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Evaluation of Peaking Time Variation in Power Generation of a Cascaded Hydropower System: A Case Study of Arun River

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Abstract

This study evaluates the energy generation performance of cascaded hydropower projects—Kimathanka Arun (KAHEP), Upper Arun (UAHEP), and Arun-4— three run-of-river projects in Nepal's Arun River Basin under varying peaking time conditions. Using simulation data across dry (December–May) and wet (June–November) seasons, the study investigates hourly and daily energy patterns for peaking durations ranging from 4 to 12 hours. Results show that a 6-hour peaking duration most effectively aligns with morning and evening peak electricity demand in the dry season, maximizing energy benefit. Beyond 6 hours, the power generation at full capacity was restricted by the available design live storage (daily pondage) capacity. Although Arun-4 is designed as a run-of-river (RoR) project, it will benefit from peaking power generation due to upstream flow regulation from PRoR plants, underlining the advantages of coordinated cascade operations. In the wet season, generation remains stable—at full installed capacity—regardless of peaking time, due to abundant flow. The study suggests that optimizing installed capacity and live storage (daily pondage) capacity and designing PRoR plants for 4–12-hour peaking can improve dry season generation. Our analysis shows that the current design (live storage and installed capacity) of the two upstream PROR projects is suitable for a 6-hour peaking capacity. Policy recommendations include revising hydropower operation guidelines to incorporate coordinated peaking strategies, optimizing generation capacity, storage and system operation planning, and benefit-sharing mechanisms. With the increase of other variable renewable energy generation like wind and solar, a higher installed (peaking) capacity for a shorter peaking duration could be highly beneficial. These measures can significantly enhance power system reliability, generation mix and support Nepal's growing power demands, particularly during critical dry periods.

Keywords: Arun River, Run-of-River hydropower projects, Cascaded hydropower system, Power Generation, Peaking Time

1 Introduction

Hydropower plants are among the most efficient and reliable renewable energy systems in the world as far as electricity production is concerned (Aryal et al., 2024). Hydropower plays a significant role in Nepal's energy sector, with more than 96% of the installed capacity currently coming from hydropower sources (NEA, 2023). While Nepal has significant hydropower potential, not all of it is economically viable. The technical potential is estimated to be around 83,000 MW, but the economically feasible potential is around 42,000 MW (H. M. Shrestha, 2017). Despite the potential, the hydroelectricity development in Nepal has not been as smooth as expected. Since 2006, Nepal had to face an electricity crisis over a decade (R. S. Shrestha, 2010). The country had to overcome technical, social, policy, economic and institutional barriers, some of which are still in place (Ghimire & Kim, 2018). In January 2025, the Government of Nepal approved the 'Energy Development Roadmap and Action Plan 2081', aiming to increase the country's total installed electricity capacity to 28,500 MW by 2035. In order to meet these ambitious targets, Nepal is planning to increase its focus on cascaded hydropower projects (Bhattarai et al., 2022). The Koshi basin hosts several rivers-Arun, Tamor, DudhKoshi and others-where multiple hydropower projects are either operating, under construction, or planned in a cascade arrangement, meaning the outflow of an upstream project becomes the inflow for the next downstream project. Studies on impacts of cascaded hydropower projects are mostly dealing with storage-type hydropower projects as they provide seasonal and even inter-annual regulation due to large live storage (Lamsal et al., 2024). Run-of-river (ROR) hydropower projects with small storages (pondages) regulate flows within a day (or week in some cases with a slightly larger storage capacity) to provide peaking capacity especially in the dry season when the river flows are lower than the design discharge of the projects. These peaking ROR (PROR) projects have positive and negative impacts downstream. For example, hourly regulated discharge can have negative impacts on ecosystems and people living downstream (Zarfl et al., 2015) but can provide grid stabilization and balancing services with other variable power generation like wind and solar (Hase & Seidel, 2021). The Arun River, a major tributary of the Koshi River, holds significant potential for hydropower development through a cascaded system of projects. Three key projects-Kimathanka Arun Hydroelectric Project (KAHEP), Upper Arun Hydroelectric Project (UAHEP), and Arun-4 Hydroelectric Project-are strategically planned along the river to operate in succession, utilizing the same water resource efficiently.

