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# Risk Analysis of Existing Hydropower Based on Future Climate Change Scenario

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Abstract. Climate change has interrupted the global hydrological cycle affecting water resource management and hydropower production. This study conducts a quantitative risk analysis of the Modi Khola Hydroelectric Power Plant. The study analyzes risks on existing hydropower potential for the duration of 2026 to 2100 due to climate change. From eight selected coupled model inter comparison project phase 6 global climate models representing four extreme climate corners, under moderate Shared Socioeconomic Pathways (SSP) 2-4.5 and high emission SSP 5-8.5 scenarios by using advanced envelope method, future streamflow projections at the dam site were adapted. The baseline energy potential of 92.50 GWh and 81 GWh were utilized to identify the energy production risk. Energy generation, compared with 92.50 GWh, shows declines by 0.41% to 16.16%, except NESM3 increases from 5.57% to 7.73% and with 81 GWh baselines, improves from -4.26% to 23.03%. The risk rises with higher energy production, particularly under SSP 5-8.5 however, SSP 2-4.5 consistently reveals lower risk for the tenure. The greatest significant risks are seen during the near future then slightly declines by the mid and far future. The quantitative risk analysis shows that at 81 GWh production target, failure risk ranges from 6% to 38% across scenarios. At 92.50 GWh target, risk increased drastically to 53% to 86%. The 81 GWh level generally represents moderate to significant risk, whereas 92.50 GWh target represents the significant risk category across all future periods and models.

**Keywords:** Climate Change, Modi River Basin, Hydropower Production, Risk Analysis.

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# 1. INTRODUCTION

Climate change has been promoted by human activity, which has affected water resource management worldwide and caused disruptions in the hydrological cycle. Climate change has increased glacier melting and altered climatic indices including temperature and precipitation [1, 2]. As an outcome, there are frequent and severe water-related incidents that alter the seasonal flow of rivers and have an impact on hydropower [3, 4]. The temporal and spatial distributions of water availability are changed by the variations in precipitation patterns making it challenging to manage reservoir operations due to the need to balance competing objectives [1].

The United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as any change in the climate that is directly or indirectly caused by human activities that alter the structure of the global atmosphere over comparable time periods [5]. Due to rapid industrialization, economic and population growth, the use of fossil fuels and natural resources has been increased which results greenhouse gas emissions and raised global temperatures [2, 6]. The IPCC AR6 reports that the Earth's surface temperature has risen by 1.1°C during the 1850–1900 baseline for the period of 2011–2020, with projections indicating an increase of 2.7 °C to 4.4 °C by 2100 under the Shared Socioeconomic Pathways (SSP) 2-4.5 and 5-8.5 scenarios, respectively [7]. In response to this challenge, several governments have reduced fossil fuel consumption and shifted towards greener energy sources and advances in technology [8, 9].

Hydropower is one of the suitable alternatives due to its renewable, efficient, and dependable nature, marked by zero carbon emissions and minimal operational and maintenance expenses [10, 11]. Major processes is the global water cycle, such as precipitation and evaporation are significantly influenced by climate change, which has an influence on hydropower generation by affecting the distribution of water resources and river water availability [2, 12]. Due to its dependency on local weather and temperature, hydropower is particularly vulnerable to climate change [13]. Numerous investigations on this subject have been carried out worldwide to find out how climate change affects hydropower potential [6] in the Nanliujiang River Basin in China, [14] in the Zambezi River Basin in Southern Africa, and [9] in Lithuania.

Nepal has great potential for producing hydropower. With elevations ranging from 60 to 8,849 MSL in a narrow north-south extension of 145 and 248 km, the nation's varied topography offers steep topographic gradients that are favorable for hydropower production [15]. Hydropower holds considerable potential because of topographic variety, terrain, and plentiful water supplies [16]. Nepal discharge 222 billion $m^3/s$ (approximately) of water into the ocean from 6000 rivers and rivulets [17]. Nepal has an estimated 83,000 MW of hydropower potential, of which 42,000 MW are both financially and technically viable for hydropower production [18]. Research by the Water and Energy Commission Secretariat, 2019 shows that there is 72,500 MW gross hydropower potential and a 32,700 MW techno-economic potential [19]. Despite this huge potential, hydropower output in fiscal year 2024/2025 will be 3,591 MW, or around 8.55 % of the economically achievable capacity compared to the peak demand of 2.901 MW [20]. Due to the variations in precipitation and the dynamics of glacier melt, Nepal's hydropower projects are extremely sensitive to climate change [21]. There is an information gap since there aren't enough research on how climate change affects the hydropower industry in Nepal [22]. There is difficulty in setting up and maintaining weather stations due to rugged terrain, which results in data gaps and dubious evaluations [23]. Various studies on risk analysis in construction projects have been carried out, but very few studies have concentrated on the risks due to climate change on renewable energy projects like hydropower plants. By using climate change scenarios [24] conducted a risk assessment of the storage type of a hydropower plant. In their study, risk analysis was carried out by calculating the percentage of failure of energy production and volume of storage. Failure was considered to have occurred when the monthly volume or the energy production was less than expected or less than the minimum guaranteed energy production [24].

