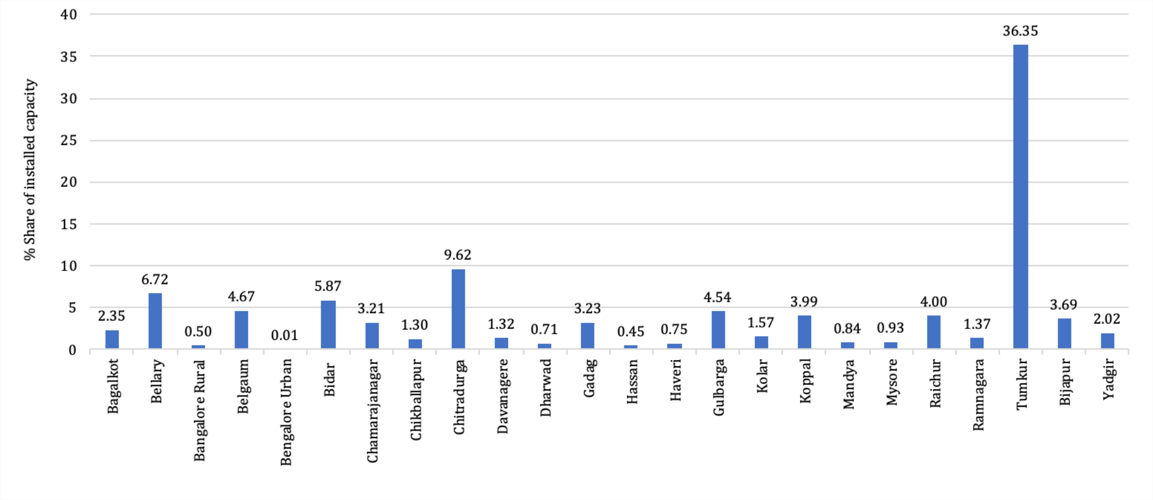

Figure 5: District-wise commissioned solar PV capacity 2019

(Source: KREDL, 2020)

Hydro: In southern India, Karnataka has the highest potential of pumped storage hydropower at 7.9 GW[7]. In 2018, hydropower accounted for 7.1% of the total power generated in Karnataka. Hydropower plants are located in nine districts, of which Uttara Kannada, Shimoga, and Udupi account for more than 85% of the total installed capacity (Figure 6).

Wind: Karnataka is counted among the top five destinations for wind energy in India and has a wind potential in excess of ~14 GW. Wind power plants are distributed in 16 districts (Figure 7) in the state. Five districts, namely, Belgaum, Chitradurga, Davanagere, Gadag, and Bijapur, account for 76% of the installed wind capacity in the state. According to the Karnataka Electricity Regulatory Commission (KERC)[8], as of January 2020, the installed

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[5] The climate risk analysis in this study (presented later) was conducted on the basis of only these eight districts.

[6] https://www.investkarnataka.co.in/wp-content/uploads/2020/07/Energy-Sector.pdf

[7] https://www.investkarnataka.co.in/wp-content/uploads/2020/07/Energy-Sector.pdf

[8] http://karunadu.karnataka.gov.in/kerc/Documents/Determination%20of%20Generic%20Tariff%20for%20wind%20Power%20Project%20for%20FY%202020-21.pdf

wind power capacity in Karnataka was 4,819.34 MW against the net allotted capacity of 10,141.29 MW.

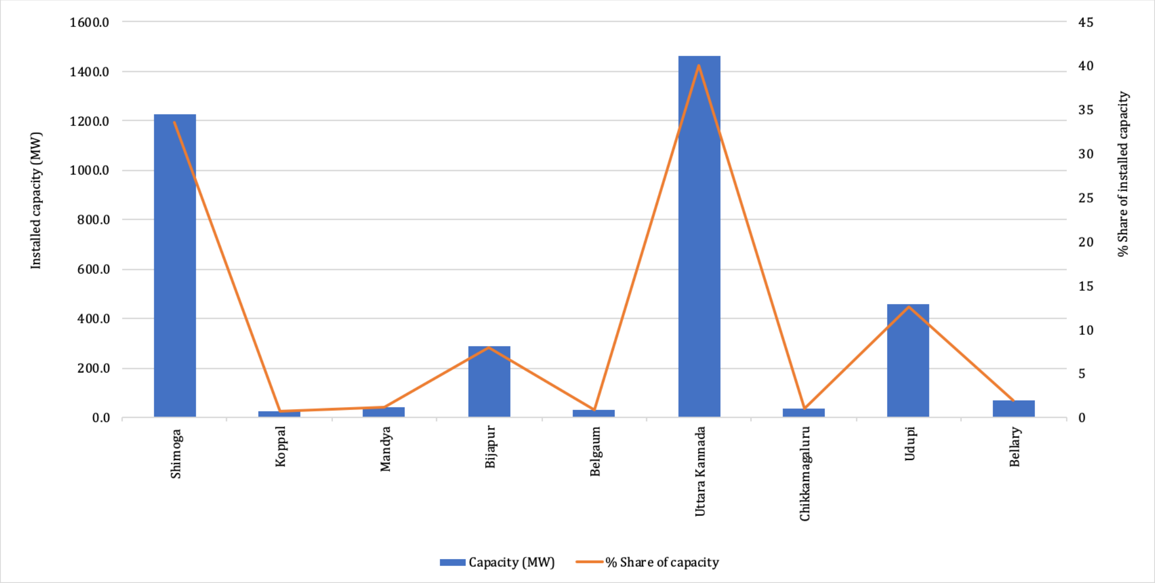


Figure 6: District-wise installed hydropower plant capacity in Karnataka

(Source: KREDL, 2020Error! Bookmark not defined.)

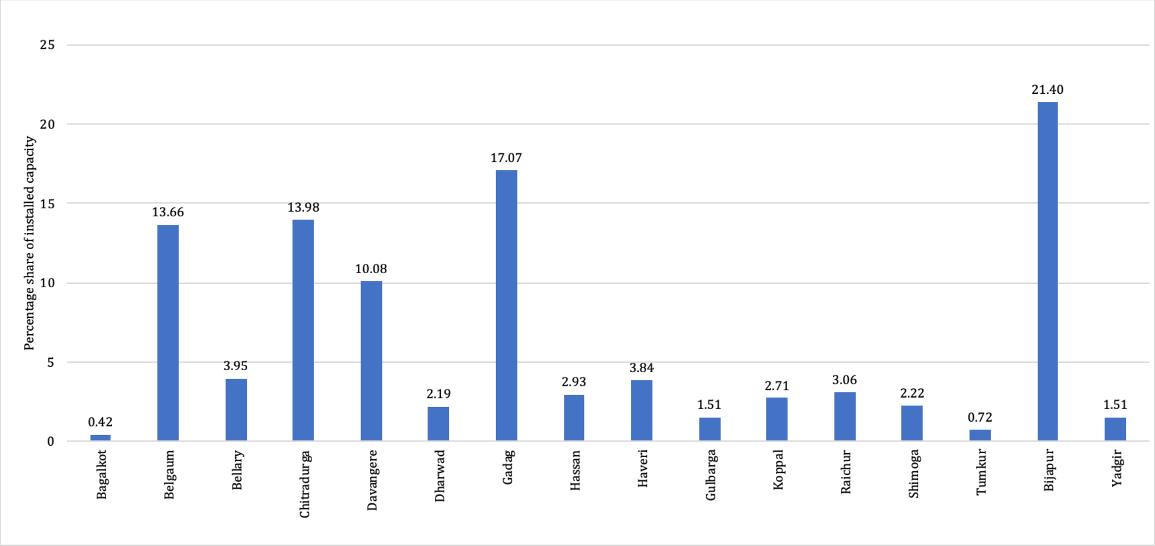
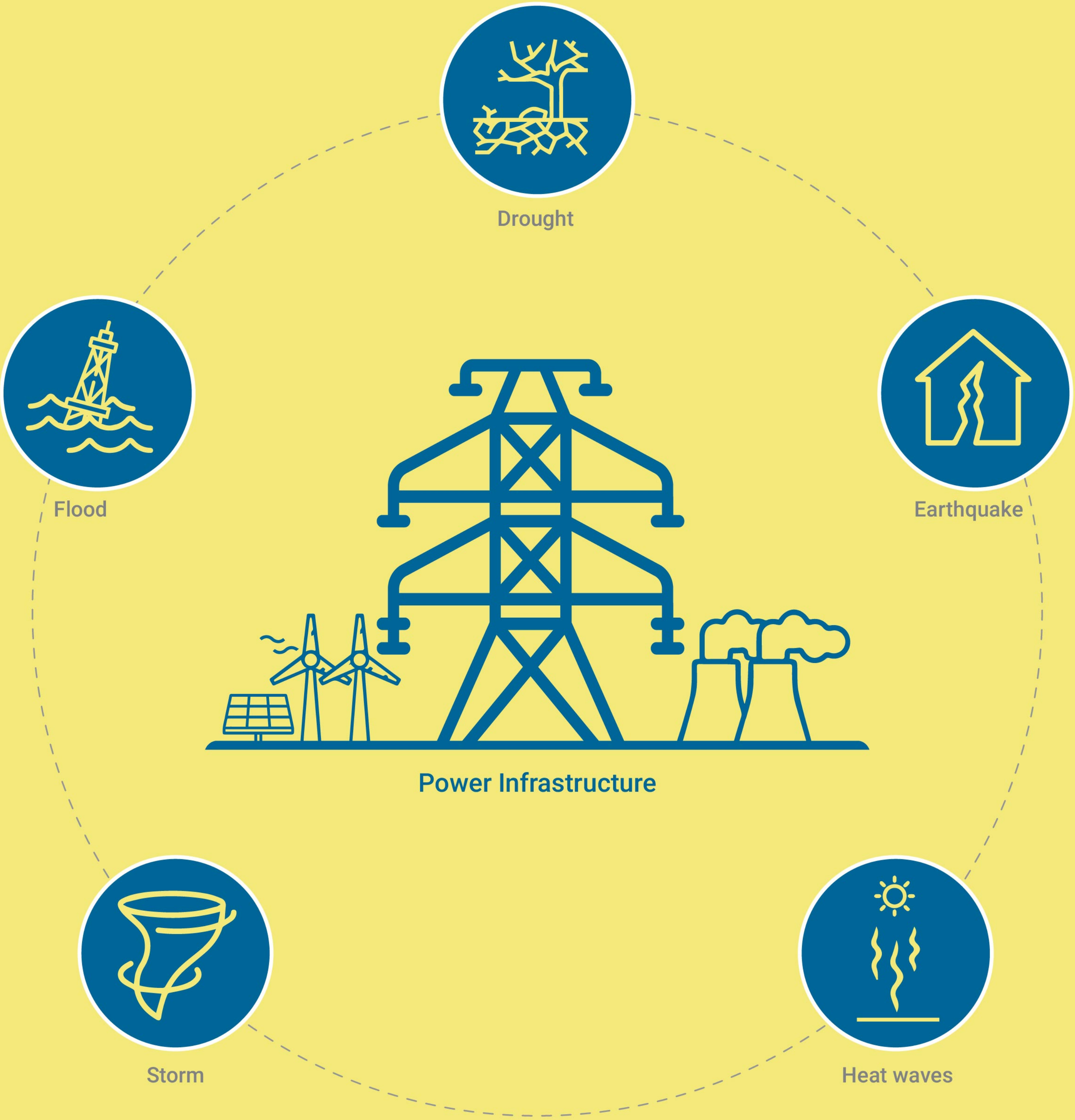


Figure 7: District-wise installed wind power capacity in Karnataka
(Source: KREDL, 2020)



Drought

Flood

Earthquake

Power Infrastructure

Storm

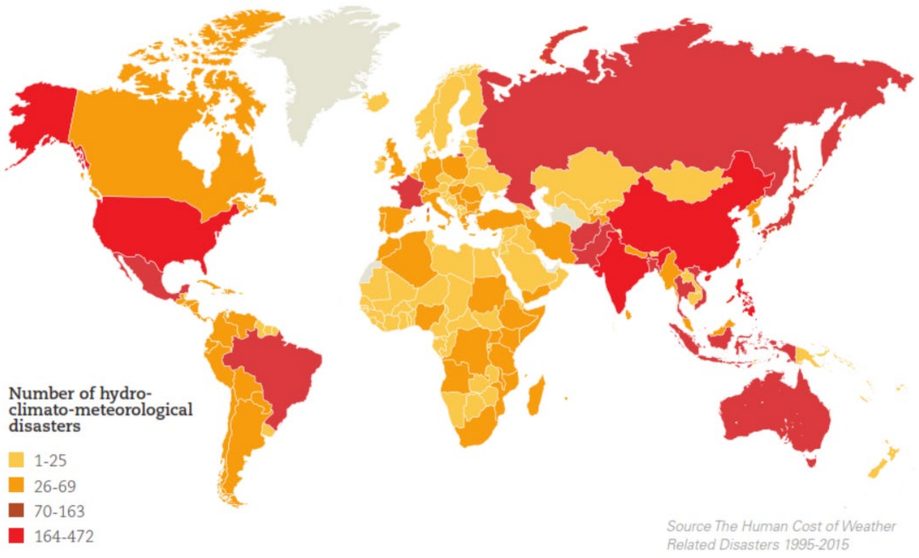
Heat waves

2. Climate Change and Power Infrastructure

The Global Climate Risk Index 2021 ranks India seventh in terms of fatalities due to extreme weather events in 2019. In recent years, these extreme weather events have highlighted infrastructure vulnerabilities that lead to failure of services, with large socioeconomic knock-on effects. There is, therefore, a need to understand the linkage between climate change and power infrastructure, the likely projected changes in climate, and the emerging climate risks to various power infrastructure segments.

