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ASSESSMENT OF NEPALESE ELECTRICITY SECURITY SCENARIO AFTER AN UNUSUAL DOWNPOUR

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Abstract

Climate change induced extreme weather events have been disrupting the services of electricity infrastructure worldwide. Nepal is one of the highly vulnerable countries to climate change due to its terrain diversity, weak geology, and unpredictable seasonal rainfall patterns. Frequent floods, landslides, and prolonged dry periods, during very cold to extreme hot seasons, are causing serious challenges to the power system operation in Nepal. This study, therefore, attempts to discuss the impacts of an unusual heavy downpour on the Nepalese power system. It focuses on the short-term and medium-term impact of the extreme weather event on generation capacity, resulting in increased interruptions and imports, which clearly indicates a low electricity supply security situation. Such an event in September 2024 caused almost 1/3 of the generation capacity loss. The effect was more pronounced in the dry period energy balance that followed the event. Therefore, the authors discuss this issue in a broader context, considering Nepal's geography and future electricity generation mix. Specific considerations of geographical diversity in generation and transmission infrastructure reinforcement and expansion are recommended. The need for cohesive partnerships, data-driven, crisis-ready electricity supply management, and wider stakeholder engagement in ascertaining electricity security is emphasized.

Keywords: Electricity security, Energy surplus and deficit, Extreme weather events, Interruptions, Peak demand, Peaking run-of-river, Run-of-river, Unusual downpour

1. Introduction

Nepal is a mountainous country situated at the center of the Himalayan range in South Asia. It is in elongated shape from east to west (about 800km), with narrower but steep north to south geography (150-250km wide, 60-8848m altitude) (Nepal Tourism Board, 2025). Although it lies in a temperate latitude, the terrain gradient is so steep that Nepal has tropical, subtropical, temperate, subalpine, and alpine climate regions from south to north in a very short range. Due to the steep gradient, plenty of monsoon rainfall, and snow-capped mountains, Nepal is blessed with large hydropower potential. Monsoon rains and snowfall, as well as glaciers in the high mountains, constitute the main water resources for livelihood, agriculture, and hydropower. Moreover, the geology of the country is very weak. Landslides and floods with a high amount of sediments (clay, debris, boulders) are common in the rainy season, turning calm turquoise winter rivers into yellow muddy nightmares. Sediments cause several problems in dam and turbine operations, while boulders may damage even stronger structures and render power plants nonfunctional for longer periods. Glacial lake outbursts and landslide induced lake/dam outbursts are also major potential threats to hydropower.

In addition, the country lies in a major earthquake region. The earthquake may further trigger landslides and lake/dam outbursts. Earthquakes, landslides, thunderstorms, and floods may also damage substations and transmission lines. Rainfall, snowfall, and seasonal patterns have recently become unpredictable and, at times, extreme. The Nepalese power system is therefore highly vulnerable to climate change and extreme weather.

Electricity has become an essential lifeline for homes, offices, commercial facilities, industries, agriculture, transport, and the overall economy in the modern world. Electricity adequacy in case of significant seasonal

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generation deficits and electricity security in the event of an unforeseen crisis are, therefore, highly important. A reliable and secure power system must survive unexpected major disturbances without interruption of customer service. Robustness of the system to contingencies (such as major generation and transmission infrastructure outages) depends on the system's operating conditions as well. All generations, lines, and transformers must always be operating well within the security limits, and system frequency must be close to nominal, as defined by the grid code (Electricity Regulatory Commission, 2023). Therefore, detailed security analysis and evaluation of security limit violations during contingencies are very important (Teeparthi & Vinod Kumar, 2020). The system can go from normal (bus voltage within ±5%, transformer loading less than 90%) to alert (bus voltage within ±10%, transformer loading 90-110%) to emergency (security lost and curtailment evident) and to extreme states (requiring significant restorative actions), depending upon severity of incidents or contingencies (Electricity Regulatory Commission, 2023), (Teeparthi & Vinod Kumar, 2020). The restorative state after an extreme event may be of long duration if system resilience is poor, posing challenges to the system operator for an extended period of time. In Nepal, lines and transformers frequently operate in overloaded conditions. Further, it has a weak and congested electricity infrastructure. They are highly vulnerable to climate change, extreme weather, and geological events. Thus, electricity security-related case studies are even more important for the Nepalese grid.