This kind of analysis will provide the response of the energy generation of existing hydropower to climate change under extreme conditions. The main objective of this study is to conduct a detailed risk analysis of the Modi Hydroelectric Power Plant, 14.8 MW, based on future climate change scenarios with comparison to the observed real energy generation by the hydropower and analysis of a range of possible future climate scenario patterns from 2026 to 2100 as the Near Future (NF), Mid Future (MF), and Far Future (FF). From eight selected Coupled Model Inter Comparison Project Phase 6 (CMIP6) Global Climate Models (GCM) representing four extreme climate corners: Warm-Wet (WW), Warm-Dry (WD), Cold-Wet (CW) and Cold-Dry (CD) under moderate SSP 2-4.5 and high emission SSP 5-8.5 scenarios by using advanced envelope method, future discharge data at dam site of Modi basin required for the study in future climate scenario at near future, mid future, and far future are adapted from the literature "Selection of CMIP6 climate models and future climatic projection in the Gandaki River Basin, Nepal" [25].

## 2. Study Area

The Modi Khola Hydroelectric Power Plant (MKHPP) is situated in the Parbat District of Nepal's Gandaki Province. Figure 1, the project area's geographic coordinates are between latitudes 28°12'0" N and 28°39'0" N, and longitudes 83°33'0" E and 84°0'0" E. The Modi River, which flows from north to south-west, is one of the main tributaries of the Kali Gandaki River. It originates from the south-western slope of Annapurna range (8039 m). Since the river originates from the snow-capped Annapurna range, it exhibits a perennial flow regime, supported by snowmelt during the dry season.

The Modi River meets the Kali Gandaki River at Modi Beni, Kusma. The river's maximum length up to the intake is roughly eighteen kilometers, with a catchment width ranging from 8.3 km to 12 km and a total catchment area of 503 square kilometer. The river flows through steep, narrow gorges and rugged terrain, creating a high topographic gradient ideal for power generation.

The study area lies within a humid subtropical climate zone, experiencing significant variations in rainfall. Descending from high-altitude glacial melts, the river maintains a robust discharge even during the pre-monsoon months, which is vital for the stability of the local power supply. This consistent flow has allowed the basin to host a dense cluster of hydroelectric projects, turning the Parbat district into a significant energy contributor.

## 3. Methodology

This study was performed to evaluate the impact of future climate change on the energy generation of the existing 14.8 MW MKHPP which is in the Parbat District, Gandaki Province, Nepal.

The core hydrological data for this analysis, specifically the future stream flow projections at the dam site, were adapted from the peer reviewed literature "Selection of CMIP6 climate models and future climatic projection in the Gandaki River Basin, Nepal" by [25]. This source study employed the Soil and Water Assessment Tool (SWAT) hydrological model to simulate stream flow for a historical baseline period (1996–2025) and for future projections extending to 2100. To capture a wide range of climate uncertainty, the analysis utilized eight selected GCMs from the CMIP6, representing four extreme climate corners: WW, WD, CD, and CW by using advance envelope methods. To represent different potential future trajectories of greenhouse gas concentrations, these projections were evaluated under two SSP, the moderate SSP 2-4.5 and the high-emission SSP 5-8.5. The future timeline was divided into three distinct periods for analysis: the NF (2026–2050), the MF (2051–2075), and the FF (2076–2100). This study calculates the corresponding annual potential and compared these potentials against the baseline energy outputs of 81 GWh and 92.5 GWh. Finally, the quantitative risk analysis determines the probability of the plant failing to meet various energy production targets under each climate scenario.

3.1. **Impact of climate change on energy generation of MKHPP.** The Modi Khola Hydroelectric power plant (MKHPP) is a peaking run-of-river type of hydropower plant. Energy production during dry and wet periods depends upon the availability of water in the river. A SWAT model was used to simulate the stream flow for the year 1996 to 2025 to examine the impact of climate change on future energy generations. The stream flow of Modi Khola obtained from the SWAT model was used as the baseline to analyze the impact of future changes in energy generation obtained after bias correction of GCMs data for precipitation and temperature. The