The impacts of climate change are visible in the increasingly greater number of disasters being reported globally. Extreme weather events such as heatwaves, flooding, and droughts are becoming more frequent and severe, leaving communities to deal with often devastating social and economic costs. Pielke (2019) reported a 74% increase in weather-related-catastrophe losses since 1990. Globally, less than half of the reported losses are insured. In developing countries, this figure plummets to well below 10%. This is despite the increasing number of losses being recorded as a result of earthquakes, storms, floods, and droughts over the years.

China and India are among the top countries most affected by weather-related disasters (Figure 8), as reported by Pascaline and Rowena (2018). India is vulnerable, in varying degrees, to a large number of disasters. The risks are compounded because of inherent vulnerabilities related to socio-economic conditions, environmental degradation, high-risk zones, climate change, etc.



Source The Human Cost of Weather Related Disasters 1995-2015

Figure 8: Country-wise number of weather-related disasters reported during 1995–2015

(Source: Pascaline & Rowena, 2018)

Trend analysis using decadal data from the Emergency Events Database (EM-DAT) shows that the number of extreme weather events in India has been increasing continuously. During 1998–2017, the average annual extreme weather events stood at 16 compared to 10 events during 1978–97. This increase is reflected in the increasing trend of economic losses due to extreme weather events (Table 1).

Table 1: Severity of extreme weather events on the rise

Year	Disaster **type**	Total damage ('000 US$)
1999	Odisha super cyclone	2,500,000
2004	Floods in Bihar, Tripura, Assam, Gujarat, and Jammu & Kashmir	2,500,000
2005	Floods in Gujarat	2,300,000
2005	Floods in Mumbai and other parts of Maharashtra, Goa, Gujarat, Madhya Pradesh, Orissa, Karnataka, Himachal Pradesh, and Jammu & Kashmir	3,330,000
2006	Floods in Andhra Pradesh, Gujarat, Maharashtra, Chhattisgarh, Rajasthan, Madhya Pradesh, Orissa, and Karnataka	3,390,000
2009	Floods in Karnataka, Andhra Pradesh, and Uttar Pradesh	2,150,000
2010	Floods in Uttarakhand, Bihar, and Uttar Pradesh	1,680,000
2013	Floods in Uttarakhand, Himachal Pradesh, Uttar Pradesh, Bihar, Karnataka, Kerala, Gujarat, and West Bengal	1,100,000
2014	Floods in Jammu & Kashmir	16,000,000
2014	Cyclone 'Hudhud'	7,000,000
2015	Floods in Chennai and parts of Tamil Nadu, Andhra Pradesh, and Puducherry	2,200,000
2015	Drought in Tamil Nadu, Rajasthan, Jharkhand, Assam, Andhra Pradesh, Himachal Pradesh, Nagaland, Maharashtra, Bihar, Madhya Pradesh, Chhattisgarh, Telangana, Jharkhand, and Orissa	3,000,000
2016	Cyclone 'Vardah'	1,000,000
2017	Floods in Bihar, Uttar Pradesh, and West Bengal	1,567,000

(Source: Singh, 2019)

India's economic losses doubled in the last decade with the cumulative losses for 2008–2017 estimated to be US$45 billion compared to US$20 billion for 1988–1997. Extreme weather events in the last two decades have resulted in not just agricultural losses but also losses from damage to infrastructure such as buildings and transport, and revenue loss to businesses, threatening India's population, economy, and development.

2.1. Need for Assessing Climate Risks to Power Infrastructure

The power infrastructure, including generating stations, transmission, and distribution (T&D) lines, and related equipment, is vulnerable to manifestations of climate change such as temperature extremes and increased frequency of cyclones, floods, droughts, etc. This is because such infrastructure segments are located at places that are geographically and climatologically different, and climate change will threaten efficient and reliable working of power generation units.

India, being a signatory to Sendai Framework for Disaster Risk Reduction, is committed to achieving the seven goals set under the framework through systematic and sustainable efforts. One of the goals is to reduce the damage to critical infrastructure because of natural disasters and to develop resilience by 2030.

Infrastructure investments are usually large and are designed to operate over the long term. For example, coal-fired plants are typically designed for 35–40 years and hydropower dams for up to 100 years. Traditionally, these are designed by taking into consideration the historical climate. However, a changing climate and the resulting change in mean and extremes will make these climate bands outdated, resulting in infrastructure operating outside thresholds. Therefore, decisions made today with respect to siting and design of infrastructure will determine their resilience under a changing climate (Vallejo and Mullan, 2017).

2.2. Objectives

Considering the impacts of climate change, large investments in infrastructure assets and their long life, the study aims to

- Develop a spatial climate risk profile for thermal, solar, and wind power infrastructure segments
- Suggest strategies for increasing resilience of the power sector infrastructure in Karnataka.

Develop projections of temperature and rainfall, and extreme events

Develop a spatial climate risk profile for power infrastructure in Karnataka

Suggest resilience building and adaptation strategies

3. Approach and Methodology

The assessment of climate risks and development of a climate risk profile for power infrastructure segments involve the following steps.

Step 1: Develop projections of temperature and rainfall, and extreme events

Assessment of climate change at the district level for Karnataka involved assessing climate over the past 30 years (1990–2019), referred to as the 'historical period', and projected for 2021–2050, referred to as 'the 2030s'. A historical climate analysis serves as a baseline for comparing the projected climate. Both temperature and rainfall data for the historical period are obtained from Indian Meteorological Department (IMD).

- A gridded daily maximum temperature dataset of 1.0° × 1.0° for the period 1990–2019 is used to assess temperature trends during March to May (MAM).
- A gridded daily rainfall dataset of 0.25° × 0.25° for the period 1990–2019 is used for analysing trends in monsoon rainfall during June to September (JJAS).

Projections of climate change are made using the Coordinated Regional Climate Downscaling Experiment (CORDEX) South Asia modelled data (Table 2) on rainfall and temperature. Ensemble mean values from bias-corrected 15 CORDEX simulations of 0.5° × 0.5° are re-gridded to a 0.25° × 0.25° resolution to harmonise with IMD data.

Table 2: List of CORDEX models used in this study for climate change projections

CORDEX simulation	RCM	GCM boundary condition
CNRM-CERFACS-CNRM-CM5_SMHI-RCA4	SMHI-RCA4	CNRM
NOAA-GFDL-GFDL-ESM2M_SMHI-RCA4		GFDL
IPSL-CM5A-MR_SMHI-RCA4		IPSL-CM5A
MIROC-MIROC5_SMHI-RCA4		MIRCO
MPI-M-MPI-ESM-LR_SMHI-RCA4		MPI-M
CNRM-CERFACS-CNRM-CM5_SMHI-RCA4	IITM–RegCM4-4	CNRM
NOAA-GFDL-GFDL-ESM2M_SMHI-RCA4		GFDL
IPSL-CM5A-MR_SMHI-RCA4		IPSL-CM5A
MIROC-MIROC5_SMHI-RCA4		MIROC
MPI-M-MPI-ESM-LR_SMHI-RCA4		MPI-M
CCma-CanESM2		CCMA
CSIRO-QCCCE-CSIRO-Mk3-6-0		CSIRO
NOAA-GFDL/GFDL-ESM2M		GFDL-ESM2M
MPI-M-MPI-ESM-LR		MPI-M
MOHC-HadGEM2-ES		HadGEM2

(RCM: regional climate model; GCM: general circulation model)

(Source: CORDEX South Asia, IITM Pune (RCP 8.5) RCM - SMHI-RCA4 (Rossby Centre Regional Atmospheric Model v.4, Swedish Meteorological and Hydrological Institute))

The analysis is conducted for RCP 8.5—one of the four Intergovernmental Panel on Climate Change (IPCC) scenarios or representative concentration pathways (RCPs)[9]—as it represents risks in the absence of further decarbonisation. RCP 8.5 is the worst-case scenario in which emissions continue to rise throughout the twenty-first century, with a global temperature increase of up to 2.6°C.

Step 2: Develop a spatial climate risk profile for power infrastructure in Karnataka

Spatial climate risk profiling involved

- Identification of districts that dominate power generation for a category
- Preparation of district-level maps of changes in summer maximum temperature, summer monsoon rainfall, and heavy rainfall events of 51–100 mm/day and >100 mm/day, relative to the historical period
- Overlaying of climate hazard maps on district maps supporting different power infrastructure segments
- Risk profiling by considering temperature, rainfall, and extreme events

Step 3: Suggest adaptation strategies

Adaptation strategies considering potential climate hazards and risks to different power infrastructure segments are suggested on the basis of literature.

Limitations of the Current Analysis

In this study, climate parameters such as wind speed, cloud cover, solar radiation, and dry spells (that may not be a drought) that could impact water availability have not been analysed owing to the limited data available for all the 15 CORDEX models—used for obtaining the ensemble mean for climate analysis. Another aspect that has not been addressed in this study is the indirect risk of climate change—the demand for power increasing with increase in temperature and shortage in production.

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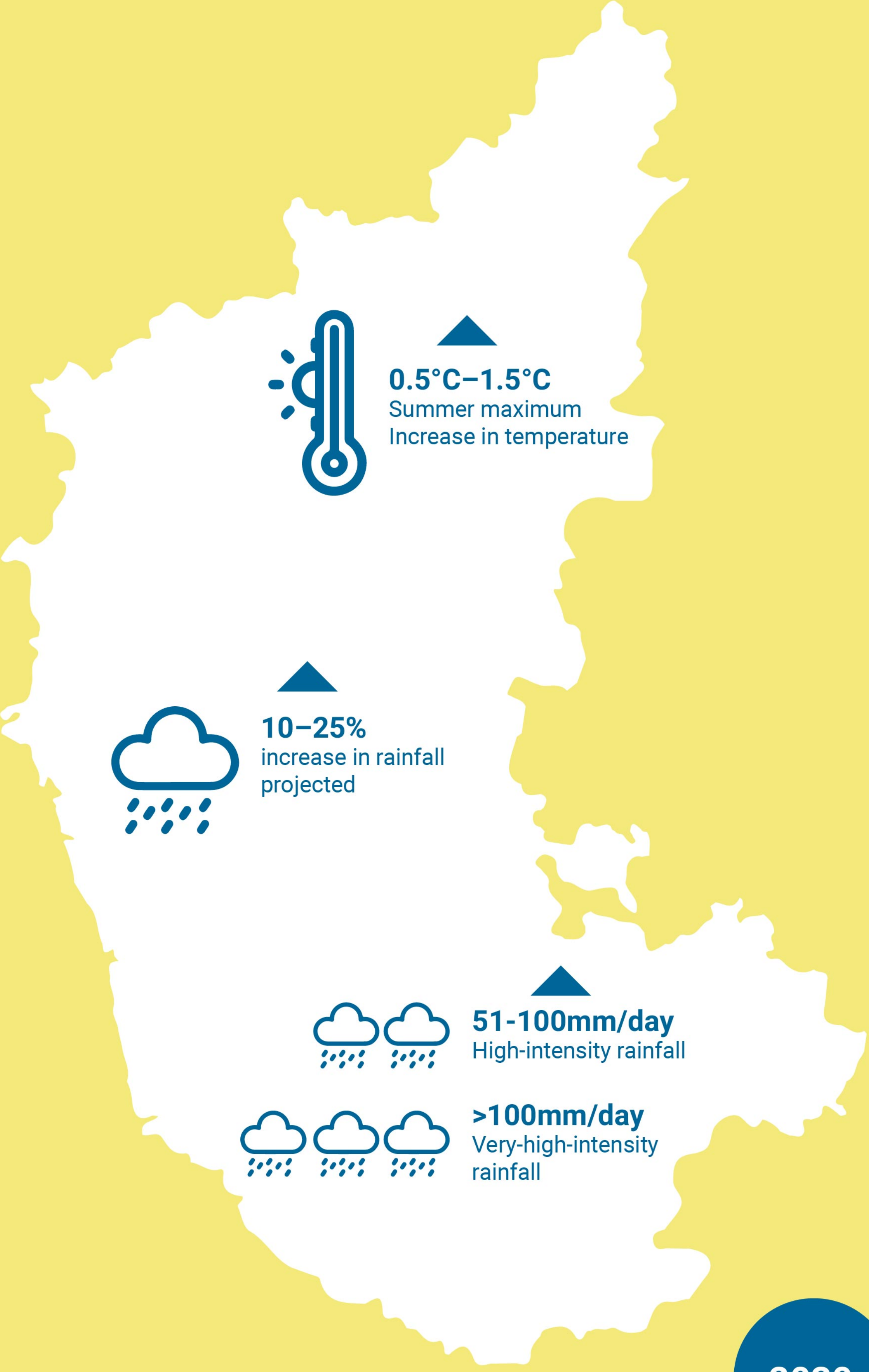
[9] Representative concentration pathways (RCP) refer to a range of future anthropogenic greenhouse gas emissions and their atmospheric concentrations.



