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Harnessing India–EU Collaboration for Advancing Hydropower in India's Energy Transition

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Title

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Introduction

From the historical perspective, hydropower is considered as one of the important energy sources for the energy mix and global energy transition. Its importance can be seen because of its stability as well as its reliability. (IHA, 2023). But the rapid scaling up of solar and wind power has reduced hydropower's relative share in the renewable energy mix, even as absolute generation continuously increasing (IRENA, 2025). This shift can be visible in India as well, where hydropower's long-standing dominance in renewable energy electricity has been recently over passed by other renewable sources, marking a structural transition in the country's energy pathway specifically for electricity (CEA, 2023). In Current decade, Europe is considered as one of the major partners of India when it comes to energy security relations. The continent, Europe has experienced a drastic policy change in recent years to improve its low carbon technologies. Power sector is one of them. Some of the country in EU has experiencing more than 95% of renewable energy mix in the total energy generation. This shift is the result of its investment in technological as well as social capital. The renewable energy was dominated with hydropower now functioning mainly as a balancing resource other than the main renewable energy contributor. When we talk about Indias hydro power scenario, In year 2022, India's installed hydropower capacity reached 46.9 GW, but its share in renewable electricity generation declined as solar and wind expanded at a faster pace (MNRE, 2023). Therefore, against these points, this chapter is going to examines the changing role of hydropower in India's energy transition and explores how targeted collaboration with the European Union (EU) can make support and strengthen its sustainability, resilience, and integration within a diversified renewable energy mix portfolio.

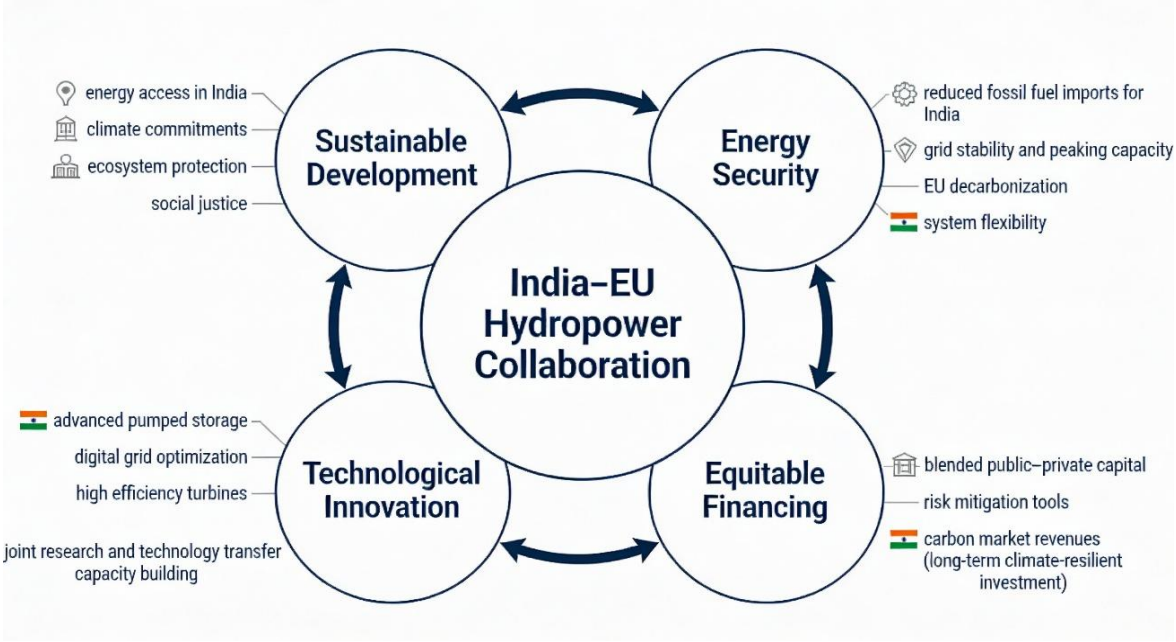
Problem Statement

This study investigates how EU practices in hydropower modernization can be adapted to India's context. Our study presents a comparative analysis of hydroelectricity trends in India, Europe, and globally between 2000 and 2022, pinpointing turning points where non-hydro renewables surpassed hydropower in generation share. It will also try to identifies potential areas of cooperation, including technology transfer, adoption of climate-resilient infrastructure, and the development of hybrid renewable energy systems, drawing from established practices of the European Union (Gernaat, et al. 2021).