Despite the expansion of hydropower development in Nepal, particularly within the Arun River Basin, a notable research gap exists regarding the operational performance of cascaded hydropower systems under varying peaking time durations. Existing studies primarily focus on individual project performance, often neglecting the interdependent nature of upstream and downstream operations within a cascade (A. Shrestha et al., 2023) This is especially relevant in the case of the KAHEP, UAHEP, and Arun-4 Hydropower Projects, where upstream flow regulation significantly affects downstream generation. Moreover, conventional analyses rarely consider how peaking time variation influences energy output across seasonal timelines—especially between the dry and wet seasons, where water availability and demand patterns differ. Rigid peaking schedules may fail to match seasonal operational requirements, leading to suboptimal energy generation (Lamsal et al., 2024). Addressing this gap is essential for improving both individual plant efficiency and the coordinated performance of the entire cascade, particularly in Nepal's context of variable river flow and growing energy demand.

Therefore, the study aims to serve to meet the following specific objectives: i) To analyze the effect of peaking time variations on the daily power generation of individual hydropower plants. ii) To evaluate how peaking time variations affect power benefit of Arun-4 Hydropower Project (ROR project without pondage downstream of two upstream peaking ROR projects) in both designed (individual operation) and cascaded hydropower plant scenarios.

Since ROR projects do not have large seasonal storage nor flood regulation capacity like the storage reservoir projects, the study focus was on dry and wet seasons. However, the study considers dry periods of the long-term hydrology to estimate the long-term power generation of the ROR projects.

2 Materials and Methods

2.1 Study Area

The Arun River is one of the most significant rivers in the Himalayan region, encompassing diverse topographical and ecological characteristics. The Arun River originates in the Tibet Autonomous Region of China, where it is called the Phung Chu, at approximately 28.3°N latitude and 87.0°E longitude. It flows southeast into Nepal at Kimathanka in the Sankhuwasabha district, entering at about 27.8°N latitude and 87.3°E longitude. The river ultimately converges with the SunKoshi River in Nepal near Tribenighat, approximately 26.9°N latitude and 87.0°E longitude, becoming part of the Koshi River system. The Arun River Basin spans across an area of approximately 37,000 square kilometers, stretching from the Tibetan Plateau to the Terai plains in Nepal. This wide altitudinal range contributes to its rich biodiversity and ecological significance. Basin area lies within Province 1 of Nepal. The energy output obtained through the development of reservoir projects in Arun River Basin can provide a significant impact on the overall energy generation of the country. So, the Arun River Basin has been selected for this study due to its suitable features that can provide shared benefits among stakeholders. The study area map showing the Arun River Basin is shown in the Figure 1