▲ **0.5°C–1.5°C**
Summer maximum
Increase in temperature

▲ **10–25%**
increase in rainfall
projected

▲ **51-100mm/day**
High-intensity rainfall

>100mm/day
Very-high-intensity
rainfall

2030s

RCP 8.5 scenario | **2021–2050**

4. Findings of Climate Change Analysis for Karnataka

A recent report by the Ministry of Earth Sciences, GoI has assessed the changes in climate over the Indian region for the period 1901–2018 (Raghavan et al., 2020). The average temperature in India has risen by around 0.7°C during this period. A decline in summer monsoon rainfall by 6% is reported for the period 1951–2015. Additionally, during the summer monsoon season, a 27% increase in dry spells during 1981–2011, relative to 1951–1980, and increase in the intensity of wet spells is reported.

Temperature projections for the end of the century (2099) show an increase of 4°C or more, compared to the recent past (1976-2005), with more frequent heat waves persisting over longer durations. Mean annual and summer monsoon rainfall is projected to increase but the variability is also projected to increase simultaneously—with more frequent and intense heavy rainfall events, and extended dry spells. Similar trends are observed across all the states of India.

Here we analyse the temperature and rainfall for Karnataka—at the district level—and present changes for the projected period (2021–2050), relative to 1990–2019. The changes in temperature and rainfall during the projected period are computed as a difference between the model-simulated ensemble average of the 30-year historical period and the projected 30-year period.

4.1. Summer Maximum Temperature

A rise in summer maximum temperature in the range 0.5–1.5°C (Figure 9) is projected for all the districts of Karnataka during the summer months of March, April, and May during 2030s under the RCP 8.5 scenario.

- Warming is projected to be in the range 0.5–1°C in the coastal and Western Ghats districts of Uttara Kannada, Shimoga, Udupi, Dakshina Kannada, parts of Kodagu, and Mysuru.
- Warming is projected to be higher—in the range 1–1.5°C—in all the northern and eastern districts of Karnataka.

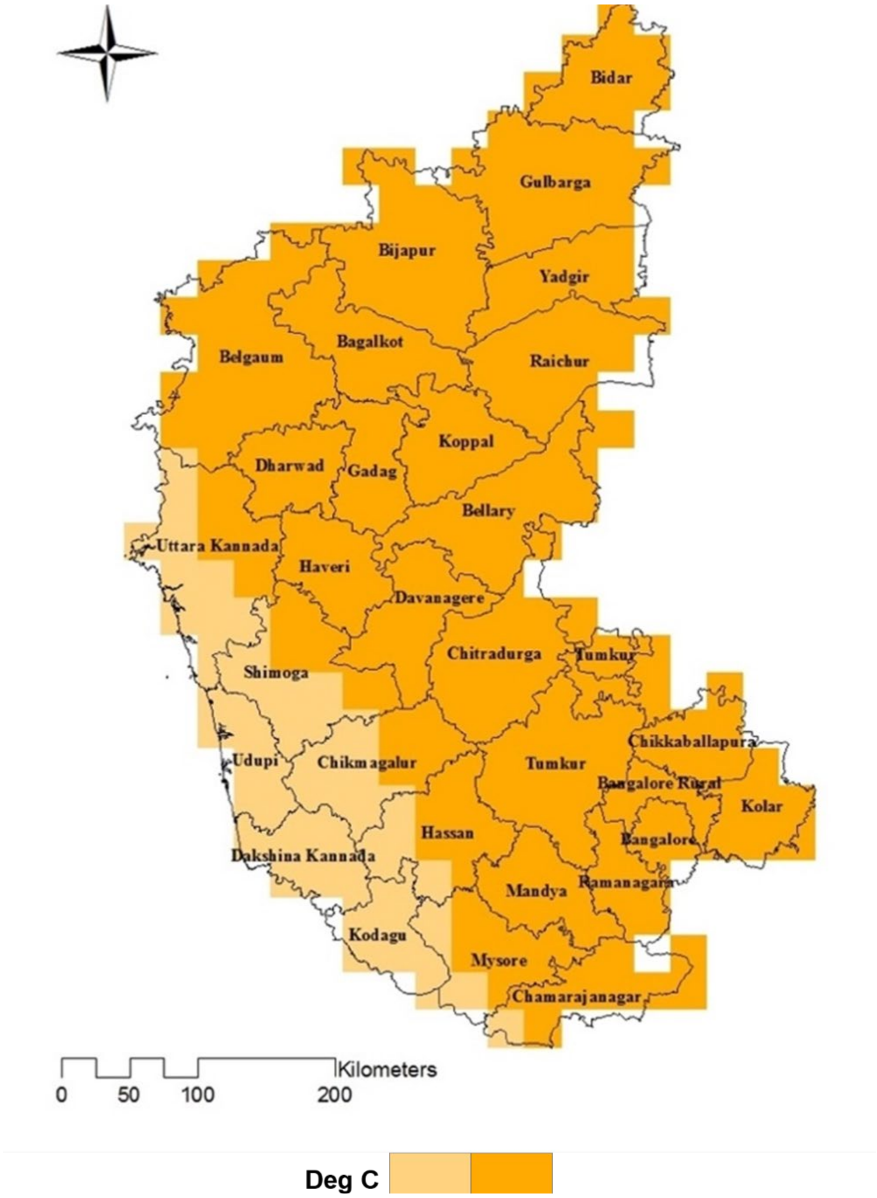


Figure 9: Projected change in summer maximum temperature (°C) relative to the historical period

4.2. Summer Monsoon Rainfall

In Karnataka, summer monsoon rainfall is received from June to September, from the southwest monsoon. An increase in summer monsoon rainfall in the range 10–25% is projected during the 2030s for the districts of Karnataka under the RCP 8.5 scenario (Figure 10).

- Maximum increase in summer monsoon rainfall in the range 20–25%, relative to the historical period is projected for the coastal and Western Ghats districts of Dakshina Kannada, Kodagu, parts of Udupi, Chikkamagaluru, and Hassan.

- An increase in the range 15–20%, relative to the historical period, is projected for the northernmost districts of Bidar, part of Gulbarga, Bijapur, Bagalkot, Belgaum, and parts of the Western Ghats districts of Chikkamagaluru, Hassan, and Shimoga.
- An increase in the range 10–15%, relative to the historical period, is projected for a majority of the districts, including Raichur, Koppal, Bellary, Gadag, Haveri, parts of Gulbarga, Bijapur, and Bagalkot.

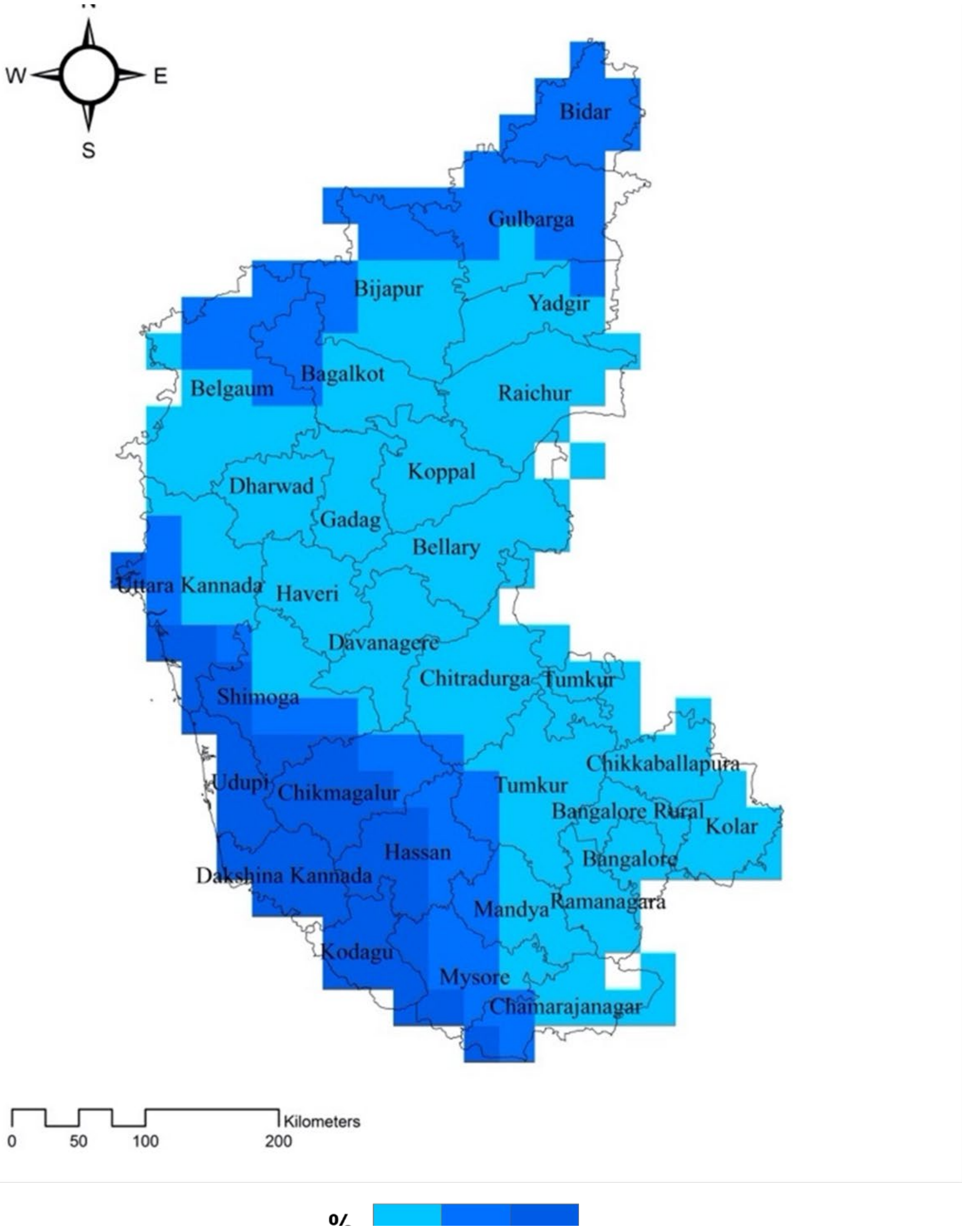


Figure 10: Percentage change in summer monsoon rainfall during the projected period relative to the historical period