Considering these issues, several multidisciplinary and predictive studies have been done in the past. A comprehensive operational security analysis was conducted for the Integrated Nepal Power System (INPS) in a thesis that evaluated voltage and power flow limit violations in the transmission infrastructures for various contingencies (Sharma, 2023). Power generation and river run-off modelling were also carried out for the purpose of ensuring power security in evolving weather conditions (Dahal et al., 2022). Polynomial regression modelling for hydropower generation, establishing a correlation between hydropower plant generation and seasonal precipitation trend shifts due to climate change, was also done (Dahal et al., 2024).

Practicing professionals and scholars in Nepal give due priority to the study of the impact of climate change and extreme weather events on hydropower generation and power system operations. The influence of different factors, such as river discharge in various basins, rainfall, snow melting, average seasonal temperatures, environmental regulations, sediments, climate change, etc., on hydropower generation has been investigated by the system operator, Nepal Electricity Authority (NEA) (Timsina & Bista, 2024). Climate-change-induced risks to run-of-river hydropower infrastructure have been studied by academic scholars with a number of real infrastructure damage scenarios (Kadel et al., 2024). Global studies also have assessed power system resilience following extreme weather events, highlighting the importance of diversified generation portfolios, resilient infrastructure, and strategic redundancy (Younesi et al., 2022). However, specific studies focusing on Nepal's unique terrain and vulnerability remain limited, highlighting a significant research gap.

It is always important to learn from the consequences of any extreme event, which will prepare the system to manage future challenges more effectively and resiliently. Therefore, this study attempts to discuss the impacts of an unusually heavy downpour on the Nepalese power system that occurred recently in September 2024. It focuses on the short-term and medium-term impact of the extreme weather event on generation capacity, resulting in increased interruptions and imports, which clearly indicates a low level of electricity supply security for INPS. Further, what-if scenarios are discussed. Considerations of resource and geographical diversity in generation and transmission infrastructure expansion are recommended for greater electricity security. This study employs quantitative operational analysis based on publicly available data from NEA to assess the immediate and mid-term impact of an extreme weather event. Comparative analyses and scenario evaluations provide a scientific basis for policy implications, ensuring both academic and practical value.

2. The Unusual Downpour Event of September 2024

An unusually continuous high intensity downpour occurred during 26-28 September 2024 in eastern to central Nepal, resulting in widespread floods and landslides. Republica news *(myrepublica.nagariknetwork.com)*, quoting NEA, reported that the event resulted in the loss of 1100MW of generation from 20 plants. Out of the total capacity of a little over 3000 MW, the system capacity was reduced to only 1,300 MW. Preliminary loss and damage assessment of flood and landslide due to the downpour was conducted by the Government of Nepal (National Disaster Risk Reduction and Management Authority, 2024). The total estimated loss was NPR 46,684,318,550, reflecting significant disruptions to the physical infrastructure sector (Roads and Highways, Bridges, Water Supply and Sanitation, Hydropower, and Telecommunications). The assessment report indicated that 26 hydropower (11 in operation with a total capacity of 625.96 MW and 15 under construction capacity of 1010.15 MW) facilities were significantly damaged, which resulted in an estimated loss of NPR 3,018,000,000. This loss had significant implications for energy supply, impacting both residential and industrial consumers. Figure 1 and Figure 2 show the