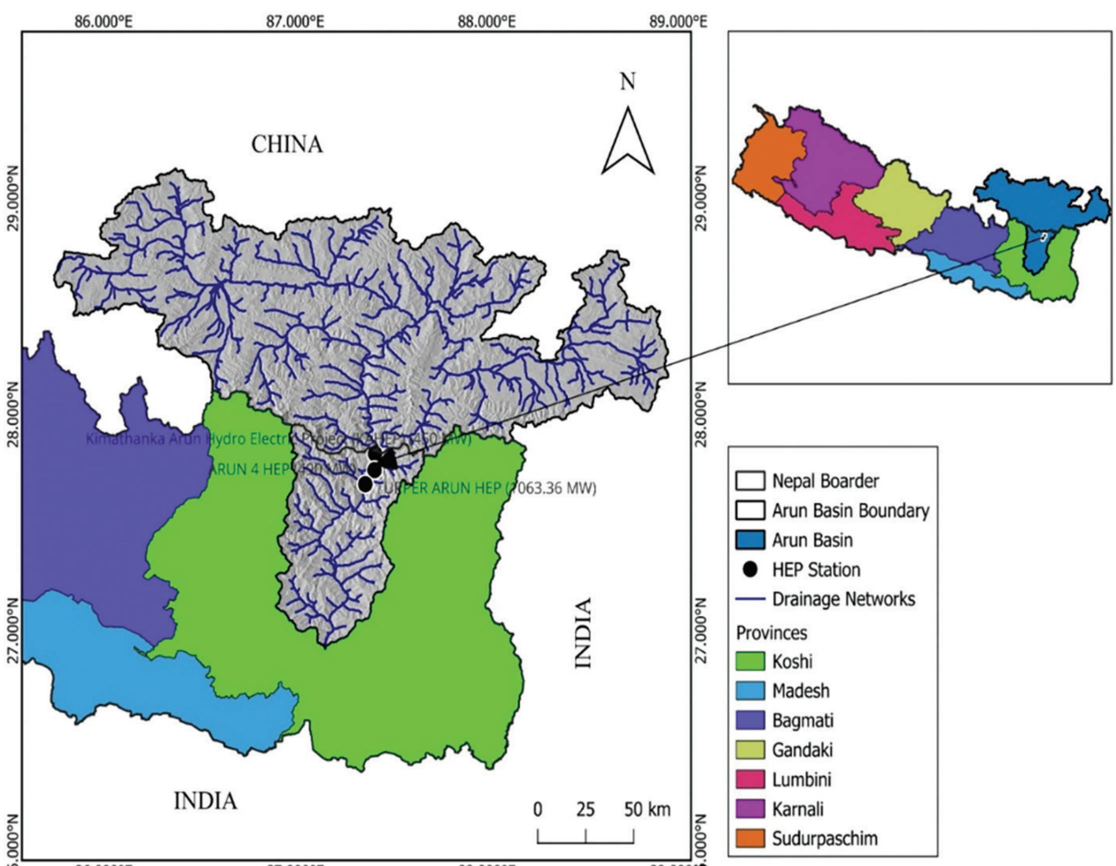

Figure 1: Location and associated details of the Study Area

KAHEP, is located in Bhotkhola Rural Municipality-2, Sankhuwasabha District of Province-1 in North-Eastern Nepal. The project will utilize the flow from the Arun River for power generation. The generated power will be fed into the integrated power system of Nepal at the nearest national grid substation proposed at Haitar, Sankhuwasabha. The Desk Study Report envisaged KAHEP as a Peaking Run-of-River (PRoR) type project with a gross head of 379.52m and design discharge of 148.5 m3/s producing peak power of 450MW(NEAEC, 2022).

UAHEP, draws water discharge from Arun River. It is located in Sankhuwasabha District of Koshi Zone in Eastern Development Region of Nepal. The Project is located at about 70 km north of Khandbari, the district headquarters. The proposed dam site is located in a narrow gorge about 350 m upstream of the confluence with Chepuwa Khola in Chepuwa Village. The powerhouse lies in Hatiya Village, at about 500 m upstream from the confluence of Arun River with LeksuwaKhola. The project area is situated within Longitude 87°20'00" to 87°30'00" East and Latitude 27°38'24" to 27°48'09" North. The project is conceptualized as a Peaking Run-of-River (PRoR) scheme having design discharge 235 m3/s and installed capacity 1063.36 MW(VUCL, 2018).

The Arun 4 hydropower project lies in the Arun River basin, a sub-basin of Koshi River basin. It's installed capacity is 490 MW. It is designed as Run of River (RoR) scheme(DOED, 2021).

2.1.1 Physical features of Hydropower Projects

The physical features of hydropower components that are considered in the study are summarized in the Table 1

Table 1 Physical features of Hydropower Projects

S. N	Dam Features	Kimathanka Arun HEP	Upper Arun HEP	Arun 4 HEP
1	Installed Capacity (MW)	450	1063.36	490
2	Design Discharge (m^3/s)	143.5	235	253.5
3	Catchment Area (km^2)	24835.6	25700	25970
4	Gross Head (m)	379.52	508.26	220
5	Efficiency (%)	85	90	90
6	Intake level (m)	2010	1630	1072
7	Tail water level (m.a.s.l)	1652.48	1080	825
8	Type of Scheme	PRoR	PRoR	RoR
9	Live Storage Capacity (MCM)	3.24	2.13	-

2.1.2 Hydrological Area Stations used in the study

The hydrological data that is used in the study is accessed from the DHM whose locations are shown in the Table 2.

Table 2 Hydrological Area Stations used in the study

St. No	Name of River	Location	Latitude (degree)	Longitude (degree)
600.02	Arun	Kimathanka	27.78	87.45
600.1	Arun	Uwa Gaun	27.6	87.35
604.5	Arun	Turkeghat	27.31	87.19

2.2 Flowchart

The framework for analyzing peaking time variation in a cascaded hydropower plants is shown in Figure 2.