Through strengthened India EU collaboration with different paths, hydropower can be repositioned as a flexible, low-carbon power system of India that may providing not only firm capacity and grid stability but also supporting the long-term sustainability of the country's net-zero transition.

Conceptual Framework

Fig 01: Flowchart for India EU hydro power collaboration



When we are talking about the conceptual framework for India EU hydropower collaboration rests on the interconnectedness of sustainable development, energy security, technological exchange, and the equitable financing. At its middle of the heart, sustainable development emphasizes hydroelectricity's dual capacity to expand India's energy accessibility while advancing climate commitments, keeping in mind that projects are designed to protect ecosystems as well as to uphold social justice. In this way hydropower's role in delivering peaking capacity and grid stability reinforces renewable energy integration of India, while the EU's have experience with sustainable hydropower which offers proven approaches to minimizing the environmental and societal trade-offs. The Energy security have further strengthened the partnership: for India, hydropower reduces the reliance on fossil fuel imports and it enhances the grid resilience; for the EU, it supports the decarbonization process and system flexibility in the wake of shifting dynamics of the energy supply.

When it comes to technological innovation, most importantly financing act as the operational drivers of this collaboration. Country, India can draw on the EU's expertise in advanced pumped storage, digital grid optimization, as well as the high efficiency turbine designs, addressing the operational inefficiencies through joint and multidisciplinary research, transfer of the technology, as well as targeted capacity building. But on the financing side, integrated approaches which combining public private capital flows, risk mitigation tools, and carbon market revenues are very much crucial to overcoming this sector's significant upfront costs and the

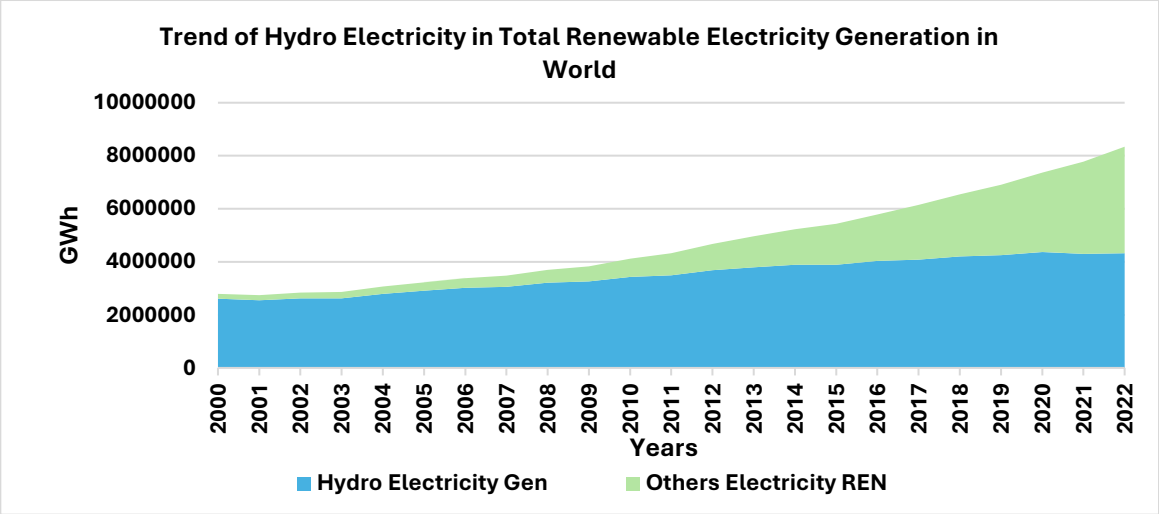
extended development timelines. This collectively shape the strategic pathway to make hydropower a central, scalable, and socially responsible component of India's energy transition, leveraging EU collaboration to deliver long-term, benefits for climate resilience.