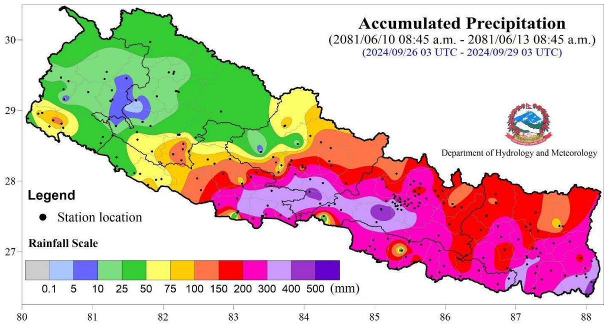

Figure 1. Accumulated precipitation in 26-28 September(Department of Hydrology and Meteorology, 2024c)

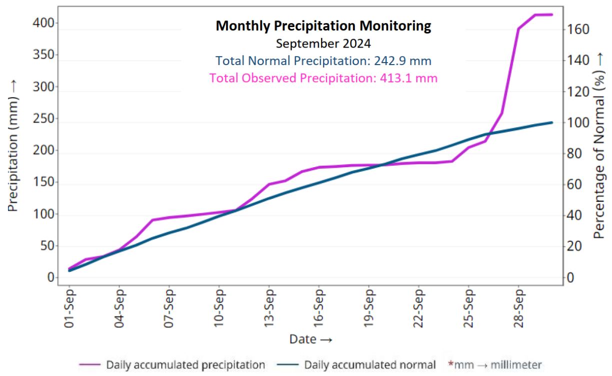

Figure 2. Cumulative national average of daily normal and observed precipitation during September 2024 (Department of Hydrology and Meteorology, 2024b)

accumulated precipitation information from the Department of Hydrology and Meteorology during the weather event and for the overall month.

3. Electricity Supply And Security Scenario In Nepal

In Nepal, Load Dispatch Center (LDC) manages grid resources. Managing INPS resources involves a complex interplay of various factors such as regional demands, transmission congestions, types of plants, ownership of plants, Power Purchase Agreement (PPA) types, geographical issues, and political priorities or limitations. There are three types of hydropower plants supplying to INPS: Run-of-River (RoR), Peaking-Run-of-River (PRoR), and storage. As of the end of Nepalese fiscal year 1080/81 (mid-July 2024), total capacity of grid-connected hydro was 2986 MW (RoR 2087 MW, PRoR 793 MW, and storage 106 MW) (Nepal Electricity Authority, 2024). There are three types of plant owners: Independent Power Producer (IPP), NEA, and NEA subsidiary companies. IPPs mainly operate RoR plants. PPA can be take-or-pay and take-and-pay with IPPs. There is also grid-connected solar (106.94 MW). Total grid-connected capacity was 3152.6MW, which is

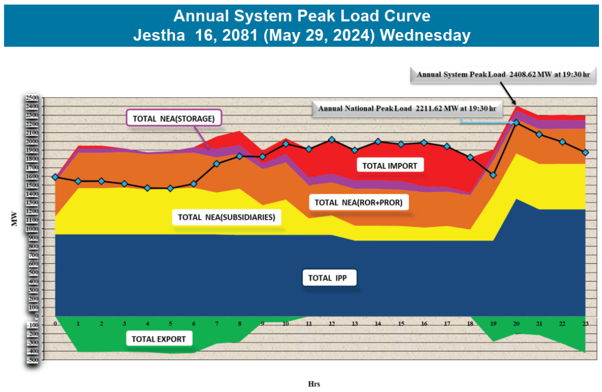

Figure 3. Load curve of INPS for annual peak day [(Nepal Electricity Authority, 2024), page 177].

more than adequate considering national peak demand (2211.6MW). As RoR capacity decreases significantly during dry seasons, the need to rely on other flexible sources increases. Among the types of plants, PRoR and storage are flexible resources that may ensure supply security at difficult times. Further, Nepal-India power exchange has been another flexible resource for the grid. Import of electricity in winter and dry summer periods, as well as export of electricity to India during the surplus monsoon and post-monsoon seasons, are very critical for electricity security and the economy. Electricity supply management on the annual peak day of 29 May 2024 is illustrated in Figure 3, which clearly illustrates the need for the consideration of capacity, energy, import, export, and economy. Economic priority and energy/capacity limits of system resources may result in reduced electricity security, leading to interruptions.