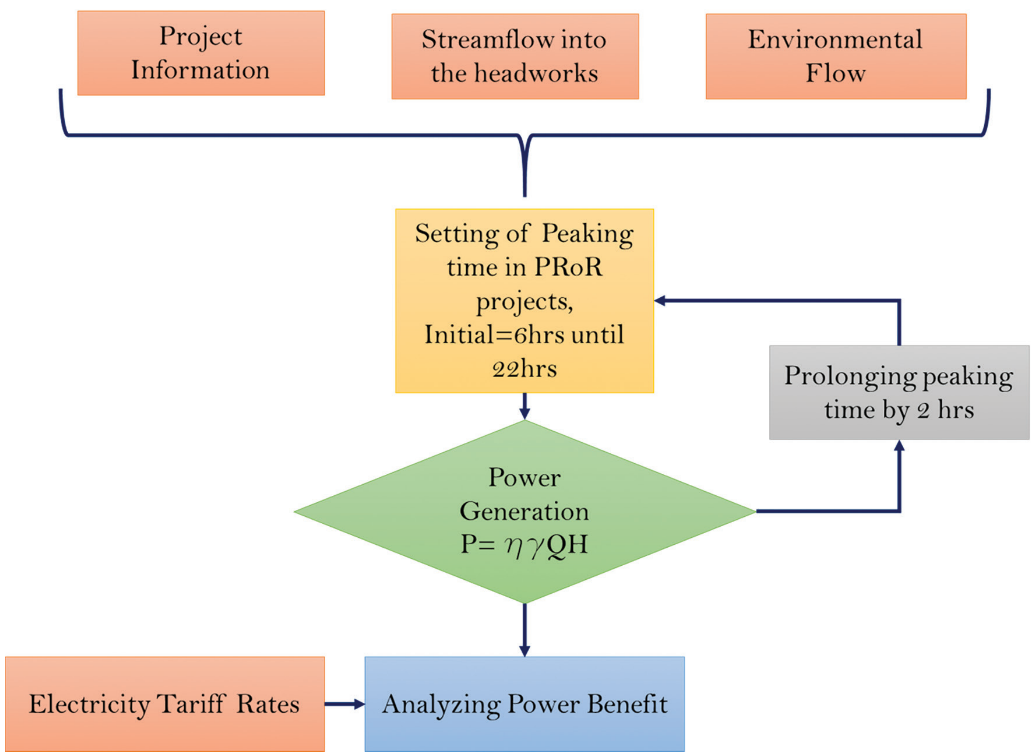

Figure 2: Methodological Framework of the Study

2.3 Inputs

2.3.1 Project Information

The project information such as Area-Elevation-Volume curve, intake level, maximum reservoir level, minimum reservoir level, tailwater level, installed capacity, design discharge, turbine efficiency, gross head, etc. is taken from the study reports.

2.3.2 Streamflow into the headworks

The inflow into the reservoir was calculated from the stream gauged station data of hydrologically similar catchment available from DHM Nepal. The additional catchment area between the hydropower projects lies within the range of existing hydrological gauge stations and is located in a hydrologically similar region (MIP, 2015). The available hydrological stations in the project regions were at Kimathanka, Uwagaun and

Turkeghat. The daily discharge (2020 A.D) magnitude that of Kimathanka hydrological station was used as it is for KAHEP. For the UAHEP, the additional discharge from additional catchment downstream KAHEP was calculated from Catchment Area Ratio (CAR) method with the known discharge difference of UwaGaun from Kimathanka hydrological station of same date. Similarly, additional discharge for Arun 4 HEP was calculated from CAR method with known discharge difference of downstream UAHEP and upstream Arun 4 HEP. Also, as the focus was on the impact of PROR and ROR projects with cascade, particularly on the downstream projects, detailed hydrological modelling wasn't carried. In addition, since the major parts of the catchments common to all the 3 projects studied in Arun River lies in Tibet, and the difference of catchment area of the 3 projects are less than 4.3%, CAR method was considered appropriate for the study and would not have any limitations on data accuracy.

2.3.3 Environmental flow

In Nepal, as per Hydropower Development Policy, 2001 (GoN, 2006), hydropower projects must release a minimum environmental flow equivalent to at least 10% of the minimum monthly average discharge of the river. Currently, the study uses 10% environmental flow requirement. It can further be used to assess the tradeoff between energy generation and peaking capacity, and the environment flows by varying the e-flow requirements.