Global Trends, Challenges, and Best Practices

The Rise of Non-Hydro Renewables

At the starting of the 21st century, hydropower has been accounted for a great majority of global renewable electricity. When 2000 started, hydro generation stood around nearly 2.61 million GWh. But over the next around twenty-two years, this increased has been gradually to approximately 4.33 million GWh by 2022 reflecting a stable but moderate growth trajectory of the hydro power.

Figure 01: Trend of Hydro Electricity in Total Renewable Electricity Generation in World



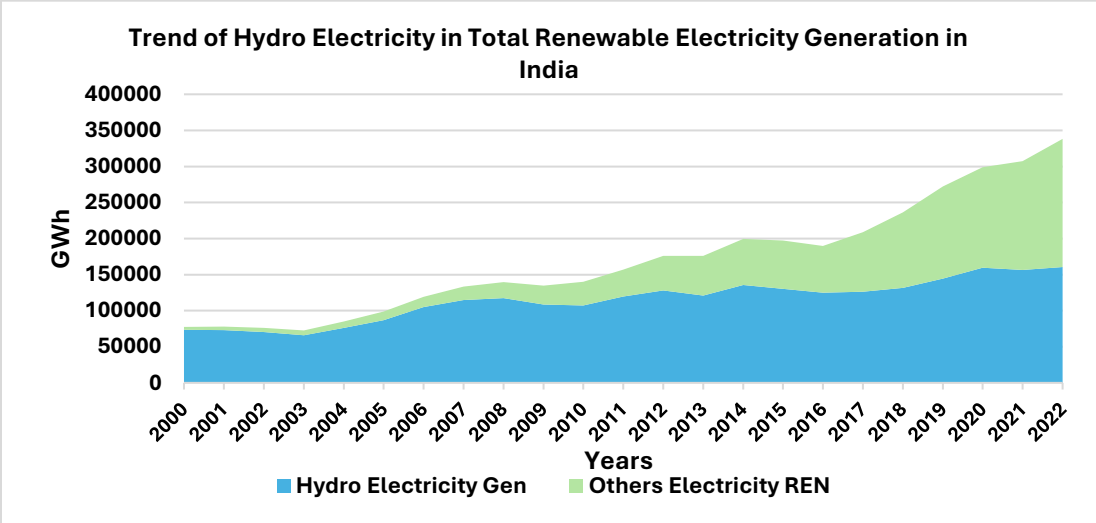
Source: International Renewable Energy Agency (IRENA) (2022), Renewable Energy Statistics 2022

If we look at the above figure, it is showing the similar thing that despite this increase, hydro's proportion of total renewable generation has declined in a steady way. Globally, hydropower's share in total renewable electricity generation declined from around 93% in year 2000 to roughly around 51% in 2022, a consequence happened because of the spectacular ascent of solar, wind, and other technologies. The global generation from "others" leapt from just 178,527 GWh in 2000 to more than 4.01 million GWh by 2022, which marks a more-than-twentyfold rise as the wind and solar energy achieved dramatic cost reductions and extensive policy support from the government.

This transformation reflects that there are several key developments when it comes to renewable energy: we have seen that wind and solar have cost reduction, enabling widespread deployment; governments across the globe have set ambitious renewable energy targets; improvements in grid integration and storage have supported the increase in variable renewables; and climate imperatives have created pressure for further expansion. As a result, the system of renewable electricity generation has becoming increasingly diversified. Hydropower is still critical, is shifting from being the largest generator to only serving as a complementary asset providing reliability, flexibility, and storage to balance fluctuating output from other renewable sources.