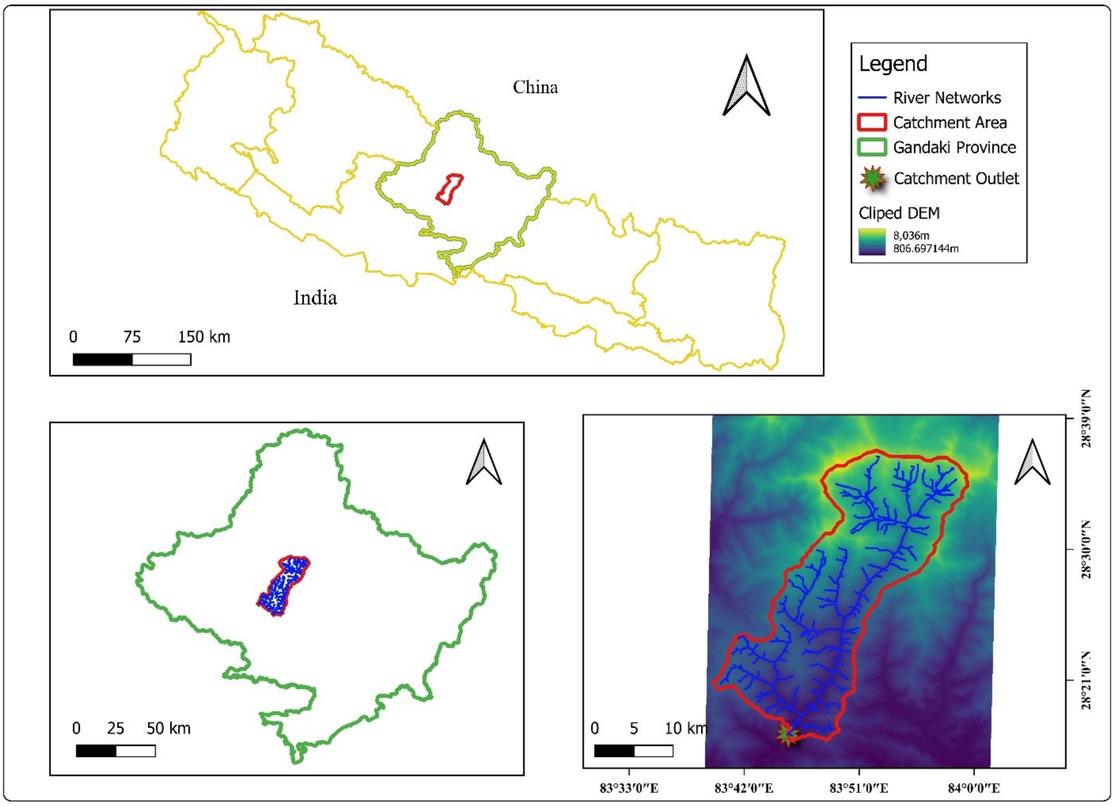


FIGURE 1. Study Area Map

TABLE 1. Selected Scenario, GCMs and climatic corner for study [25]

| **Scenario** | **GCMs** | **Climatic Corner** |
|---|---|---|
| SSP 2-4.5 | GFDL_CM4 | WW |
| SSP 2-4.5 | NESM3_SSP | WD |
| SSP 2-4.5 | GFDL_ESM4 | CD |
| SSP 2-4.5 | INM-CM4-8 | CW |
| SSP 5-8.5 | EC-Earth3 | WW |
| SSP 5-8.5 | EC_Earth_Veg_LR | WD |
| SSP 5-8.5 | GFDL_ESM4 | CD |
| SSP 5-8.5 | MRI_ESM2_0 | CW |

impact of climate change on power generation was analyzed for three future time horizons namely NF, MF, and FF.
Hydroelectric power is calculated using the following equation:

$$P = \eta\gamma QH \tag{1}$$

Where $\eta$ is the dimensionless efficiency of a turbine, $\gamma$ is the specific weight of water, $Q$ is the flow in cubic meters per second, and $H$ is the net head equals to 66.96 meters for MKHPP. Annual Energy production in MW h can be calculated using relation

$$\text{Annual Energy (KWh)} = \text{Power} \times \text{hours in a day} \times \text{day in a year} \tag{1}$$

3.2. **Risk Analysis.** Risk analysis was carried out by varying annual hydroelectric energy generation (E) within a specified range. The annual energy generation was chosen to vary between the