In Nepal, variability in electricity consumption originates from seasonal weather patterns in the region and the extent of activity of productivity. Particularly important is the demand in the winter for increased cooking and heating loads from December to February. Cooling loads, as well as increased industrial and agricultural activity, demand more electricity in April-May. Since generation capacity largely depends on the seasonal rainfall, generation during the winter and the dry part of summer is low. Therefore, electricity security during the deficit periods is attained with increased imports from India. Also, interruptions become common during these periods due to import limitations and the economy of system operation.

Figure 4 shows capacity balance of INPS on monthly system peak days, where increased interruptions in winter and dry periods (purple) can be seen, which indicates low electricity security and also dependence on imports from India (red). Further, it is seen that the capacity of NEA with PRoR (orange) and NEA Subsidiary with PRoR (yellow) remains at a similar level for the entire year, while the

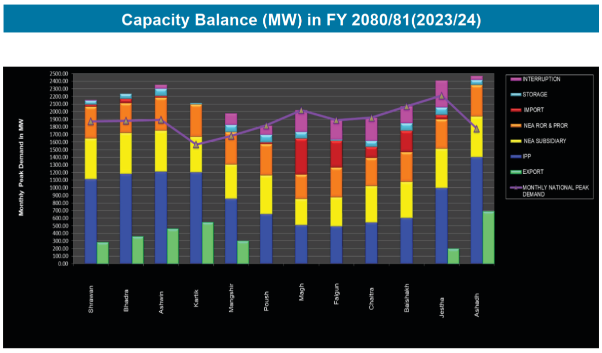

Figure 4. Capacity balance of INPS for peak day of months [(Nepal Electricity Authority, 2024), page 178]

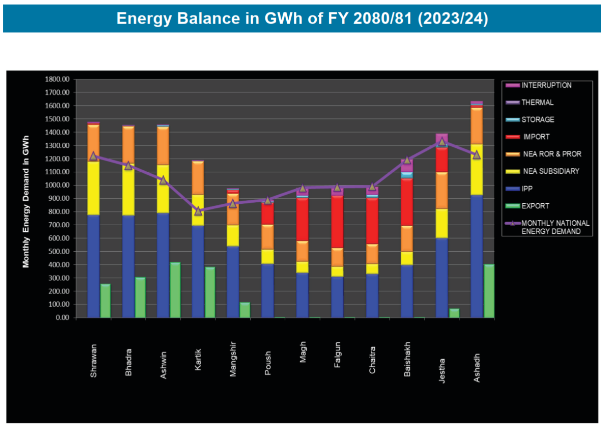

Figure 5. Energy balance of INPS for various months [(Nepal Electricity Authority, 2024), page 179]

capacity of IPPs (dark blue) reduces as they are all RoR. The storage (sky blue) fills up the deficit when needed, as it is the most flexible resource.

Figure 5 shows the monthly energy balance of INPS compared to the capacity balance. It also indicates more dependence on imports. The daily energy generation capacity of both NEA and NEA subsidiary decreases in a similar way to the IPP. This is because PRoR is similar to RoR in MWh capacity, but PRoR stores water during off-peak to be able to supply at almost the rated MW during the peak. Therefore, INPS supply resources in dry periods are limited by the reduced MW capacity of RoR, as well as the reduced MWh capacity of RoR and PRoR.

Figure 6 indicates role of the storage resource, Kulekhani cascade plant. Although it used to play a larger role in the past when the energy demand in the system was low, its contribution to the total energy and capacity mix has diminished. Moreover, it still plays a significant role during various times of contingencies and special requirements. The use may also suggest that it plays a significant role in irrigation, as the discharges are higher from mid-March to the beginning of June (the pre-monsoon season).