4.3. Heavy Rainfall Events

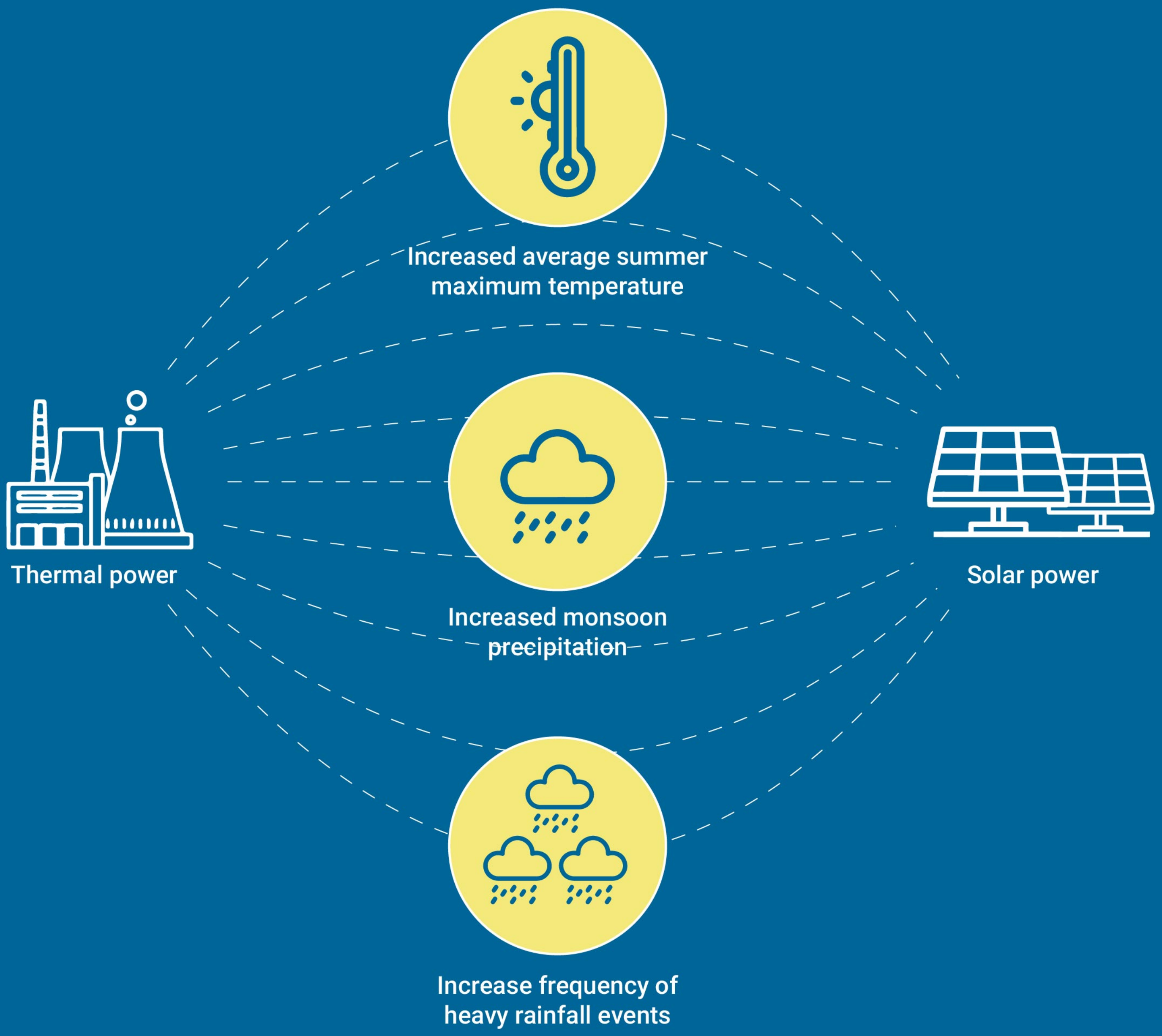
In this section, rainfall during the summer monsoon has been analysed across three categories of intensity—<50 mm/day, 51–100 mm/day (high intensity), and >100 mm/day (very high intensity)—for the historical period and the projected period under the RCP 8.5 scenario. In this section, the number of events under high- and very-high-intensity categories that could have adverse impacts are discussed, as number of events per year during the projected 30-year period of 2021–2050.

- High-intensity (51–100 mm/day) rainfall events: Increase in high-intensity rainfall events relative to the historical period is projected for all the districts of Karnataka, except Bangalore Rural where no change is projected (Figure 11).
    - The increase annually is by four events in Uttara Kannada, six events in Udupi, and seven events in Dakshina Kannada.
    - The increase annually is by three events in Mandya, Shimoga, Hassan, Kolar, and Kodagu districts.
    - The increase annually is by one to two events in 21 districts, including Kolar, Bengaluru Rural, Gulbarga, and Mandya; and two events in 13 districts, including Bellary, Bagalkot, Bidar, Tumkur, Raichur, Gulbarga, Chitradurga, etc.
- Very-high-intensity (>100 mm/day) rainfall events: Increase in very-high-intensity rainfall events relative to the historical period is projected for all the districts of Karnataka, except Gadag and Udupi where no change is projected (Figure 11).
    - The increase annually is highest in Uttara Kannada—by three events.
    - The increase annually is by two events in 10 districts, including Raichur, Gulbarga, Bellary, Bidar, Shimoga, etc.
    - The increase is by one event in 17 districts, including Bijapur, Tumkur, Belgaum, Chitradurga, Koppal, etc.

District	Low-intensity (<50 mm rainfall/day)		High-intensity (51-100 mm rainfall/day)		Very-high-intensity (>100 mm rainfall/day)	
	Historical	RCP 8.5 scenario	Historical	RCP 8.5 scenario	Historical	RCP 8.5 scenario
Bagalkot	3644	3592	14	67	2	20
Bangalore Rural	3629	3603	31	39	0	41
Bangalore Urban	3621	3544	36	110	3	45
Belgaum	3607	3542	45	89	8	47
Bellary	3641	3540	18	69	1	60
Bidar	3608	3560	44	98	8	71
Bijapur	3644	3625	14	61	2	22
Chamarajanagar	3647	3610	12	34	1	31
Chikballapur	3640	3584	19	44	1	29
Chikkamagaluru	3646	3591	13	65	1	33
Chitradurga	3646	3561	14	88	0	40
Dakshina Kannada	3020	2929	547	762	93	140
Davanagere	3641	3564	19	67	0	45
Dharwad	3626	3567	27	80	7	49
Gadag	3627	3582	27	56	6	18
Gulbarga	3625	3538	29	101	6	56
Hassan	3624	3539	32	112	4	72
Haveri	3642	3545	16	71	2	34
Kodagu	3484	3379	152	250	24	77
Kolar	3644	3585	15	95	1	30
Koppal	3636	3576	22	88	2	45
Mandya	3641	3570	15	90	4	42
Mysore	3639	3590	17	87	4	64
Raichur	3637	3570	21	85	2	47
Ramnagara	3611	3563	43	70	6	43
Shimoga	3635	3542	25	101	0	67
Tumkur	3627	3575	30	90	3	37
Udupi	2857	2715	615	800	188	191
Uttara Kannada	3376	3180	239	370	45	122
Yadgir	3651	3592	9	55	0	32

Figure 11: Number of high and very-high-intensity rainfall events during the historical and projected periods

It is evident from the climate analysis that even during the short-term period of 2030s, there will be changes in the summer maximum temperature and the magnitude of summer monsoon rainfall. Further, heavy rainfall events are projected to increase in frequency in many Karnataka districts.


Increased average summer maximum temperature
Thermal power
Solar power
Increased monsoon precipitation
Increase frequency of heavy rainfall events

5. Climate Hazard Mapping and Climate Risks to Power Infrastructure in Karnataka

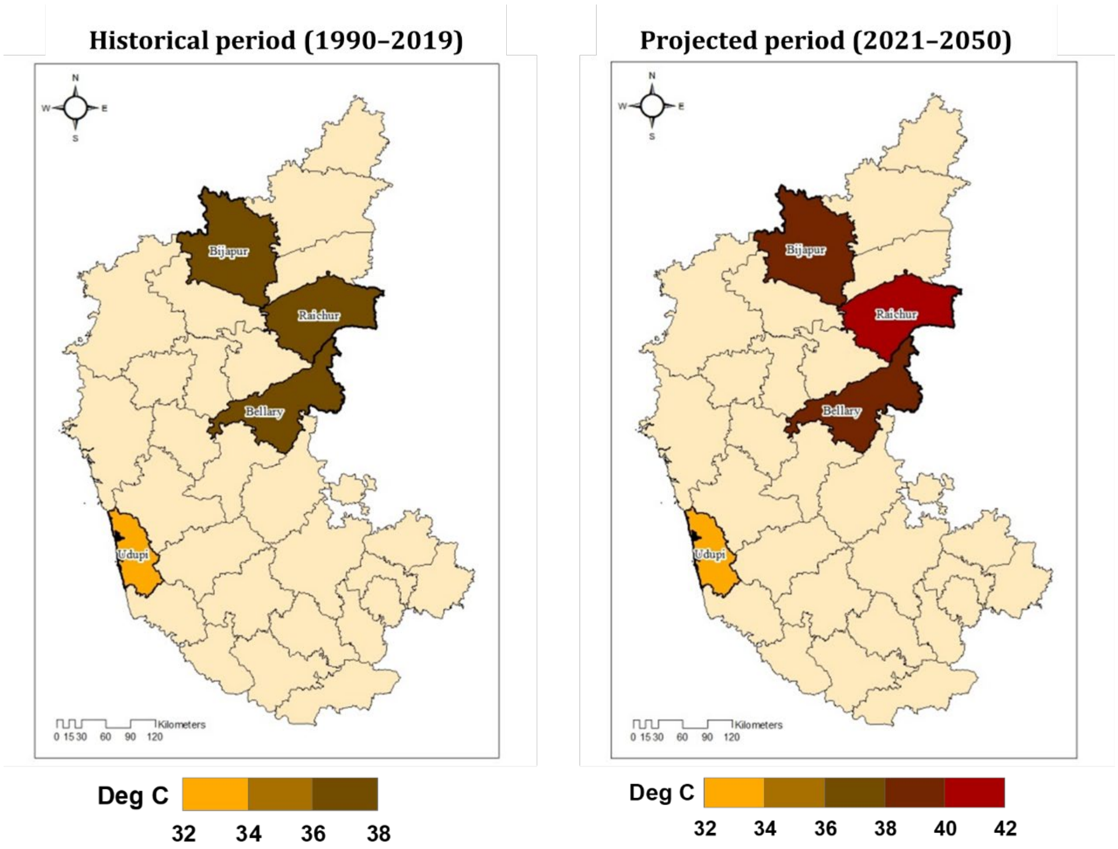
Table 3 presents a summary of changes in temperature, rainfall, and heavy rainfall events in the selected Karnataka districts housing power infrastructure. Figure 12-Figure 16 present the spatial overlay of climate hazards on power infrastructure segments in different districts of Karnataka during the historical and projected periods.

It is evident from the figures that in all the districts, a rise in temperature and an increase in rainfall and heavy rainfall events is projected for the 2030s, compared to the historical period. Moreover, heavy rainfall events are projected in some districts that historically have never recorded such events—a sign of an emerging new normal.

Table 3: Changes in temperature, rainfall, and extreme events, relative to the historical period, under projected RCP 8.5 scenario during the 2030s

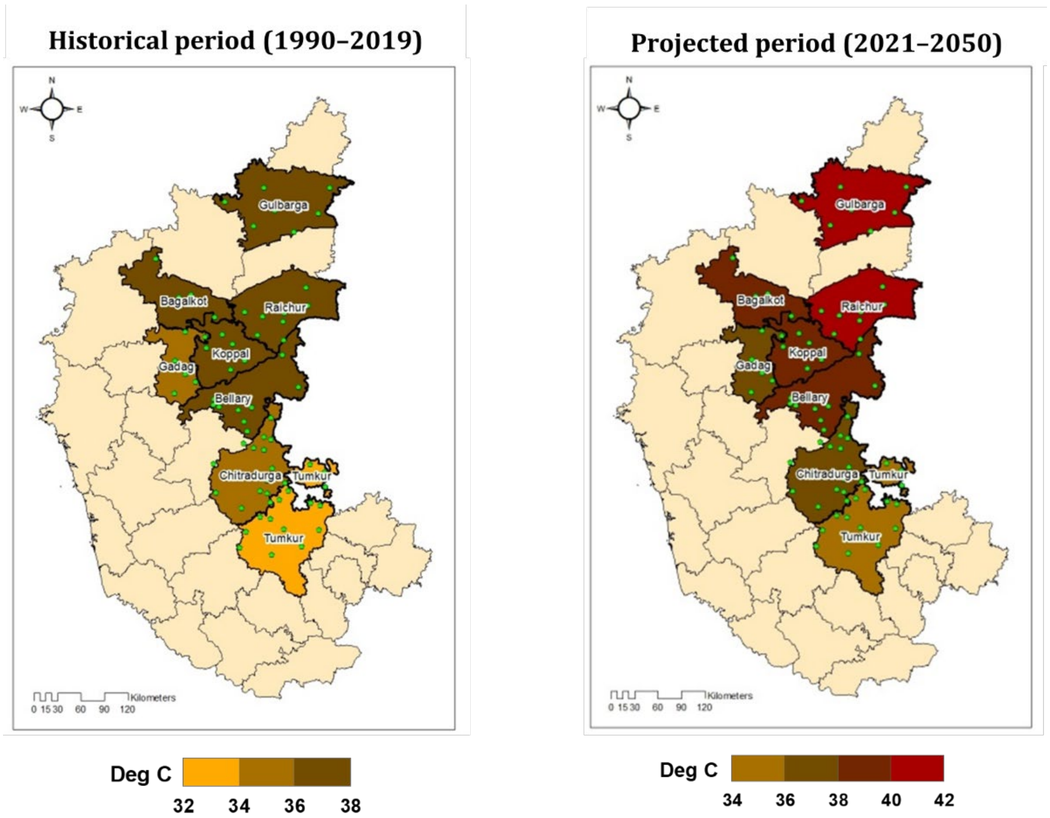
District	Changes relative to the historical period			
	Maximum temperature (°C)	**Monsoon rainfall (%)**	**Number of heavy rainfall events/annum#**	
			51–100 mm/day	**>100 mm/day**
Bagalkot (S)	+2.3	+18	Nil to 2	Nil to 1
Bellary (T, S)	+1.9	+13	Nil to 2	Nil to 2
Belgaum (W)	+1.7	+19	2 to 3	Nil to 2
Bijapur (T, W)	+2.2	+22	Nil to 2	Nil to 1
Chitradurga (S, W)	+1.8	+12	Nil to 3	Nil to 1
Davanagere (W)	+1.9	+11	1 to 2	Nil to 2
Gadag (S, W)	+1.8	+15	1 to 2	Nil to 1
Gulbarga (S)	+2.2	+16	1 to 3	Nil to 2
Koppal (S)	+1.8	+13	1 to 3	Nil to 2
Raichur (T, S)	+2.4	+12	1 to 3	Nil to 2
Tumkur (S)	+1.8	+16	1 to 3	Nil to 1
Udupi (T)	+1.4	+18	21 to 27	6-both