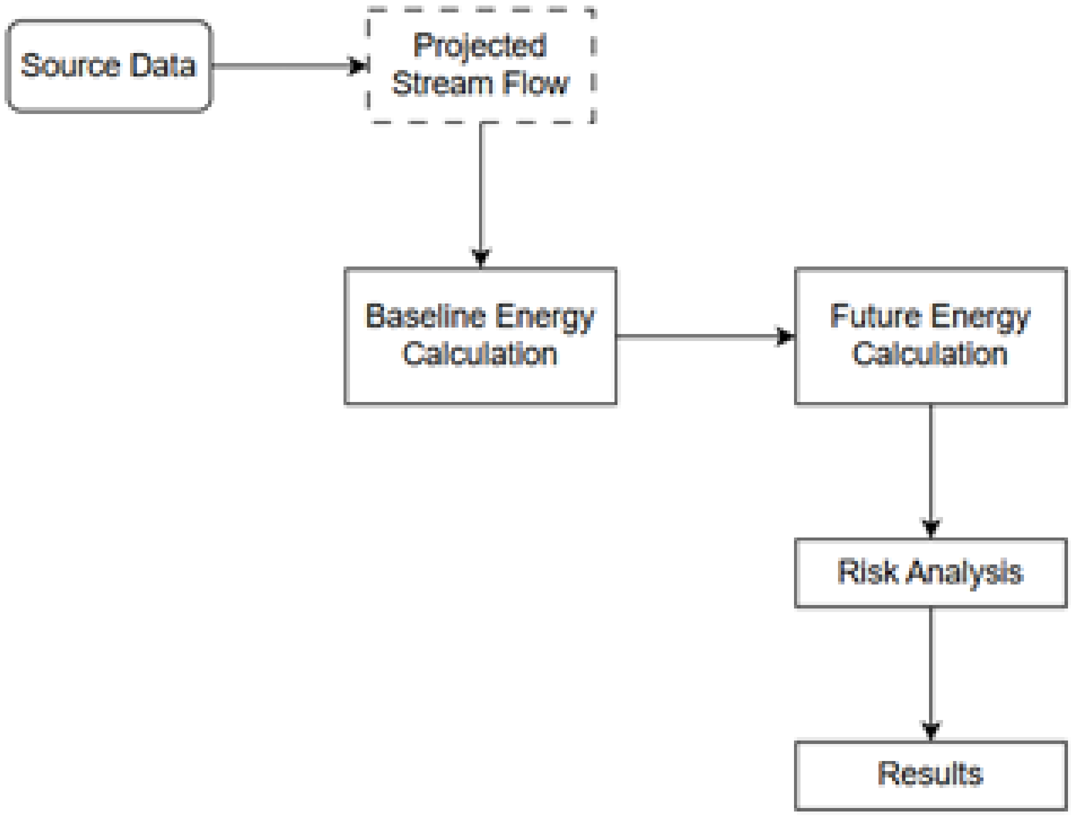


FIGURE 2. Methodology Flowchart

minimum assured energy production of 5 GWh which is obtained from minimum river discharge of 12.18 $m^3/s$ to 81.00 GWh, obtained at the mean average annual river discharge of 56.21 $m^3/s$. Risk analysis was carried out for projections of future climate as per the eight GCMs as mentioned earlier: each under SSP 2-4.5 and SSP 5-8.5 scenarios from the CMIP6.
The failure or risk value for each scenario were computed by using the relative percentile of the frequency of monthly failures within the series. When the monthly energy E does not adhere to the limitations specified in equation (2), a risk considers having occurred. For each GCMs and the time periods for the SSP 4-2.5 and SSP 5-8.5 scenarios, the risk related to the specified E was computed. The energy $E_t$ produced in the month t must exceed the designed value in order for there to be no danger [24].

$$E_t \geq b_t E \tag{2}$$

where $E$ is the annual energy production (GWh), $E_t$ is the energy (GWh) produced during month $t$ and $b_t$ is the monthly distribution coefficient of the designed annual energy production. The monthly distribution coefficient was calculated based on the mean value of energy production during the design period. In all three future time horizons NF (2025–2050), MF (2051–2075), and FF (2075–2100), the risk analysis was carried out for primary energy targets ranging from 5 to 80 units at an interval of 5 units (16 energy levels). For each target level, the risk of failure was computed as the percentage of time that the simulated generation did not meet the corresponding primary energy requirement.

## 4. Results

4.1. **Energy Generation Analysis.** The river discharge is expected to oscillate over time due to changes in temperature and precipitation, which will also have an impact on hydropower potential. The discharge at the intake of hydropower acquired from the SWAT model has been found to be 56.21 $m^3/s$. For the historical baseline period (1996–2020). With a mean stream flow of 56.21 $m^3/s$, the projected historical energy production was found to be 81.00 GWh only. However, the designed annual energy generation capacity of MKHPP is 92.5 GWh. Hence, 81.00 GWh and 92.5 GWh are used as baseline energy for the analysis.

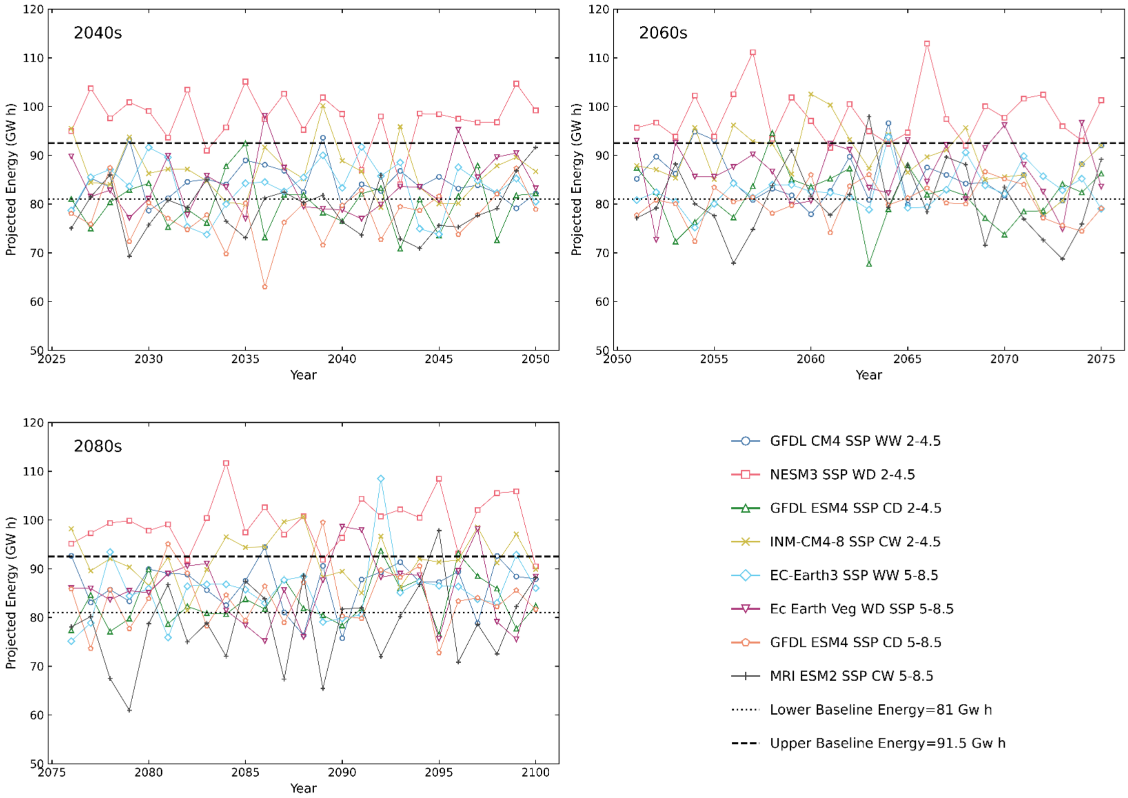


FIGURE 3. Projected annual energy generation for MKHPP using eight GCMs outputs for near, mid, and far future under two socioeconomic pathways.