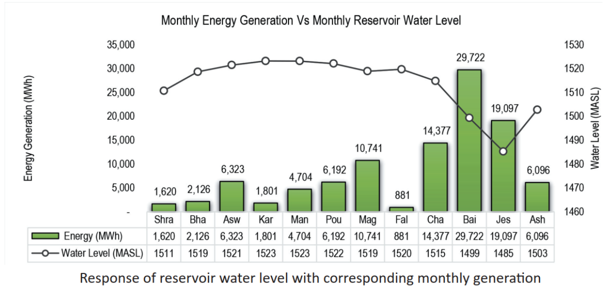

Figure 6. Storage plant generation scheduling [(Nepal Electricity Authority, 2024), page 18]

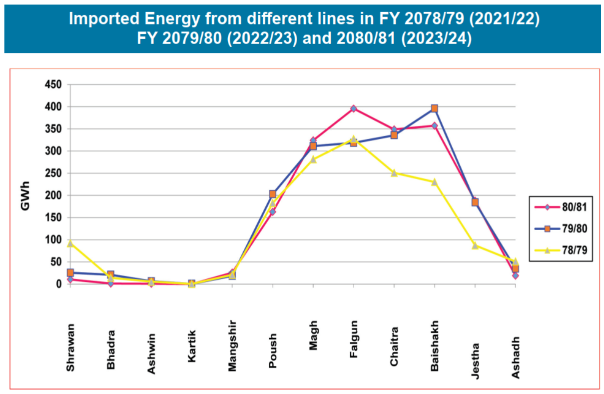

Figure 7. Electricity import from India [(Nepal Electricity Authority, 2024), page 180]

Figure 7 shows the energy imports from India for various fiscal years in various months. Although domestic generation has increased over the years, imports from India in the winter and dry season have not decreased. This implies low electricity security during these periods, as it may not always be possible to import the required amount of energy and capacity. Particularly, when demand gets higher in India in the pre-monsoon dry season due to extreme heat and increased requirements in agriculture, the import becomes difficult.

A recent notice from NEA dated 27 April 2025 indicates an alarming security scenario in the pre-monsoon season, as indicated in Table 1. The notice informs about possible interruptions due to import constraints from India, as well as operational challenges due to pre-monsoon thunderstorms.

Table 1. INPS Capacity Balance Scenario 27 April 2025

Installed Capacity	NEA: 662MW Hydro + 25MW Solar + 53MW Thermal NEA Subsidiary: 623MW Hydro IPP: 2149MW (Hydro & Solar) **Total: 3512MW**
Mix	106MW Storage, 789MW PRoR, rest RoR, and Solar
Current Generation	Average 1175MW and peak **1593MW**
Peak Demand	**2077 MW** (A deficit of 484 MW)

4. Analysis of INPS Operations during and after the Unusual Downpour Event

After having presented summaries about the unusual downpour event and operational characteristics of INPS in the last fiscal year, this section now focuses on impact of the unusual downpour event on INPS. This impact analysis is done on the basis of Integrated Nepal Power System (INPS) daily operational data publicly available on the NEA website *(nea.org.np)*.

The INPS operational capacity balance data during peak time for one week from 25 September 2024 are summarized in Table 2.

Table 2. INPS Capacity Balance in MW During the Event

Date	Generation	National Demand	Interruption	Export (-) / Import (+)
25/09/2024	2683	2007	0	-676
26/09/2024	2538	1753	0	-785
27/09/2024	2439	1629	0	-810
28/09/2024	**1264**	**1380**	**200**	**-84**
29/09/2024	1831	1740	90	-181
30/09/2024	1896	1862	80	-114
01/10/2024	2033	1968	100	-165

The data indicates that the generation capacity remains nominal during the first two days, with a good surplus available for export. A little drop in generation and peak demand is seen on 27 September, which may be due to the rain intensifying and affecting some generation and transmission infrastructures. On 28, there is a significant loss of generation, indicating shutdown of power plants. Interruption is seen, which signifies a loss of system capacity. The export reduces significantly. The generation recovers following the damage, but not completely. This may be due to the fact that the most important PRoR plant, Upper Tamakoshi of capacity 456 MW, was shut down due to the flood damaging its headworks and settling basins. The overall loss of 625.96 MW capacity is more or less consistent with post 28 September data. Export could not recover due to a significant loss of capacity, resulting in revenue losses. Moreover, electricity supply security could recover due to the fact that water availability in the operational plants was at a higher level, and national peak demand was way less than the total installed capacity.