(S: solar; T: thermal; W: wind; #Heavy rainfall events are presented as change from historical to projected)


Historical period (1990–2019)

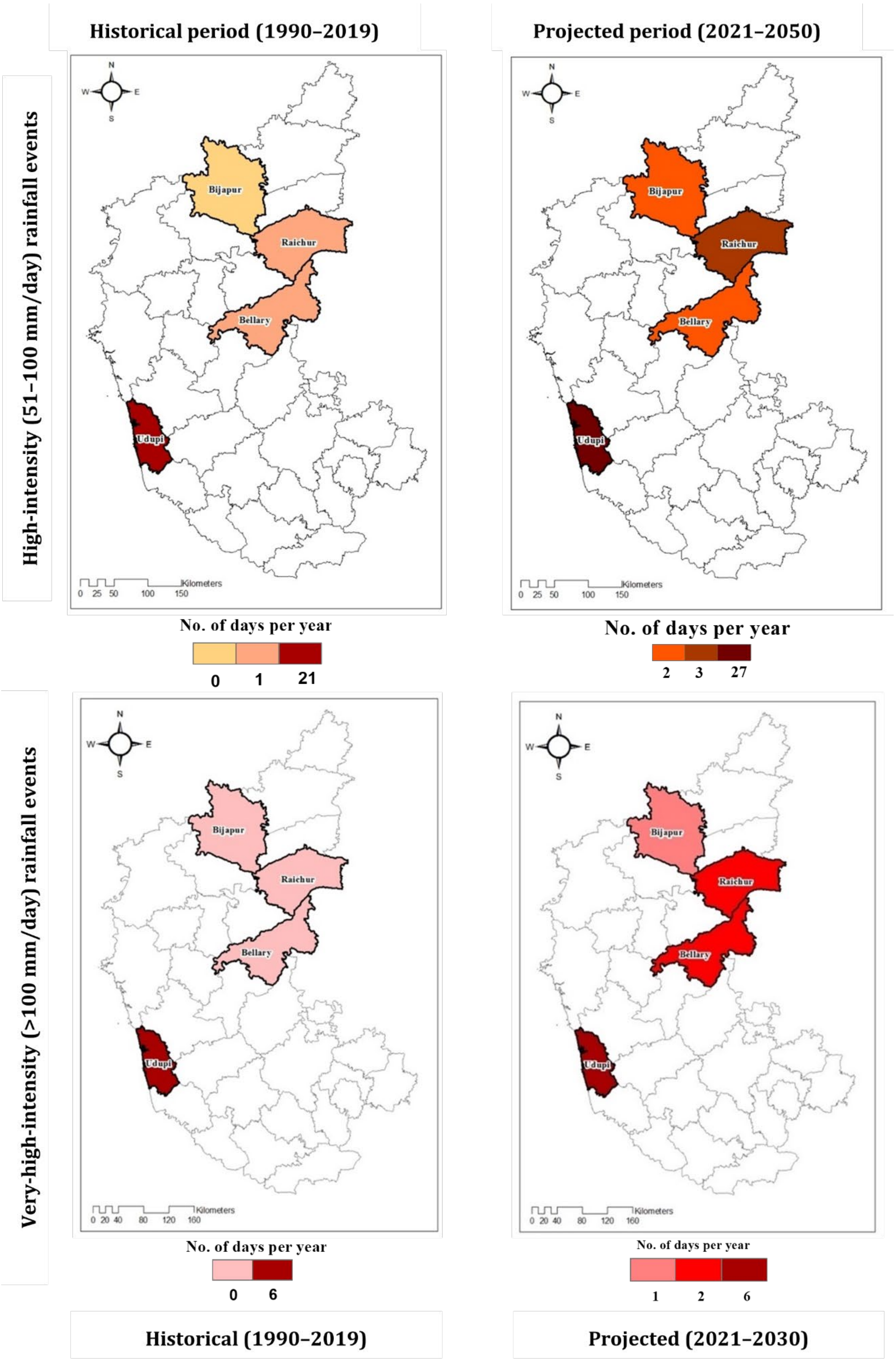
Projected period (2021–2050)

Figure 12: Summer maximum temperature in case-study districts of thermal power generation during the historical and projected periods


Historical period (1990–2019)

Projected period (2021–2050)

Figure 13: Summer maximum temperature in case–study districts of solar power generation during the historical and projected periods



Historical period (1990–2019)

Projected period (2021–2050)

High-intensity (51–100 mm/day) rainfall events

Very-high-intensity (>100 mm/day) rainfall events

Historical (1990–2019)

Projected (2021–2030)

Figure 14: Number of high- and very-high-intensity rainfall events in case-study districts of thermal power generation during the historical and projected periods

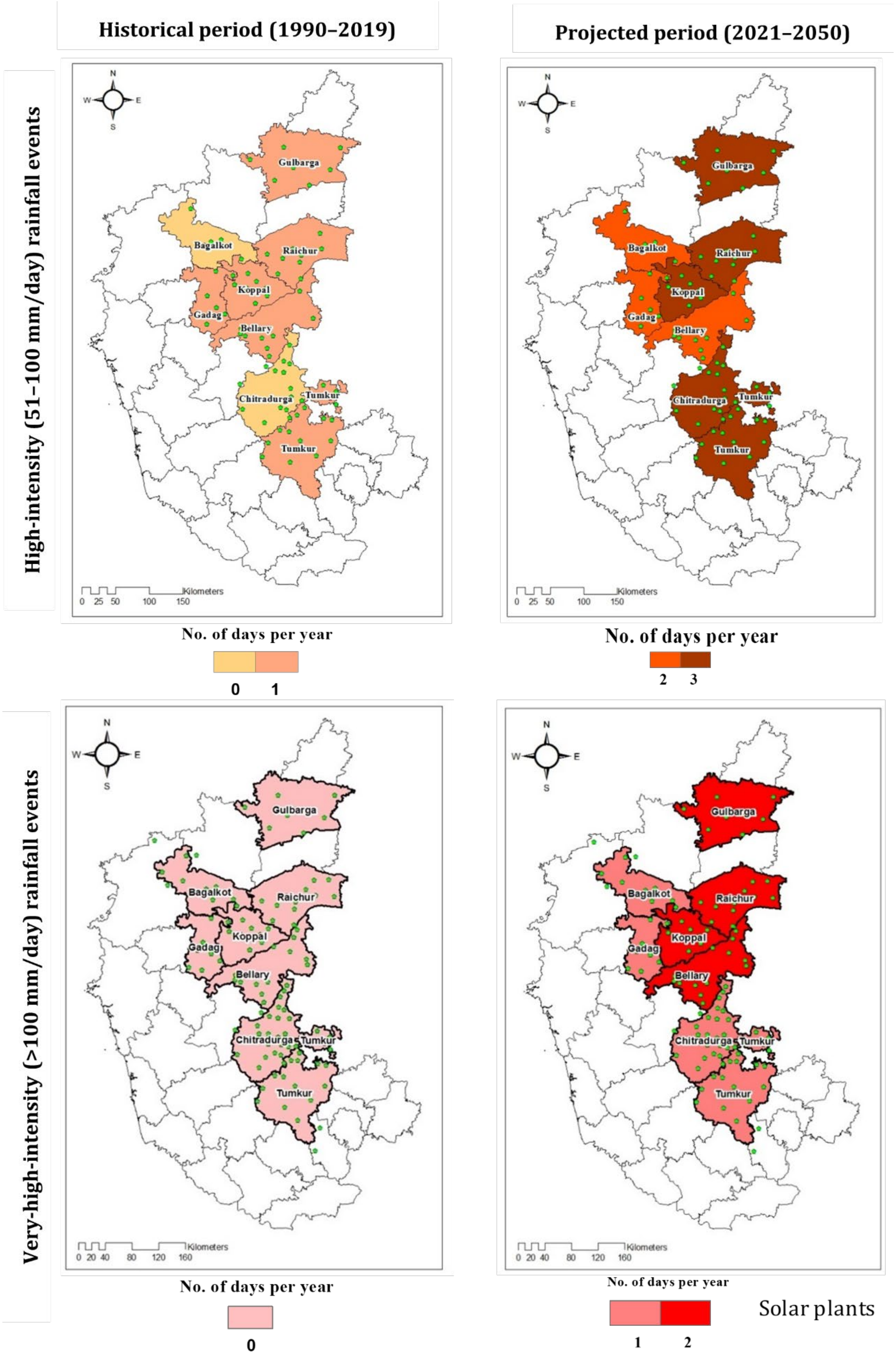


Figure 15: Number of high- and very-high-intensity rainfall events per annum in case-study districts of solar power generation during the historical and projected periods

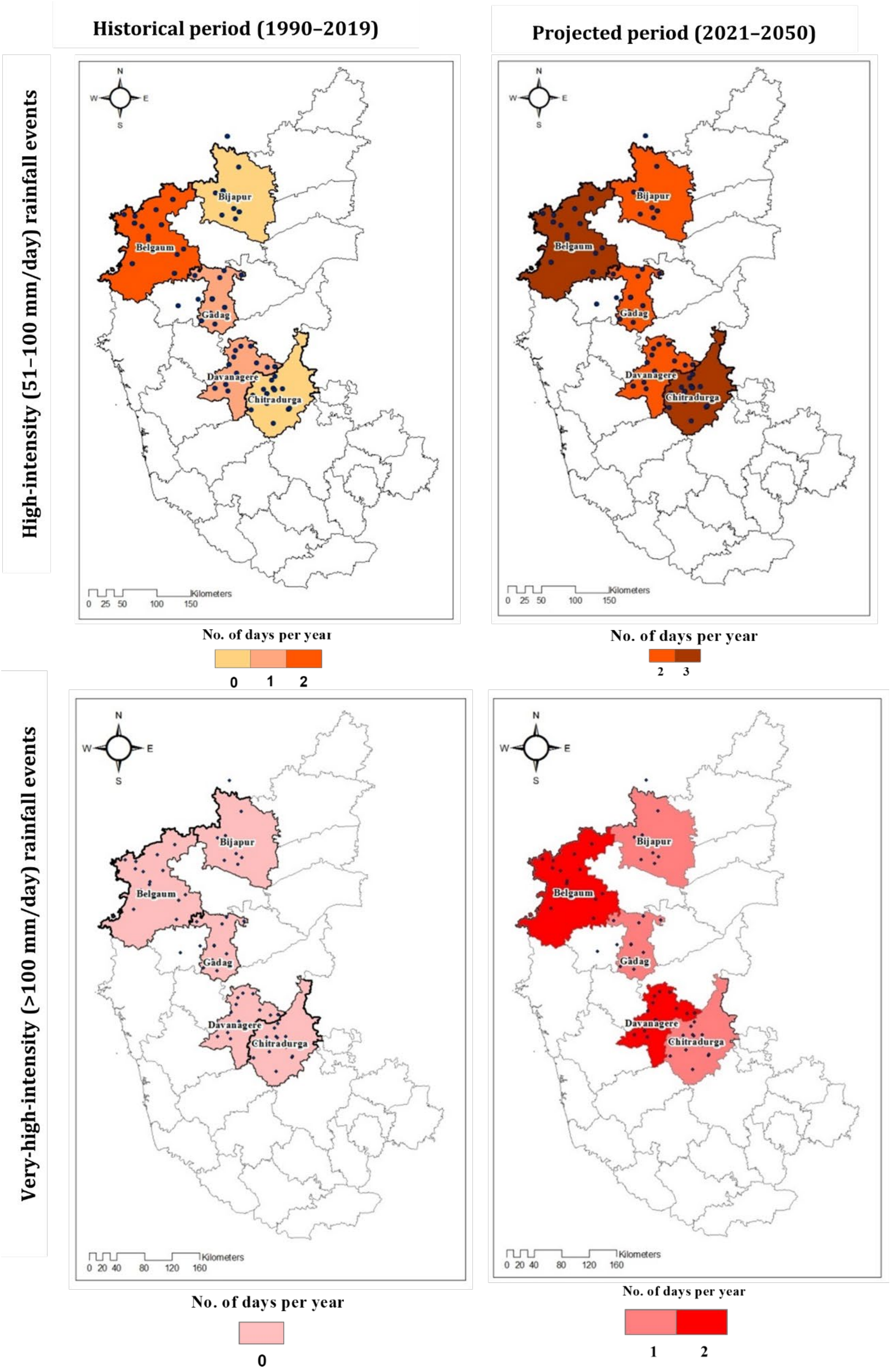


Figure 16: Number of high- and very-high-intensity rainfall events per annum in case-study districts of wind power generation during the historical and projected periods

Direct impacts of climate change are only half the story. For instance, increase in temperature has cascading impacts on water availability and water temperature. This was experienced in 2016, when lack of cooling water forced coal plants to shut down across India, costing power companies INR 2,400 crore because of a loss of 7,486 MU in power generation. Invariably, droughts and heat waves coincide and exacerbate the severity, as seen during 2015–16 in Karnataka.