2.4 Methodology

2.4.1 Data Collection

The various properties of hydropower station would be required were accessed through study reports prepared by different government organizations. The volume-storage was determined from past reports on studies related to the projects.

2.4.2 Reservoir Operation Policy

Accounting for the storage effect alters reservoir operating policies, which subsequently influence both energy production and water availability within the system (Goor et al., 2010). All the trial rule curves used in the study follow these three fundamental reservoir operating rules:

- Store water during non-peak hours considering the requirement of the peak hours to generate at full capacity. The hourly water to be stored is computed based on the daily water available, live storage capacity and peak hours. This is applicable in the dry season, as the wet season available flow normally exceeds the design discharge.
- Fulfill the required water demand for hydropower generation (during the dry season, lower in non-peak hours and at maximum capacity in peak hours) as long as the reservoir level is above the Minimum Water level.
- Excess inflows (when inflows are larger than the required water for hydropower) are stored in the reservoir till the water level reaches the Maximum water level, and then are discharged through turbines and then spillways (A. Shrestha et al., 2023).

2.4.3 Setting of peaking time

The peaking time was scheduled to begin at 4 hours, gradually extending to 12 hours, with the duration increasing in 2-hour intervals. This pattern was designed to assess the impact of different time frames on energy production and the operational efficiency of the hydropower system.

3 Results and Discussion

3.1 Individual Project Energy Production

The energy generation by hydropower projects individually during a cascade scenario of different peaking time conditions in dry season (December-May) and wet season (June-November) is as shown in Figure 3, Figure 4 and Figure 5 respectively.

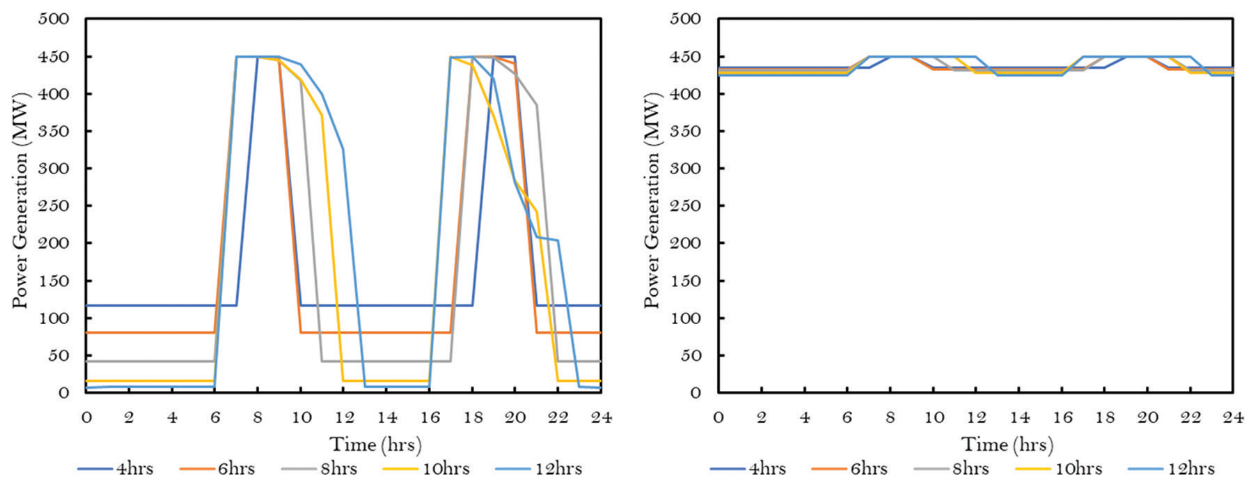

Figure 3: Daily Power Variation of KAHEP in Dry Season (Left) and Wet Season (Right)