The near future projected energy chart, covering 2026–2050, and shows moderate oscillations with most models ranging between 75 and 95 GWh. The NESM3 model performs reliably highest, often exceeding the 92 GWh baseline and reaching 105 GWh. Most projections oscillate around the central 81 GWh baseline, indicating general stability. However, GFDL_ESM4 stands out as an outlier, dropping sharply to about 63 GWh in 2036. Overall, the NF outlook indicates relative stability with occasional short-term deficits in specific models.

The mid future projected energy (2051–2075) chart shows the greatest variations among the three periods. NESM3 dominates the projections, peaking at approximately 113 GWh in 2066 and remaining mostly above 92.50 GWh. In contrast, MRI_ESM2 records sharp declines to 68 GWh in 2056 and 2073. GFDL_ESM4 also shows a substantial decline near 67.50 GWh in 2063, while Ec_Earth_Veg rebounds strongly to nearly 97 GWh by 2074. This period is characterized by sharp peaks and drops, reflecting high uncertainty in mid-century projections.

The far future projected energy (2076–2100) chart presents the most inconsistent behavior with extreme highs and lows. NESM3 remains the strongest performer, reaching about 111 GWh in 2084. However, MRI_ESM2 drops dramatically to the lowest observed value of 60 GWh during

2079. EC-Earth3 shows large variability, surging to nearly 108 GWh in 2092 after a stagnant phase. Overall, the FF scenario suggests increased unpredictability with sudden spikes and significant declines in projected energy output.

TABLE 2. Comparison of future projected energy generation relative to the baseline energy production of 92.50 GWh for different GCMs.

| Scenario | GCMs | Climate Corner | Baseline Energy (GW h) | Energy Generated (GW h) | | | Percentage Difference | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 2040 | 2060 | 2080 | 2040 | 2060 | 2080 |
| SSP 2-4.5 | GFDL_CM4 | WW | | 84.24 | 85.39 | 86.65 | -8.93 | -7.69 | -6.33 |
| | NESM3 | WD | | 97.65 | 98.26 | 99.65 | 5.57 | 6.22 | 7.73 |
| | GFDL_ESM4 | CD | | 80.08 | 81.49 | 83.14 | -13.42 | -11.90 | -10.12 |
| | INM-CM4-8 | CW | | 86.82 | 89.75 | 92.12 | -6.14 | -2.98 | -0.41 |
| | | | 92.5 | | | | | | |
| SSP 5-8.5 | EC-Earth3 | WW | | 83.60 | 82.86 | 85.47 | -9.62 | -10.42 | -7.60 |
| | Ec Earth Veg | WD | | 83.91 | 86.70 | 85.99 | -9.29 | -6.27 | -7.04 |
| | GFDL_ESM4 | CD | | 77.55 | 80.40 | 84.12 | -16.16 | -13.08 | -9.06 |
| | MRI ESM2 0 | CW | | 78.92 | 80.81 | 78.52 | -14.68 | -12.64 | -15.11 |

Table 2 illustrates projected changes in energy output relative to the baseline production of 92.5 GWh for different GCMs under SSP 2-4.5 and SSP 5-8.5 scenarios. Under SSP 2-4.5, most models indicate a reduction in future energy generation compared to the baseline. GFDL_CM4 projects decrease of 8.93%, 7.69%, and 6.33% for 2040, 2060, and 2080, respectively. GFDL_ESM4 under cold-dry conditions shows even larger declines, ranging from 13.42% in 2040 to 10.12% in 2080. INM-CM4-8 under cold-wet conditions indicates moderate reductions initially, improving to near-baseline levels (-0.41%) by 2080. In contrast, NESM3 under warm-dry conditions is the only model projecting consistent increases, with gains of 5.57%, 6.22%, and 7.73% across the three future periods.
Under SSP 5-8.5, all models project reductions in energy production. EC-Earth3 shows declines between 7.60% and 10.42% over the projection years. Ec_Earth_Veg_LR also indicates steady negative changes, though slightly less severe in 2060. GFDL_ESM4 projects substantial reductions, reaching a maximum decline of 16.16% in 2040. The largest decrease overall is projected by MRI_ESM2_0, with reductions ranging from 12.64% to 15.11%. Overall, the high-emission SSP 5-8.5 scenario results in more pronounced and widespread declines compared to SSP 2-4.5.

TABLE 3. Comparison of future projected energy generation relative to the baseline energy production of 81.00 GWh for different GCMs.

| Scenario | GCMs | Climate Corner | Baseline Energy (GW h) | Energy Generated (GW h) | | | Percentage Difference | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 2040 | 2060 | 2080 | 2040 | 2060 | 2080 |
| SSP 2-4.5 | GFDL_CM4 | WW | | 84.24 | 85.39 | 86.65 | 4.00 | 5.42 | 6.97 |
| | NESM3 | WD | | 97.65 | 98.26 | 99.65 | 20.56 | 21.31 | 23.03 |
| | GFDL_ESM4 | CD | | 80.08 | 81.49 | 83.14 | -1.13 | 0.61 | 2.64 |
| | INM-CM4-8 | CW | | 86.82 | 89.75 | 92.12 | 7.19 | 10.80 | 13.73 |
| | | | 81.00 | | | | | | |
| SSP 5-8.5 | EC-Earth3 | WW | | 83.60 | 82.86 | 85.47 | 3.21 | 2.30 | 5.52 |
| | Ec Earth Veg | WD | | 83.91 | 86.70 | 85.99 | 3.60 | 7.04 | 6.16 |
| | GFDL_ESM4 | CD | | 77.55 | 80.40 | 84.12 | -4.26 | -0.74 | 3.85 |
| | MRI ESM2 0 | CW | | 78.92 | 80.81 | 78.52 | -2.56 | -0.24 | -3.06 |