Thus, there is no one dominant hazard that threatens all power infrastructure assets and segments, nor are there hazards that can be ignored completely. Further, the vulnerabilities to these different hazards are variable. The projected changes in climate hazards and vulnerabilities can be scored on the basis of the likelihood of occurrence and consequence (Table 4). The physical nature of an asset and its sensitivity determines the vulnerability of the asset, its components, or its operation.

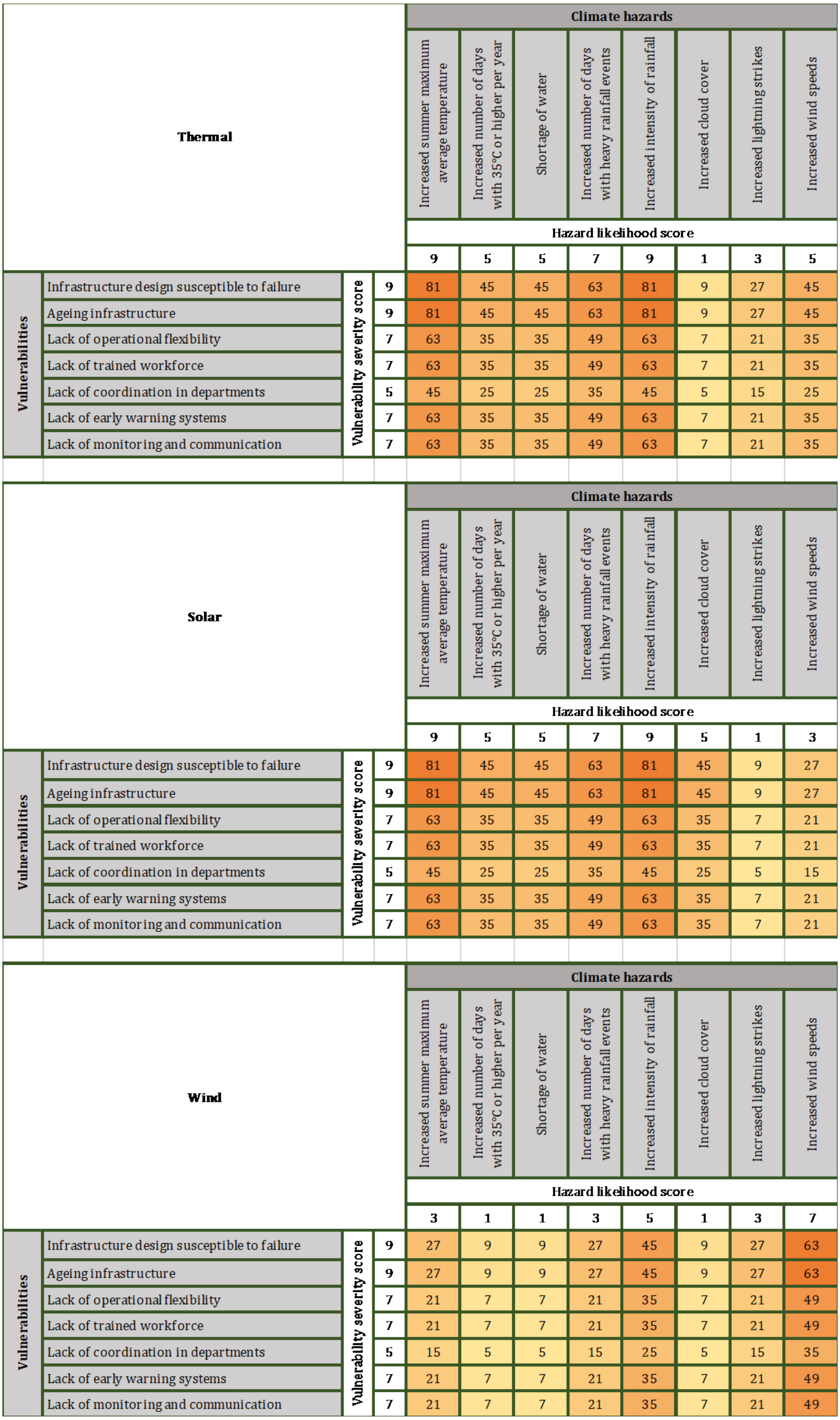
Table 4: Scoring rationale for hazard likelihood and vulnerability consequence

Category	Numerical score	Rationale for hazard likelihood	Rationale for vulnerability consequence
High	9	Almost certain to occur because of historical and projected frequency of occurrence	Highest magnitude of consequence; the entire power system could be impacted
Medium-High	7	More likely to occur than not	Significant consequence with some level of adverse impacts
Medium	5	May occur	Specific systems or functions may be impacted
Low-Medium	3	Possibility of occurrence but likely not to occur	Temporary lag in operations that can be resolved with backup solutions
Low	1	Very low likelihood of occurrence; even if it occurs, will be rare	Lowest magnitude of consequence

Risk is defined as the potential for loss, damage, or destruction of key resources, resulting from exposure to a hazard. Risk is a product of the threat/hazard likelihood and vulnerability severity score.

$$Risk\ Score\ =\ Threat\ Likelihood\ Score\ x\ Vulnerability\ Severity\ Score$$

The risk matrix (Figure 17) maps risk using climate hazards and vulnerabilities for thermal, solar, and wind power segments, and presents the relative severity of different risks. The map facilitates understanding the interactions between hazard threats and vulnerabilities, identifying potential solutions, and prioritising resilience planning efforts. The overall risk to the power infrastructure assets of a segment is determined by the extent of change projected in climate parameters, likelihood of occurrence, and vulnerability of the assets in that specific location.



Thermal	Vulnerability severity score	Increased summer maximum average temperature	Increased number of days with 35°C or higher per year	Shortage of water	Increased number of days with heavy rainfall events	Increased intensity of rainfall	Increased cloud cover	Increased lightning strikes	Increased wind speeds
Hazard likelihood score		9	5	5	7	9	1	3	5
Infrastructure design susceptible to failure	9	81	45	45	63	81	9	27	45
Ageing infrastructure	9	81	45	45	63	81	9	27	45
Lack of operational flexibility	7	63	35	35	49	63	7	21	35
Lack of trained workforce	7	63	35	35	49	63	7	21	35
Lack of coordination in departments	5	45	25	25	35	45	5	15	25
Lack of early warning systems	7	63	35	35	49	63	7	21	35
Lack of monitoring and communication	7	63	35	35	49	63	7	21	35

Solar	Vulnerability severity score	Increased summer maximum average temperature	Increased number of days with 35°C or higher per year	Shortage of water	Increased number of days with heavy rainfall events	Increased intensity of rainfall	Increased cloud cover	Increased lightning strikes	Increased wind speeds
Hazard likelihood score		9	5	5	7	9	5	1	3
Infrastructure design susceptible to failure	9	81	45	45	63	81	45	9	27
Ageing infrastructure	9	81	45	45	63	81	45	9	27
Lack of operational flexibility	7	63	35	35	49	63	35	7	21
Lack of trained workforce	7	63	35	35	49	63	35	7	21
Lack of coordination in departments	5	45	25	25	35	45	25	5	15
Lack of early warning systems	7	63	35	35	49	63	35	7	21
Lack of monitoring and communication	7	63	35	35	49	63	35	7	21

Wind	Vulnerability severity score	Increased summer maximum average temperature	Increased number of days with 35°C or higher per year	Shortage of water	Increased number of days with heavy rainfall events	Increased intensity of rainfall	Increased cloud cover	Increased lightning strikes	Increased wind speeds
Hazard likelihood score		3	1	1	3	5	1	3	7
Infrastructure design susceptible to failure	9	27	9	9	27	45	9	27	63
Ageing infrastructure	9	27	9	9	27	45	9	27	63
Lack of operational flexibility	7	21	7	7	21	35	7	21	49
Lack of trained workforce	7	21	7	7	21	35	7	21	49
Lack of coordination in departments	5	15	5	5	15	25	5	15	35
Lack of early warning systems	7	21	7	7	21	35	7	21	49
Lack of monitoring and communication	7	21	7	7	21	35	7	21	49

Figure 17: Risk matrix for thermal, solar, and wind power infrastructure in Karnataka

A power infrastructure asset could become vulnerable to climate change because of design susceptibility to failure, age, lack of operational flexibility, absence of trained workforce, lack of coordination among departments, lack of early warning systems, and lack of monitoring and communication. In the case of thermal and solar power plants, plant design and age, coupled with increased summer maximum temperature and heavy rainfall events, place the plants at 'high' risk. For solar power plants, in addition to the abovementioned factors, increased cloud cover, along with design, age, and lack of operational flexibility, results in 'medium' risk. Wind power plants are at 'high' risk because of high wind speeds during heavy rainfall events, and their design and age.

It is evident from this analysis that the form and magnitude of climate risk varies for different power infrastructure segments. Further, the risk varies within a power infrastructure segment too, depending on the location, magnitude of hazard, likelihood of occurrence, and vulnerability of the asset. Table 5 provides the plant-level scoring criteria for temperature and rainfall.

Table 5: Scoring criteria for increase in temperature and number of heavy rainfall events (>50 mm/day)

Increase in temperature	Rank	Score	Percentage increase in heavy rainfall events	Rank	Score
1°C–1.5°C	Low	1	Up to 50%	Low	1
1.5°C–2.0°C	Medium	2	50–75%	Medium	2
>2°C	High	3	75–100%	High	3
			No occurrence to occurrence	Very High	4

By applying this scoring criteria to projected increase in temperature and heavy rainfall events in the districts with thermal power plants, we find that if only temperature increase is considered, then Bijapur and Raichur plants are at 'high' risk as the increase is >2°C in both the districts. If increase in heavy rainfall events alone is considered, then plants in Bellary and Bijapur are at 'very high' risk as heavy rainfall events have never been recorded in these districts but are projected. Raichur and Udupi are 'high' and 'low' risk, respectively. When both the climate risks are combined to obtain an average score on a scale of 1 to 5, the risk to the Bijapur plant can be categorised as 'medium-high', to the Raichur and Bellary plants as 'medium', and to the Udupi plant as 'very low' (Table 6).

A similar analysis for solar power plants in eight districts of Karnataka shows that when only temperature increase in considered, all solar plants except Bagalkot and Raichur are in the 'medium' risk category. When only heavy rainfall events are considered, the Bagalkot plant falls in the 'medium-high' risk category; plants in Bellary, Chitradurga, Gadag, and

Raichur in the 'medium' risk category; and plants in Gulbarga, Koppal, and Tumkur in the 'low-medium' risk category (Table 6).

Table 6: Climate risk matrix for thermal and solar power plants in Karnataka

	District	Increase in temperature		Increase in heavy rainfall events		Average score	Rank
Thermal	Bellary	2	Medium	4	Very High	3	Medium
	Bijapur	3	High	4	Very High	3.5	Medium-High
	Raichur	3	High	3	High	3	Medium
	Udupi	1	Low	1	Low	1	Very Low
Solar	Bagalkot	High	3	Very High	4	3.5	Medium-High
	Bellary	Medium	2	Very High	4	3	Medium
	Chitradurga	Medium	2	Very High	4	3	Medium
	Gadag	Medium	2	Medium	2	3	Medium
	Gulbarga	Medium	2	High	3	2.5	Low-Medium
	Koppal	Medium	2	High	3	2.5	Low-Medium
	Raichur	High	3	High	3	3	Medium
	Tumkur	Medium	2	High	3	2.5	Low-Medium

In summary, this study illustrates the various climate-related risks faced by the power sector segments (Figure 18) in Karnataka. Further, it establishes that these risks are determined not only by geographical and climatological factors but the vulnerability of the power plants as well.