The INPS daily energy balance data for the week are summarized in Table 3. A similar impact pattern is seen in the daily energy balance data. Additionally, operational data indicate 1166 MWh of energy was needed to be imported on 28 September. The data in Tables 2 and Table 3 clearly indicate a major impact from the extreme weather event and reduced electricity security, which was partially overcome by increasing imports. The vulnerability of INPS infrastructure and resources to extreme weather events thus became evident.

Further, analyzing impact of the weather event on the generation considering different types of plants, based on ownership, was carried out. The average generations

Table 3. INPS Energy Balance in MWh During the Event

Date	Generation	National Demand	Interruption	Net Export (-) / Import (+)
25/09/2024	59137	40940	0	-18196
26/09/2024	58050	38137	65	-19913
27/09/2024	50809	32047	30	-18761
28/09/2024	**29404**	**25287**	**1090**	**-4117**
29/09/2024	40717	33606	923	-7111
30/09/2024	42932	36948	40	-5983
01/10/2024	43795	38092	140	-5704

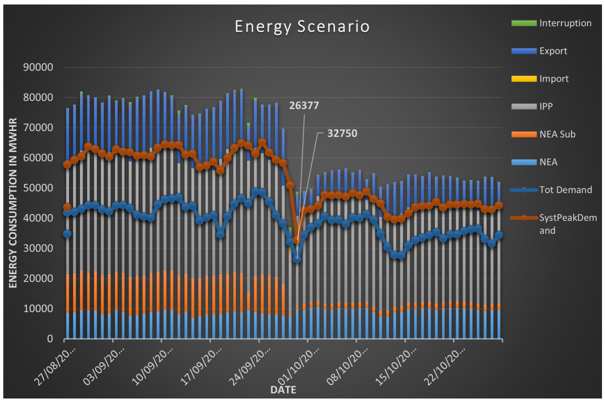

Figure 8. Energy scenario before, during, and after the downpour event

for a month (30 days) before 27 September and after 29 September are summarized in Table 4.

Table 4. Change in Monthly Average MWh Before and After the Extreme Weather Event

Parameter	Before 27 Sep	After 29 Sep	% Change
NEA Generation	8616	9667	12%
NEA Subsidiary	12657	2043	-84%
IPPs Generation	39376	32623	-17%
Total Generation	**60649**	**44334**	**-27%**
Interruption	309	91	-71%
Import	155	0	NA
Export	17773	9068	-49%

The data indicate a significant loss of generation for NEA Subsidiary, which had the country's largest generation station of 456MW out. Similarly, total generation and export were greatly reduced, reducing revenue to a significant extent. The reduction in interruption may indicate that there was no need to disconnect additional lines due to transmission or other constraints, as many lines were naturally disconnected from the system, and the transmission system was not overloaded, as the export as well as domestic consumption were low. Similarly, there was no need to import. NEA production, however, increased as there was no need to spill excess energy, and the overall generation had to be ramped up to meet deficits. Hence, the data reveal expected as well as unexpected kinds of consequences of the extreme weather event. The scenario is also shown graphically in Figure 8.

The event was expected to have a considerable impact on the forthcoming winter and dry seasons. This is because the largest generating semi-flexible PRoR resource was out of the system, which resumed partial production only from 25 December (120MW) *(myrepublica.nagariknetwork.com)*. Therefore, the data for 15 winter days prior to 25 December were analyzed and compared with the previous year's data, shown in Table 5.