Table 3 compares projected energy output with the baseline production of 81 GWh under SSP 2-4.5 and SSP 5-8.5 scenarios. Under SSP 2-4.5, most GCMs show an increase in energy generation over time. GFDL_CM4 projects steady growth from 4.00% in 2040 to 6.97% in 2080. NESM3 under warm–dry conditions show the highest increase, rising from 20.56% to 23.03% by 2080. GFDL_ESM4 shows a slight decline of 1.13% in 2040 but turns positive by 2060 and 2080. INM-CM4-8 indicates consistent improvement, reaching a 13.73% increase in 2080.
Under SSP 5-8.5, projections show mixed but generally moderate changes. EC-Earth3 and Ec_Earth_Veg_LR indicate increases across all periods. GFDL_ESM4 shifts from a 4.26% decline in 2040 to a 3.85%

increase in 2080. In contrast, MRI_ESM2_0 shows slight overall reductions, with the largest decrease of 3.06% in 2080.

## 5. Risk Analysis

Figure 4 shows the evolution of risk values for various future periods. The risk analysis of climate change on hydropower production was carried out by calculating the percentage failures associated with the different values of annual energy output ($E$) for different periods the 2040s (2025–2050), the 2060s (2051–2075), and the 2080s (2076–2100) and scenarios using eight GCMs. For all eight GCM and SSP scenarios, the results indicate an increase in the risk percentage with an increase in the yearly energy production. The monthly energy output and the river's stream flow determine whether the risk value increases or decreases. As stream flow and energy production increase, the risk value tends to decrease.

Although stream flow and energy output will generally improve in the upcoming periods for NESM3 SSP 2-4.5 WD as well as Ec-Earth-Veg-LR SSP 5-8.5 WD for three future windows. Energy production levels during MRI-ESM2_0 SSP 5-8.5 CW for all future periods and GFDL-ESM4 SSP 5-8.5 CD for only near future, will fail to be reached in the planned or baseline Energy. As a result, there is a danger during such times when the energy isn't generated as anticipated.

**Near Future (2040s):** In comparison to the other GCMs, GFDL ESM4 SSP 5-8.5 exhibits the highest risk profile in the 2040s. The risk increases steeply with increasing primary energy production, rising from approximately 1–2% at low production levels (5–10 GWh) to nearly 39% at the maximum energy level of 80 GWh. This indicates a strong sensitivity of system failure risk to higher generation targets under the high-emission pathway. Close behind are EC-Earth3 SSP 5-8.5 and MRI_ESM2 SSP 5-8.5, which also show sharply rising trends exceeding 30% at higher production levels. In contrast, NESM3 SSP 2-4.5 consistently predicts the lowest risk among all models, with values increasing gradually from below 1% to only about 9% at maximum production. Overall, SSP 5-8.5 scenarios demonstrate significantly higher risk compared to SSP 2-4.5 during the near future.

**Mid-Future (2060s):** Although the peak risk levels are slightly lower than those observed in the 2040s, the deviation between moderate (SSP 2-4.5) and high-emission (SSP 5-8.5) scenarios remains evident in the 2060s. GFDL ESM4 SSP 5-8.5 continues to show the highest risk reaching approximately 31–32% at 80 GWh and EC-Earth3, SSP 5-8.5 closely follows, with risks approaching 30% at peak generation. The SSP 2-4.5 models (GFDL CM4, GFDL ESM4, INM-CM4-8, and NESM3) present more moderate increases generally ranging between 5% and 22% depending on the energy target. NESM3 SSP 2-4.5 records the lowest overall risk, remaining below 8% even at the highest production level. This period reflects sustained emission-driven stress but with slightly moderated extreme peaks compared to the 2040s.

**Far-Future (2080s):** By the 2080s, the dynamics of risk have shifted clearly. The highest risk is projected by MRI_ESM2 SSP 5-8.5, increasing from around 2–3% at low production to roughly 27% at 80 GWh. Unlike the earlier decades, the maximum projected risks are generally lower than the extreme 2040s peak of 39%. GFDL ESM4 SSP 5-8.5 and EC-Earth3 SSP 5-8.5 also show significant increases but remain below 26%. Meanwhile, SSP 2-4.5 models-particularly NESM3 SSP 2-4.5 and INM-CM4-8 SSP 2-4.5-maintain the lowest risk values, typically remaining below 6–8% across the entire energy range. This suggests possible stabilization or adaptation effects later in the century under certain scenarios.

Overall, the SSP 5-8.5 scenarios (especially under GFDL ESM4 and MRI_ESM2) demonstrate consistently high system risk compared to SSP 2-4.5 pathways. Risk is strongly dependent on targeted primary energy production, increasing almost linearly with higher generation levels. The minimum risk observed is approximately 0.5–1% at low production under SSP 2-4.5 scenarios, while the maximum risk reaches nearly 39% in the 2040s under SSP 5-8.5.