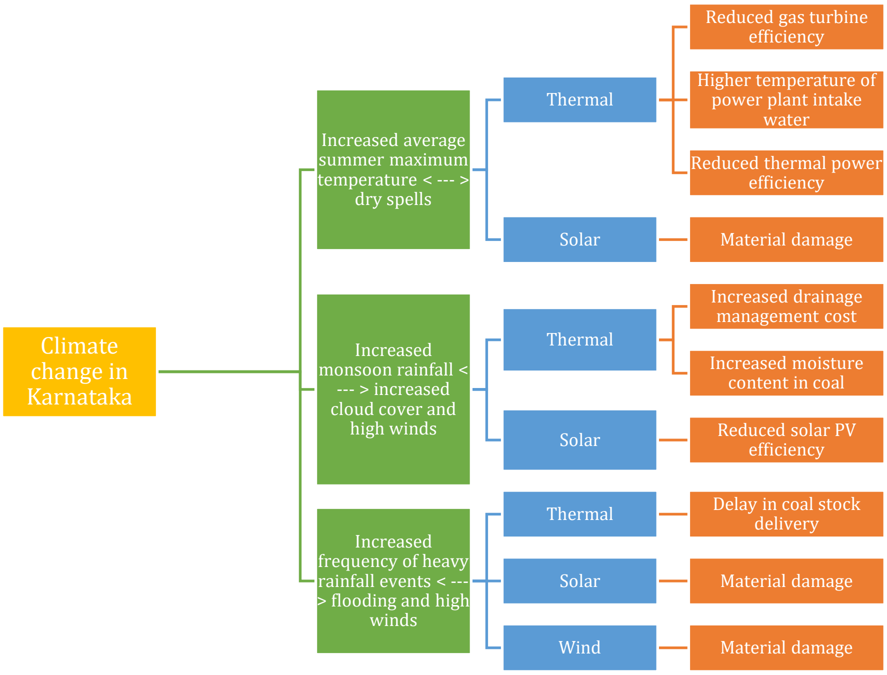
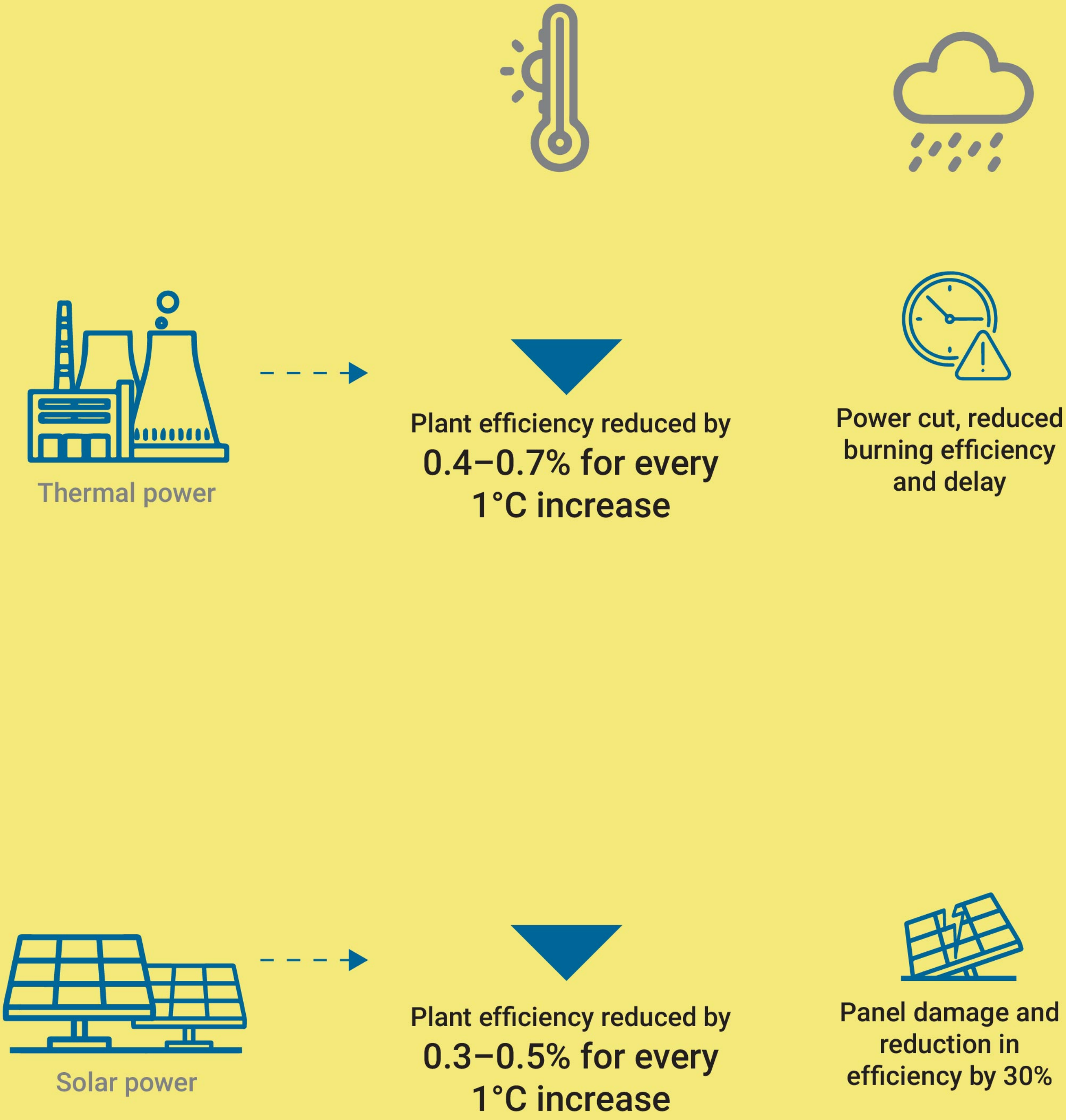


Figure 18: Overview of the potential direct and indirect impacts of climate change on power infrastructure



Thermal power

Plant efficiency reduced by
0.4–0.7% for every 1°C increase

Power cut, reduced burning efficiency and delay

Solar power

Plant efficiency reduced by
0.3–0.5% for every 1°C increase

Panel damage and reduction in efficiency by 30%

6. Implications of Climate Risks to Power Infrastructure in Karnataka

This section presents an assessment of climate change risks to power infrastructure assets in districts that account for 50% or more of the total installed capacity in the respective power segment. The assessment is based on spatial climate hazard mapping and review of studies on power infrastructure–climate interactions.

6.1. Thermal Power

Raichur, Bellary, Bijapur, and Udupi power plants account for 96.25% of the total installed capacity in Karnataka.

6.1.1. Implications of Increase in Maximum Temperature

The summer maximum temperature ranged from 32°C in Udupi to 38°C in Bellary, Raichur, and Bijapur during the historical period (Figure 13). During the projected period, the summer maximum temperature in Raichur is expected to rise to as high as 42°C, and in Bijapur and Bellary to 40°C (Figure 13). This is an increase of 2.4°C in Raichur, 2.2°C in Bijapur, 1.9°C in Bellary during the 2030s. The rise in temperature has implications for air and water temperature, and availability of water as temperature increase and droughts usually coincide.

- The increase in temperature of the heat sink (air or water) reduces the thermal efficiency of power plants by approximately 0.4–0.7% for every 1°C rise in temperature—hot temperature exacerbates the impact of average warm conditions, resulting in less energy conversion and decreased cooling efficiency (Ibrahim et al. 2014; Linnerud et al. 2011).
- Shortages in water supply required for cooling could force power stations to reduce load or even shutdown under extreme shortages. In 2016–2017, 13 coal-based thermal power facilities in India faced loss of power generation due to raw water problems[10], including those in Bellary and Raichur, with a reported loss in generation of 7,151.51 MU (at 80% PLF). The associated costs of disruptions to the power grid are likely to rise as temperatures increase (Fant et al., 2020).

Among the existing power plants, the ones in Raichur and Bijapur, accounting for 58% of the installed thermal capacity, are most at risk with a projected >2°C rise in maximum

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[10] https://www.manthan-india.org/wp-content/uploads/2017/05/Report-raw-water-problem-18-May-17.pdf

temperature. However, the Raichur thermal plant will reach end-of-life by 2022, in accordance with the 2018 plan.

Transmission infrastructure, too, works less efficiently during periods of high temperature because of the additional resistance induced, increased conductor sag, and lowered ground clearances, impacting the maximum current allowed at a given temperature[11].

6.1.2. Implications of Increase in Monsoon Rainfall and Heavy Rainfall Events

The overall summer monsoon rainfall is projected to increase by 22% in Bijapur, 19% in Udupi, 13% in Bellary, and 12% in Raichur. Additionally, an increase in the frequency of both high-intensity (51–100 mm/day) and very-high-intensity (>100 mm/day) rainfall events is projected in these districts.

The frequency of high-intensity rainfall events is projected to increase the most in the coastal high-rainfall district of Udupi—by six events (Figure 14). In Bellary and Raichur, high-intensity rainfall events are projected to double and treble, respectively; in Bijapur, where no such events have been recorded in the past 30 years, two events per annum are projected. Likewise, one to two very-high-intensity rainfall events per annum are projected in Bellary, Bijapur, and Raichur, with no historical occurrence of such an event (Figure 14). The implications of an increase in rainfall and heavy rainfall events on thermal power infrastructure is more on transmission than generation and on the asset itself, unless located in a low-lying area. The risks include

- Potential flooding with projected increase in the magnitude of rainfall and heavy rainfall events, impacting power transmission as tree branches along transmission lines can cause short circuits, triggering the protection system to cut off power.
- Increase in the moisture content of coal, resulting in reduced burning efficiency, and reduced power output.
- Delay in coal supply as thermal power plants in Karnataka rely on out-of-state coal delivered through railway lines that could be flooded, hampering transport and thereby impacting production.

6.2. Solar Power

Solar power plants have been commissioned or are approved in Karnataka in all the districts, except Kodagu and Bengaluru Rural. We analyse climate change and its

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[11] https://powergridindia.com/sites/default/files/footer/climate_change/Building_Climate_change_Resilience_for_Electricity_Infrastructure.pdf

implications for eight districts that account for 65% of the commissioned and approved plants to be built.

6.2.1. Implication of Increase in Maximum Temperature

The summer maximum temperature is projected to increase during the 2030s in all the eight districts considered for this analysis (Figure 15). More than 2°C increase is projected in Bagalkot, Gulbarga, and Raichur, with temperatures projected to cross 40°C during summer in Raichur and Gulbarga. In the remaining districts, a 1.8°C increase is projected, except in Bellary where a 1.7°C increase is projected.

Considering 35°C as the optimum temperature for solar PV efficiency, we found that in the projected period, the maximum temperature will be higher than 35°C in various districts for the following number of days: 162 days in Gulbarga; 110–120 days in Gadag, Bagalkot, Bellary, Koppal, and Raichur; 89 days in Chitradurga; and 62 days in Tumkur (Figure 19).

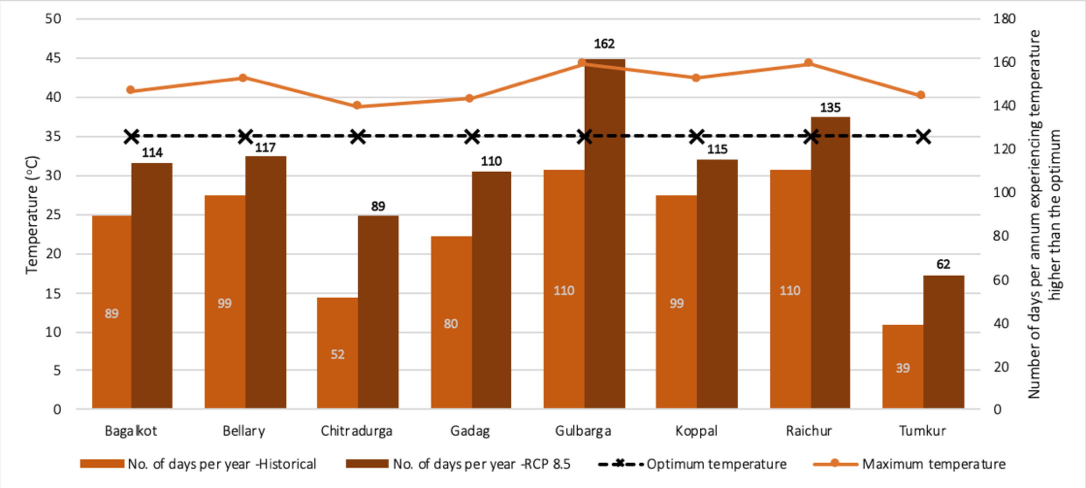

Figure 19: Optimum temperature for solar efficiency and temperature higher than the optimum during the projected period and number of days per annum

The implications of increase in the summer maximum temperature and in the number of days with maximum temperature higher than the optimum required for solar PV efficiency include

- Reduction in the efficiency of solar panels (Pasicko et al., 2012), as it reduces the conversion performance of PV modules (Vick and Clark, 2005), thin film modules (Mohring et al., 2004), and other types of modules (Makrides et al., 2009). However, the efficiency of solar heating increases. The efficiency loss beyond the optimum temperature is estimated to be 0.3–0.5% per 1°C temperature increase (Patt et al., 2013; Skoplaki and Palyvos, 2009).
- Material damage to PV panels and reduction in power generation (IAEA, 2019).