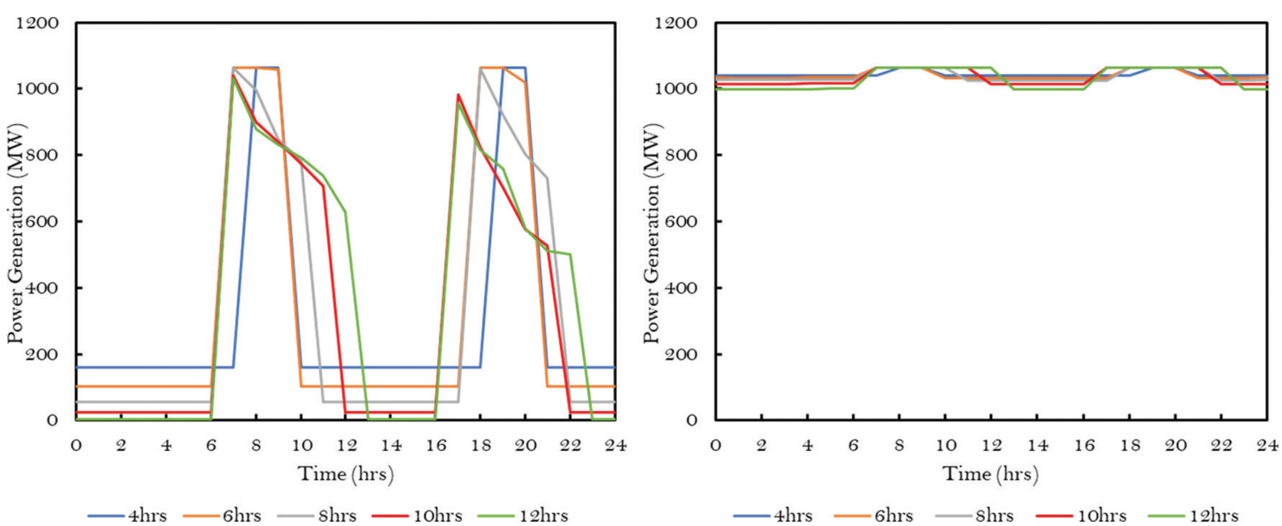

Figure 4: Daily Power Variation of UAHEP in Dry Season (Left) and Wet Season (Right)

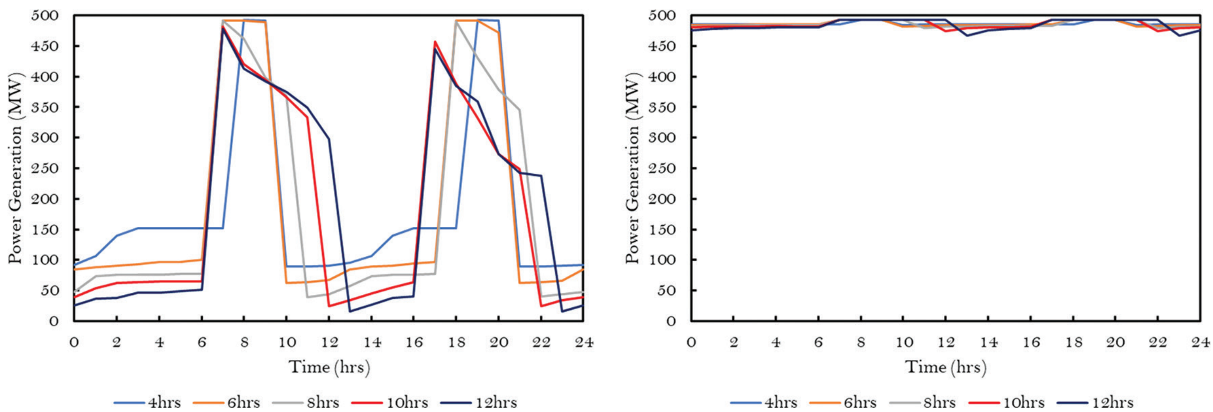

Figure 5: Daily Power Variation of Arun -4 HEP in Dry Season (Left) and Wet Season (Right)

The graph shown in Figure 3, presents hourly power generation (in MW) of KAHEP over a 24-hour period during the dry and wet seasons for various peaking durations ranging from 4 to 12 hours. Dry season curve corresponds to the generation profile of a system that initiates its peak output at a designated time. For peaking durations up to 6 hours, the power generation appears sufficient to generate at the installed capacity, particularly aligning with the morning demand surge, which tapers off soon after this period due to the limitations of the live storage (pondage capacity). However, from a peaking duration of 8 hours onward, the generation profiles indicate a lack of desired peaking output, suggesting that the system is unable to generate at the full capacity during the designated peak periods due to the limitation of available live storage (pondage) .