The risk values in the future increase significantly when the expected energy production levels of 81 GWh and 92.50 GWh are compared against the lower reference production levels. The percentage

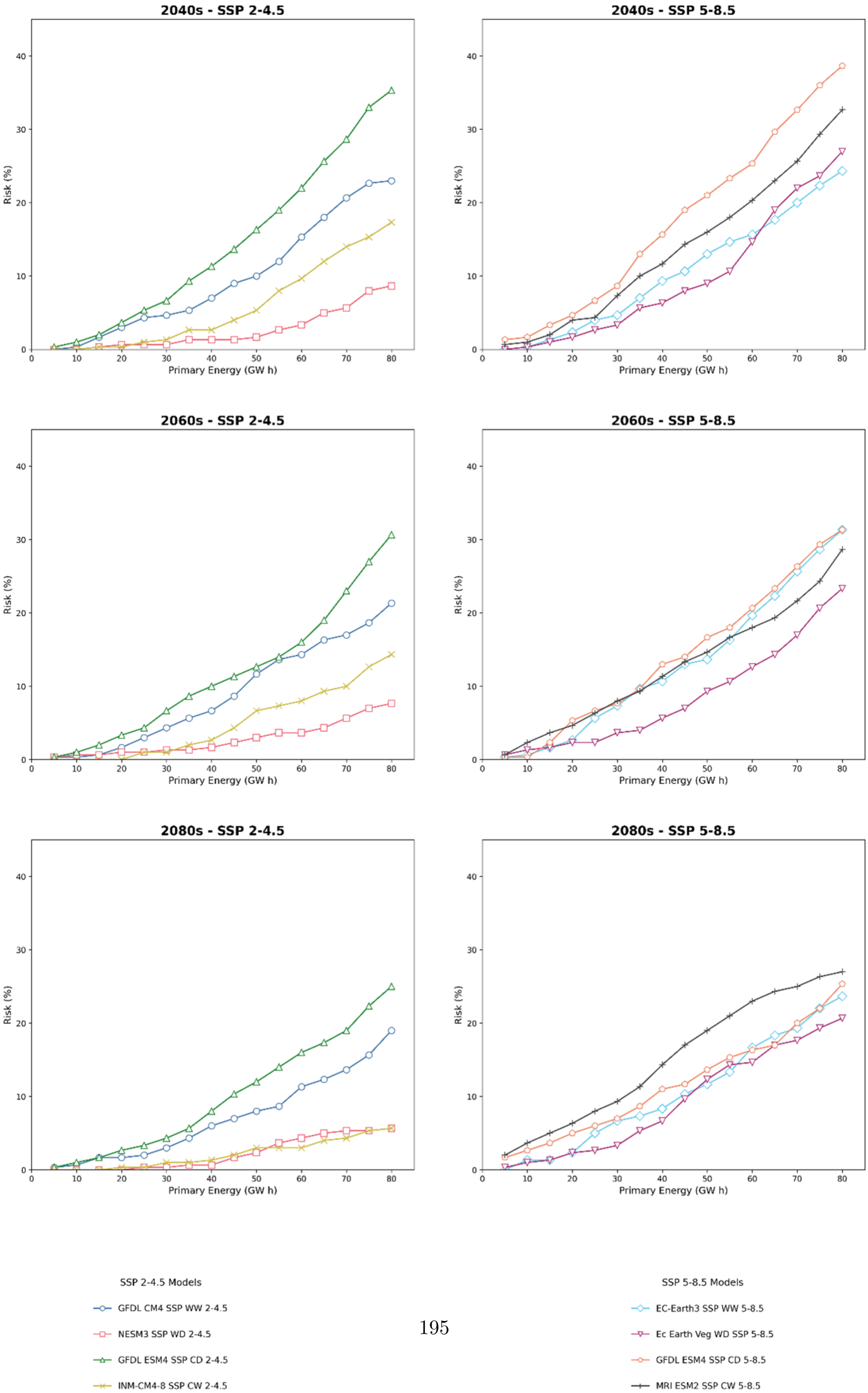




FIGURE 4. Risk vs. annual energy output for the 2040s, 2060s, and 2080s under SSP 2-4.5 and SSP 5-8.5 scenarios for various GCMs.

risk ranges from a minimum of approximately 6% to a maximum exceeding 85%, depending on the selected GCM, SSP scenario, and time horizon.