Table 5. Impact on Winter Days (10 to 24 Dec)

Parameter & Values	Interruption		Import	
	MWh	MW	MWh	MW
Avg. (10–24 Dec 2024)	2228	353	4107	187
Max. (10–24 Dec 2024)	3800	370	7310	368
Avg. (10–24 Dec 2023)	85	57	3569	12
Max. (10–24 Dec 2023)	300	120	5399	52
% Changes from Previous Year				
Avg. (Increased by)	2531%	523%	15%	1399%
Max. (Increased by)	1167%	208%	35%	608%

The data clearly indicates severely degraded electricity security in terms of interruptions and increased dependence on imports. Since the winter was deepening, the resumption of Upper Tamakoshi, which added about 2500 MWh of daily energy to the system, did not improve the security much. Data from the Department for Electricity Development (DoED, doed.gov.np) indicate the addition of 275MW of RoR installed capacity to the grid since the event, but the security situation on current dry days remained poor, as indicated by data in Table 1.

5. Discussions on Challenges and Possible Solutions

Unexpected major disturbances to electricity supply systems may happen due to climate change-induced extreme weather and other catastrophic events. Although some smaller hydropower installations get used to be damaged due to floods, landslides, and glacial lake outbursts in previous years, the event of September 2024 gave a wake-up call by damaging the largest regulating power plant in Nepal. The overall electricity supply and security situations were seriously compromised. A structured security assessment of INPS specific to the studied event is illustrated in the security state diagram of Figure 9.

This diagram intends to depict how INPS may have transitioned through various operational states during the September 2024 downpour event. Initially operating normally, the system quickly moved into an alert state as continuous rainfall began. Flooding and landslides transitioned the system into an emergency state with significant generation loss (1100 MW). Immediate operator actions, such as load shedding and increased electricity imports, prevented further deterioration into an extreme or in extremis state. Gradual restoration measures over subsequent weeks eventually returned the system towards a partial normal operating state by December 2024. Although restoration to the full extent is still going on and may take longer, this state-specific framework allows clearer

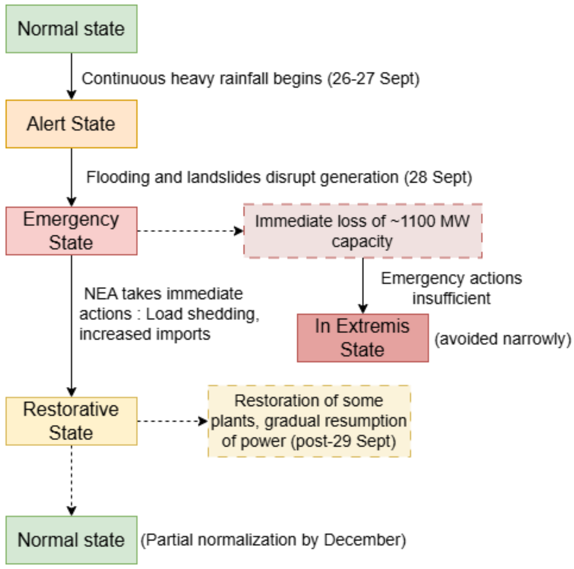

Figure 9. Security State Diagram that may illustrate INPS state transitions during and after the unusual downpour event of September 2024

visualization and assessment of operational resilience and preparedness for similar future contingencies.

A white paper published recently by NEA on 02 May 2025 gave due emphasis to electricity security (Nepal Electricity Authority, 2025). It mentions two approaches for enhanced security: 1) supply adequacy assurance and 2) strengthening of the grid. On the supply side, immediate development of Battery Energy Storage System and Pumped Storage Plant (PSP) has been promised, along with promoting storage and PRoR plants. It also mentions about 960MW solar in the PPA process. On the grid side, it emphasizes accelerating the construction of several 400kV and 220kV domestic and international interconnections. Since there are several hydropower plants being added to the system, it duly realizes that the wet and dry season imbalance is going to be an even bigger challenge. It projects a wet season surplus of 2648MW and 3316MW in the next two fiscal years, while a deficit in winter is projected to be 791MW and 728MW, respectively. While domestic productive electricity use demand needs to be increased for the economy as well as for utilizing the country's clean energy generation, it may further create increased insecurity in the dry periods. Hence, the system development and management are complex.