6.2.2. Implications of Increase in Monsoon Rainfall and Heavy Rainfall Events

The summer monsoon rainfall is projected to increase by 13% in Gadag; 14% in Raichur and Chitradurga; 15–20% in Bellary, Koppal, and Tumkur; 21% in Bagalkot; and 23% in Gulbarga. Additionally, an increase in the frequency of high-intensity (51–100 mm/day) rainfall events (doubling and trebling) is projected, with such an event not recorded during the historical period in Bagalkot and Chitradurga (Figure 15). Very-high-intensity (>100 mm/day) rainfall events, which have never been recorded during the historical period, are projected for all the districts—one event per annum in Bagalkot, Chitradurga, Gadag, and Tumkur, and two events per annum in Bellary, Gulbarga, Koppal, and Raichur (Figure 15).

The implications of increase in monsoon rainfall and the number of heavy rainfall events for solar power infrastructure are both direct and indirect. They include

- Damage of solar panels because of heavy rainfall, as witnessed in July 2019 in Madhya Pradesh when a 250 MW solar PV project was significantly damaged by monsoon and severe weather[12].
- A 30% reduction in the efficiency of solar panels in case of dark rain clouds before the onset of heavy rainfall events or during the event, as changes in insolation and cloudiness reduce the output of solar PV plants (Vick and Clark (2005). In the first half of 2019,[13] rainfall in India was unpredictable and solar radiation was lower by 4–6% than average, hurting power generation.

6.3. Wind Power

Wind power plants are located in 18 of the 30 districts of Karnataka, with 21% of the installed wind power in Bijapur, followed by Gadag, Chitradurga, Belgaum, and Davanagere. Wind power generation is sensitive to changes in mean wind speed. Wind hazards have not been assessed in this study. However, heavy rainfall events are typically accompanied by high wind speeds, and such heavy rainfall events are projected to increase in the case-study districts in the projected period (Figure 16).

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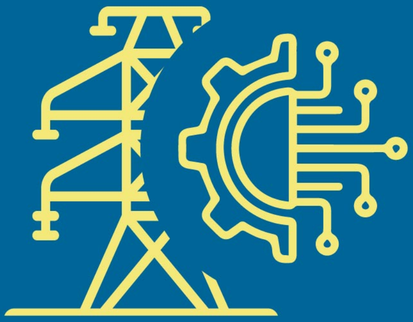
[12] https://mercomindia.com/monsoon-solar-project-damaged-rewa/

[13] https://economictimes.indiatimes.com/industry/energy/power/freak-weather-events-pose-new-risk-to-indias-renewables-goals/articleshow/70255386.cms?from=mdr

6.3.1. Implications of Increase in Monsoon Rainfall and Heavy Rainfall Events

Increase in rainfall and its intensity is likely to cause structural or superficial damage to wind turbines. Lightning strikes associated with these events can damage blades by direct strikes and connected devices by indirect strikes. Further, heavy rains could cause surface flooding or erosion that may affect the foundation. Additionally, they could affect access to wind farms and the electrical infrastructure required for export of electricity.

Thus, power infrastructure in Karnataka will have to adapt, manage, and respond to both long-term mean changes in climate and extreme events, based on the type of the power infrastructure segment, its location, its vulnerability, and the extent of projected climate change.



Technological

Planning

Policy

Recommendations

7. Adaptation Strategies for Building Resilience in Power Infrastructure

Climate resilience is the ability to anticipate, absorb, accommodate, and recover from the effects of a potentially hazardous event. The benefits of resilient power infrastructure are much greater than the costs, considering the growing impacts of climate change. It is estimated that for every dollar invested in climate-resilient infrastructure, six dollars can be saved[14]. According to the World Bank (Nicolas et al., 2019), if the actions needed for resilience are delayed by ten years, the cost will almost double.

Improving the robustness of all power infrastructure is desirable, but costly. Therefore, targeting resilience building in infrastructure with likely high exposure to climate hazards is the way forward. Resilience could be built in existing infrastructure by tweaking the design, operation, and maintenance. However, for new infrastructure, revised planning criteria and methodology to include resilience in design as well as siting of the asset are recommended. This requires data on the probability and spatial distribution of climate hazards, as well as their potential evolution due to climate change—to help identify the type of hazard that most threatens a power infrastructure, as done in this study. Similar assessment of hazards, vulnerabilities, and susceptible exposed elements at the local level has been done by Peru's Disaster Management Centre. In the United Kingdom, once during every Parliament's tenure, a National Infrastructure Assessment[15] is conducted for assessing and outlining long-term needs for resilience building in existing and proposed infrastructure.

Once the spatial mapping of climate hazards and risks is done, adaptation strategies need to be formulated. Adaptation strategies could be categorised into three broad categories: (i) technological, which promote better design, improved standards, and deployment of new technologies, (ii) planning related, which include decisions on investments in climate-related information or siting of assets, and (iii) policy related, which span adoption and/or promotion of policy frameworks, incentive mechanisms, diversification of the energy mix, and development of insurance mechanisms.

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[14] https://www.un.org/press/en/2019/sgsm19807.doc.htm

[15] https://www.apm.org.uk/media/18686/national-infrastructure-briefing-lr-pages.pdf

7.1. Technological

Advance warning to climate hazards can help avoid damage and loss, particularly in high-risk areas. Examples of such systems are in place in Argentina where the government-developed website SIMARCC provides climate risk maps under different scenarios, to help plan better for and reduce climate vulnerabilities. Other technological interventions include

7.1.1 Adjustment of Design Criteria in High-Risk Areas

Increasing transmission tower height, burying distribution lines, using stainless steel to reduce corrosion from water, using lightning arrestors to protect equipment, and replacing conventional transformers with energy-efficient amorphous-core transformers in areas projected to experience heavy rainfall events and flooding are some such strategies.

- Technological interventions such as hardening of transmission and distribution infrastructure in New Zealand and grid upgradation in Tonga have demonstrated the potential to reduce damage and losses. Estimates show that the $6 million spent in New Zealand[16] to harden transmission and distribution infrastructure resulted in $30–50 million reduction in direct asset replacement costs. Similarly, in Tonga[17], which is highly exposed to cyclones, grid upgradation brought down the damage to 4.7%, compared to 45.9% damage in portions that were not upgraded.

7.1.2 Alternate Cooling Systems

Strategies adopted by thermal power plants to improve a plant's performance during high-temperature periods and droughts include replacing the water cooling system with air cooling, dry cooling, or a recirculating system (PGCIL, 2015).

7.1.3 Early Warning Systems and Communication

Robust communication facilities to alert, monitor, and control, and early warning system alarms are some technological interventions that can help cope with extreme events.

7.2. Planning

Climate risks will likely incur costs over the lifetime of assets as power infrastructure assets are designed for long timescales; moreover, they are designed by typically assuming a future

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[16] https://openknowledge.worldbank.org/bitstream/handle/10986/31910/Stronger-Power-Improving-Power-Sector-Resilience-to-Natural-Hazards.pdf?sequence=1&isAllowed=y

[17] https://openknowledge.worldbank.org/bitstream/handle/10986/31910/Stronger-Power-Improving-Power-Sector-Resilience-to-Natural-Hazards.pdf?sequence=1&isAllowed=y

climate that is much the same as the current climate. With the existing grid infrastructure likely to be upgraded, an understanding of the extent of climate risks is critical for devising plans to mitigate these risks.

7.2.1 Climate Hazards and Risk Mapping

The first step in planning for climate risk mitigation is the mapping of climate hazards.

A vulnerability atlas for India (BMTPC, 2019) mapping hazards such as earthquakes, floods, and cyclone in the country has already been developed on the basis of historical data. However, a district-level spatial climate risk analysis, as has been presented here, that maps future climate hazards and risks provides an understanding of variabilities in projected climate parameters such as temperature, rainfall, and extreme events—a must for planning and formulating strategies.

In this study, the district-level climate risk analysis for power infrastructure in Karnataka overlays the locations of solar and wind power plants on temperature and rainfall projections. This district-level climate hazard map could serve as a ready reckoner for infrastructure commissioning in various districts. For example, a two-stage stochastic planning model was adopted to analyse the impact of climate risks on a power system expansion plan in Bangladesh. In New Zealand, the Orion Electric Company, through appropriate planning and design, achieved quicker power restoration after the Christchurch earthquake.

Such planning can guide the formulation of strategies for exposure reduction, including locating generation and transmission facilities in areas which are less susceptible to floods and high wind speeds, and investing in infrastructure that prevents flooding of distribution assets.

7.2.2 Increased Share of Renewable Energy Sources

Informed planning for increased penetration of renewable energy sources and flexibility in the grid to cater to changing patterns and nature of power demand are other strategies that can help build climate resilience for electricity infrastructure.

7.3 Policy

Currently, there are no policies at the central or state level for mainstreaming climate resilience in infrastructure planning and investment. To rectify this, first, a set of criteria needs to be developed for integrating climate resilience into the full range of infrastructure decision-making—investment, project design, and development. This criteria identification could then lead to policies that mandate the following for all infrastructure projects and investment decisions.

7.3.1 Inform Decisions with Climate Projections

Using the best available data on climate risks better informs the various project stages—design to construction and long-term maintenance. Projected increases in mean and maximum temperatures, rainfall, and heavy rainfall events are likely to affect design decisions for infrastructure—from selection of construction materials that can withstand high temperatures to inclusion of flood water management features and designs to cope with flooding. Climate projections also help assess the vulnerability of existing projects as well as those in the design phase, and help identify strategies for improving resilience.

7.3.2 Transparency in Data and Decisions on Climate Risks

For power infrastructure projects to qualify for investment, pertinent details on the methodology used for risk and vulnerability assessment that led to decisions on design, construction, and maintenance should be made public, including the climate data used. Additionally, making climate data available in a form that aids decision-making to assist public and private entities undertaking climate resilience planning will promote collaboration among different stakeholders.

7.3.3 Prioritise Projects with Flexible and Adaptable Designs

To avoid under- or over-investing in resilience building, it is imperative to prioritise infrastructure projects and designs that offer some level of flexibility and adaptability with respect to future climate conditions.

7.3.4 Plan for Operations, Maintenance, and Repair to Maintain Resilience

Many of the climate vulnerabilities faced are exacerbated by neglected infrastructure maintenance. Therefore, adequate allocation of funds that allow regular repair and maintenance to reduce vulnerabilities, and upgradation of existing systems considering climate risks are essential.

7.4 Recommendations for Building Power Infrastructure Resilience in Karnataka

The climate risk analysis presented in Section 5 and the implications of these risks on the different power infrastructure segments clearly highlight the need for building power infrastructure resilience in Karnataka. Karnataka can be a pioneer if the Government of Karnataka formulates and implements the following measures to build resilience in existing and proposed power infrastructure.

7.4.1 Climate-proofing Existing Infrastructure

1. Develop a Resilience Index with a Minimum Acceptable Standard. This index is to be developed considering climate change projections, infrastructure location, design, and past data on infrastructure performance under extreme climate conditions such as a heat wave or a heavy rainfall event.
2. Periodically survey and review power infrastructure based on the Resilience Index, particularly during years recording increase in temperature, increase or decrease in rainfall, and extreme events.
3. Create a compendium of climate-proofing strategies for different categories of power infrastructure to help climate-proof those infrastructure segments that do not meet the Minimum Acceptable Standard.
4. Draft a Retrofit Code and impose legal liability on infrastructure that do not conform to the Minimum Acceptable Standard.
5. Adopt green infrastructure where retrofitting is counterproductive, in pursuance of a hybrid approach incorporating grey and green infrastructure models.

7.4.2 Adaptation Strategies for Proposed Power Infrastructure

1. Develop a comprehensive data collection, integration, and dissemination network with existing resources to address information paucity and aid planning.
2. Introduce climate insurance, incentivising pooling of resources and funding much-needed innovation and risk-assessment tools.
3. Establish a technological consortium to promote innovation, research, and development of technologies to achieve climate resilience.
4. Harmoniously construe existing legislations to build climate-resilient infrastructure in coastal regions, and adopt a hybrid approach in high-risk non-coastal regions.

Development of all-encompassing technological, planning, and design measures is needed for increasing the awareness and capacity of utilities to identify short- and long-term climate risks and vulnerabilities in systems; for understanding how climate risks impact different points along the power system chain, and for identifying mechanisms to minimise the risks of climate change.

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