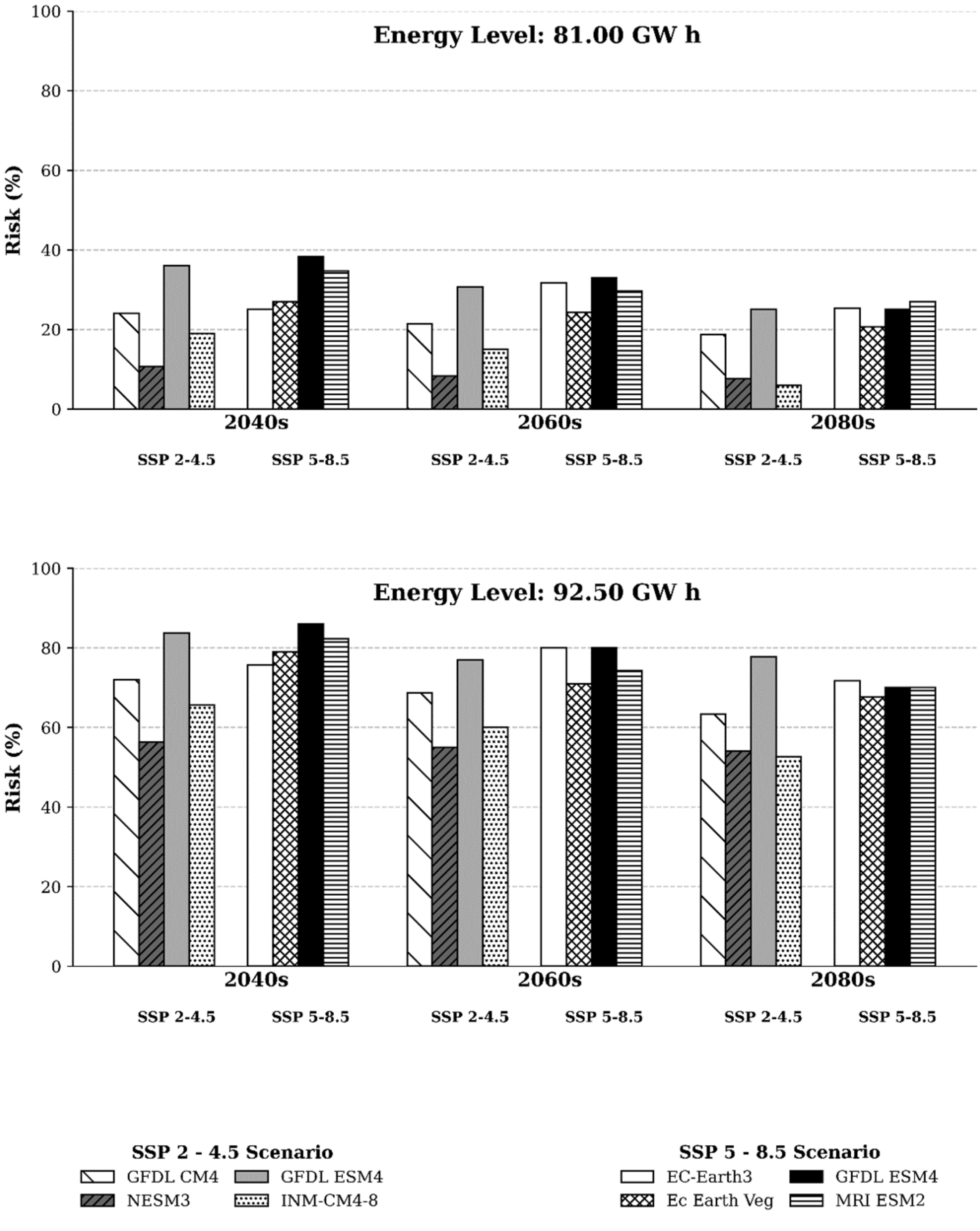


FIGURE 5. Percentage risk associated with hydropower production in future periods, relative to the baseline production of 81.00 GWh and 92.50 GWh, for different GCMs and two SSP scenarios.

At the energy level of 81 GWh, the risk under SSP 2-4.5 varies roughly between 6% and 36%. The lowest risk is observed under the NESM3 and INM-CM4-8 models in the 2080s around 6–8%,

whereas the highest value under SSP 2-4.5 appears in the 2040s for GFDL ESM4 about 36%. Under SSP 5-8.5, the risks are consistently higher, ranging between 20% - 38%, with the peak occurring in the 2040s for GFDL ESM4. Although the risk remains significant in the 2060s and 2080s, a slight decreasing trend is visible toward the far future under some models. At the higher energy level of 92.50 GWh, the risk becomes markedly severe. Under SSP 2-4.5, the values range from 53% to 84%, while under SSP 5-8.5, they range from about 67% to 86%. The highest overall risk occurs in the 2040s under SSP 5-8.5 for GFDL ESM4. Even in the 2080s the risk remains above 50% for nearly all models indicating extreme sensitivity of hydropower reliability to higher production targets.
The risk values obtained from this analysis can be classified into performance levels based on the percentage change in the performance indicator as defined by [26]. According to this classification, mild risk corresponds to a change below 10%, moderate risk ranges from 10% to 20%, and significant risk is defined as greater than 20%. Based on these thresholds the 81 GWh energy level generally falls within the moderate to significant risk category, particularly under SSP 5-8.5 where most values exceed 20%. Under SSP 2-4.5 in the 2080s, some models show mild to moderate risk. However, at the 92.50 GWh energy level, the risk is consistently significant for all GCMs and scenarios across all future periods as all percentages greatly exceed the 20% threshold. Overall, the chart shows risk increases sharply with higher energy production targets, and the SSP 5-8.5 scenario consistently produces higher risk values compared to SSP 2-4.5. The 2040s emerge as the most critical period, particularly at 92.50 GWh, where risk reaches its maximum across all scenarios.

## 6. Conclusion

This thorough risk analysis of the 14.8 MW MKHPP under future climate change scenarios shows vital risks in hydropower reliability across the 21st century. The study shows that climate change will change the hydrological regime of the Modi River basin, with monsoon flows determining progressively from the near future through the far future. Energy generation projections indicate high uncertainty and scenario sensitivity while the NESM3 model under SSP 2-4.5 warm-dry conditions increases up to 23.03% relative to the 81.00 GWh baseline, most other projections, especially under SSP 5-8.5 indicate declines ranging from moderate (7-10%) to severe (15-16%). The quantitative risk assessment provides the most critical insight for operational planning at the conservative 81 GWh production target, the plant faces a 6-39% probability of failure depending on the climate scenario and period, with risks consistently higher under SSP 5-8.5 (20-38%) compared to SSP 2-4.5 (6-36%). At the design capacity of 92.50 GWh, risk becomes severe across all scenarios, ranging from 53% to 86%, with peak vulnerability occurring in the 2040s under high-emission pathways. These findings clearly place the plant in the significant risk category (¿20% performance degradation) according to established classification frameworks particularly at higher production targets.

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