The graph as shown in Figure 4 illustrates hourly power generation (in MW) of UAHEP during dry and wet seasons over a 24-hour period for various peaking durations between 4 and 12hours. Dry season curve represents the output pattern of a system starting its peak generation at a specific time. For peaking durations of up to 6 hours, the system effectively generates at the installed capacity, particularly during the morning surge, which subsides shortly afterward. In contrast, for durations of 8 hours and beyond, the generation curves show a diminished peaking capacity, indicating the system's inability to generate at full capacity during the intended peak periods due to the limitations of the live storage capacity.

The graph as shown in Figure 5 illustrates hourly power generation (in MW) of Arun-4 HEP during dry and wet seasons over a 24-hour period for various peaking durations ranging from 4 to 12hours. Peaking durations of dry season demonstrate that up to 6 hours the system's capability to adequately generate at the full capacity, particularly aligning with the morning demand surge, which declines shortly afterward. Conversely, for durations of 8 hours and longer, the output profiles exhibit a reduced peaking characteristic, reflecting the system's limited ability to generate at full capacity during the designated peak demand periods due to the limitations of the storage capacity. Due to the ponding effect of runoff during off-peak hours by upstream hydropower projects, Arun 4 HEP is also seen to exhibit the characteristics as of the peaking RoR project even though it is considered to be constructed as RoR project.

The graph of wet season for every hydropower station shows that the hydropower operation is generating mostly at their installed capacity depicting that the change in peaking time doesn't largely affect power generation fluctuation in wet days. This is because the design discharge is lower than the available inflows in most of the wet season months.

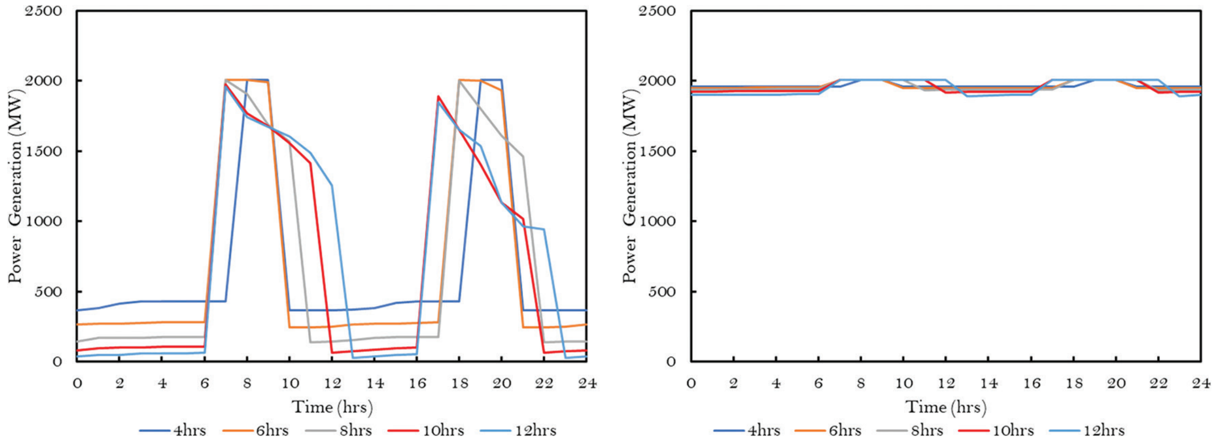

Figure 6: Daily Power Variation in Cascaded Hydropower System of Arun River

Peaking durations of up to 6 hours demonstrate the system's ability to effectively generate peak capacity, particularly aligning with the morning demand surge, which tapers off shortly thereafter as shown in Figure 6. In contrast, for peaking durations of 8 hours or more, the generation profiles display a diminished peaking pattern, indicating the system's reduced capacity to generate at full capacity during designated peak demand periods due to limitations on the storage capacity. Among all scenarios, the 6-hour peaking duration yields the desired level of energy generation over the 24-hour period as per the operation condition of effective generation in peaking time and maintains an approximately constant output throughout the peaking window.

3.2 Comparison of Power Benefit of Arun-4 Hydropower Project in both designed (Individual Operation) and cascaded hydropower scenarios by varying peaking hours.