In the wake of the extreme weather event of September, there are several points to ponder. What if just RoR plants were affected? Did the damage to the largest PRoR plant make the situation more severe? What if there were major plants in the western part where the event had a low impact? What could have been the role of solar power? What if there had been other major interconnections with India than the only already congested major Dhalkebar-Mujaffarpur 400kV line? Is enough study done in system planning considering the weather and geological events? And so on. As more climate change-induced extreme events that may be worsened by other geological phenomena, such as earthquakes and landslides, are expected, there must be consideration of wider stakes, geographical diversity, and other complexities in the future planning for electricity security. While the white paper clearly tries to address the challenges, the following can be added.

1. Rain rate in different hydropower basins varies in Nepal (Department of Hydrology and Meteorology, 2024a); also seen in Figure 1. As there is less hydropower and grid developed in the relatively less vulnerable western region, future development shall be emphasized there for better security.
2. As there is more solar potential in the sub-Himalayan western rain-shade regions, Figure 10 (The World Bank, 2017), transmission corridors shall be extended to those regions, promoting national-scale solar farms there.
3. Infrastructure and resource diversification with due consideration to climatic as well as geological characteristics of different geographical regions must be a key consideration for electricity development and national investment priorities.
4. Continuous hydrological, geological, and infrastructural vulnerability studies around all major flexible resources need to be carried out, and appropriate hardening and disaster risk reduction measures must be taken.
5. Enhanced crisis management protocols for electricity security are needed. Developing stronger, data-driven crisis response frameworks capable of quickly reallocating resources and managing imports efficiently during major disruptions is suggested.
6. Obviously, as electricity security becomes more complex and more critical, the government and system operators must put aside a good amount of funding for multidisciplinary, applicable, and evidence-based research at institutions in Nepal.

6. Summary and Conclusion

In this paper, the impact of an unusual downpour event on electricity security in the Integrated Nepal Power System was analyzed. This extreme weather event caused major damage to the generation resources, including the largest and most important power plant in Nepal. Security was found to have degraded considerably, increasing system interruptions and reliance on imports. Further, a considerable decrease

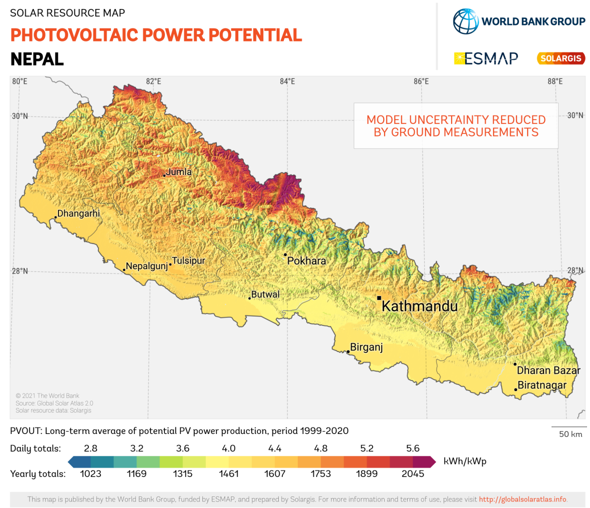

Figure 10. Photovoltaic potential in Nepal, https://globalsolaratlas.info/download/nepal

in generation and export after the event indicated revenue losses and a subsequent annual electricity trade deficit with India.

In conclusion, this was a serious wake-up call for INPS as well as scholars in Nepal about the unexpected consequences that may happen in the electricity supply system due to climate change and extreme weather events. Considering geological vulnerability together, more catastrophic events may happen in the future. Therefore, these challenges need to be managed with wider consideration of the complexities. The system shall not resort to limited opinion and influence-based premature planning decisions. Although NEA and the Government are putting effort, wider opinions based on data, evidence, and state-of-the-art knowledge must be heard. Resources must be put into the research on electricity as well as overall energy security.

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