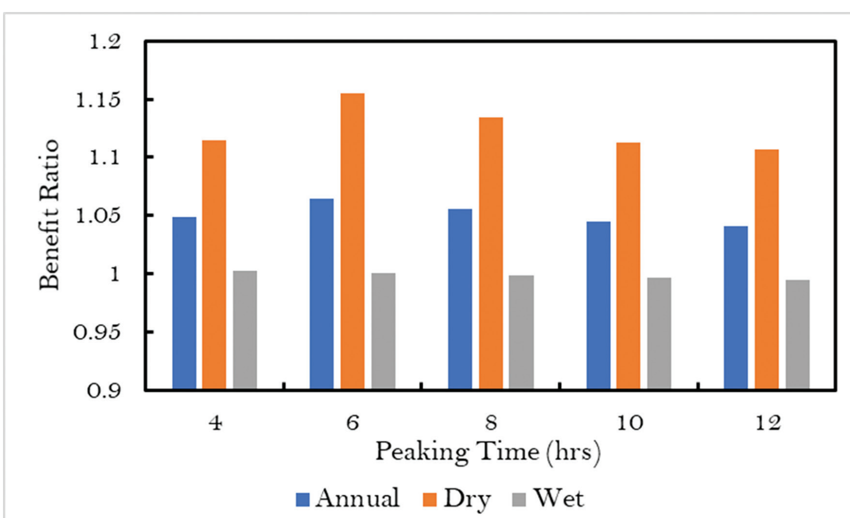

Figure 7: Comparison of Arun-4 RoR HEP Energy Benefit at various Peaking Time Setting of upstream HEPs

The bar graph in Figure 7, illustrates the variation in power benefit ratio (cascade benefits versus designed) for the Arun- 4 hydropower project under different peaking time durations, ranging from 4 to 12 hours. The power benefit ratio is categorized into dry season energy, wet season energy, and annual energy. The graph shows that the dry energy benefit ratio is significantly higher than both wet and annual ratios, with the peak occurring at a 6-hour peaking time. This indicates that the recommended operational strategy of 6 hours peaking performs substantially better than the designed one during dry periods when water availability is limited and power demand is typically high. In contrast, the wet and annual energy benefit ratio remains relatively constant across all peaking durations, suggesting that the cascade operation has no effect on energy generation during the wet season, due to abundant water flow. Therefore, based on this analysis, for Arun 4 HEP, 6-hour peaking time appears to be the most effective, as it optimizes dry season performance while also enhancing or maintaining annual energy generation.

4 Conclusions

From this study, it is concluded that the daily variation analysis reveals that dry season power benefit of downstream RoR plant i.e., Arun-4 HEP in the case of cascaded hydropower development is most effective with peaking duration of 6 hours, where systems can align closely with peak demand, especially during the morning surge. Beyond 6 hours, the power generation at installed capacity is restricted due to the limitations of live storage capacity (daily pondage). The presence of upstream PRoR plants benefit the downstream cascaded RoR plant from surplus generation during the peaking period.

This study analyzes the impact of varying peaking durations on energy generation across individual and cascaded ROR hydropower systems in the Koshi River Basin, focusing on KAHEP, UAHEP and Arun-4 HEP projects. In cascaded scenarios, coordinated operation enhances efficiency of downstream RoR. The following policy recommendations can be proposed from the findings of this study.

- NEA's published PPA rates provide highest dry season tariff for peaking hours between 4 – 6 hours in the dry season (NPR 10.55/KWh) and non-peak hours rate of NPR 8.40/KWh. The purpose of PROR projects should be mainly to increase the availability of peaking capacity to maximum time (i.e. be able to generate at full installed capacity by using storage (daily pondage) water from non-peaking hours) within the day in the dry season, when the river flows are lower than the design discharge of PROR projects. Since the current dry season load curve has about 3 to 4 hours peak in the morning and evening, we recommend that PROR be design with 4 to 12 hours.
- Considering the design live storage (daily pondage) capacities of the KAHEP and UAEHP, our findings show that the 6 hours peaking yields the maximum benefits.
- We have considered the installed capacity of the 3 projects as per the current design. However, we recommend that the design installed capacity be reviewed and optimized considering the available daily storage as well as the system load pattern. With the increase of other variable renewable energy generation like wind and solar, a higher installed (peaking capacity) for a shorter peaking duration could be highly beneficial.
- Our results demonstrate the increase of peaking power generation from PROR/ROR projects in cascade. We therefore recommend changes in the hydropower policy on the operation and management of hydropower projects in cascade. Such a policy should take care of benefit-sharing, optimizing installed capacity and storage capacity, and operational rules among projects in cascade.

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