India's Transitional Path: Slowdown in Hydro, Rapid Expansion of Others

Figure 02: Trend of Hydro Electricity in Total Renewable Electricity Generation in India



Source: International Renewable Energy Agency (IRENA) (2022), Renewable Energy Statistics

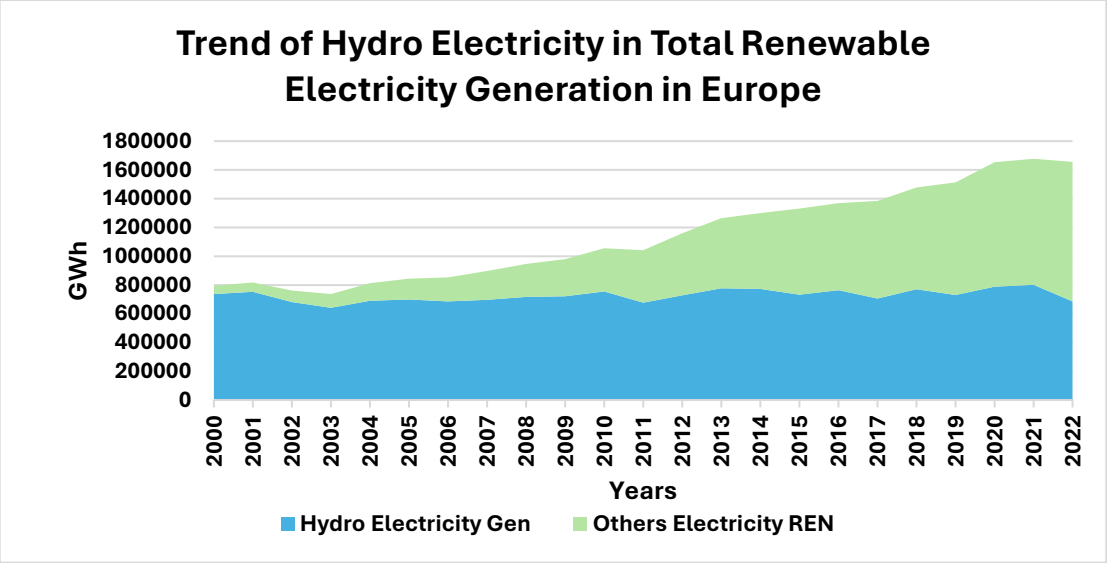
In India, the share of the hydroelectricity in total renewable electricity generation has decreased from almost around 95% in year 2000 to under 50% by year 2022. By 2022, other renewables had surged up to 177,616 GWh, showing that these all has overtaken hydropower, which stood at 160,573 GWh a landmark reversal in India's renewable mix. Government initiatives like the National Solar Mission, competitive tariff auctions, and ambitious renewable targets at the state level has catalyzed the deployment of these sectors. This changing energy mix scenario has underscores structural challenges for hydropower: slow project delivery, environmental clearance bottlenecks, financing difficulties, displacement issues, and water supply uncertainty all of which have been exacerbated by climate change. On the other hand, the wind and solar projects in India are rapidly deployed and scalable, permitting higher velocity expansion and more modular adaption to the demand for self-sustained electricity. Despite losing its dominance, hydropower has retained crucial importance for country like India. It

supplies peak-load electricity, supports frequency regulation, offers black start capabilities, and, via pumped storage, provides bulk energy storage for maintaining the growing shares of variable renewables sources.

Lessons from Europe: Evolving Hydro's Role in a Diversified Mix

European Union countries can be taken into consideration as a mature example of a hydro-dominated market transforming into a diverse renewable portfolio. The Hydropower output remained relatively steady through the early 2000s, also fluctuating with precipitation and water availability. But by year 2010, non-hydro renewables reached 300,432 GWh, that is setting the stage for a dramatic transition.

Figure 03: Trend of Hydro Electricity in Total Renewable Electricity Generation in Europe



Source: International Renewable Energy Agency (IRENA) (2022), Renewable Energy Statistics

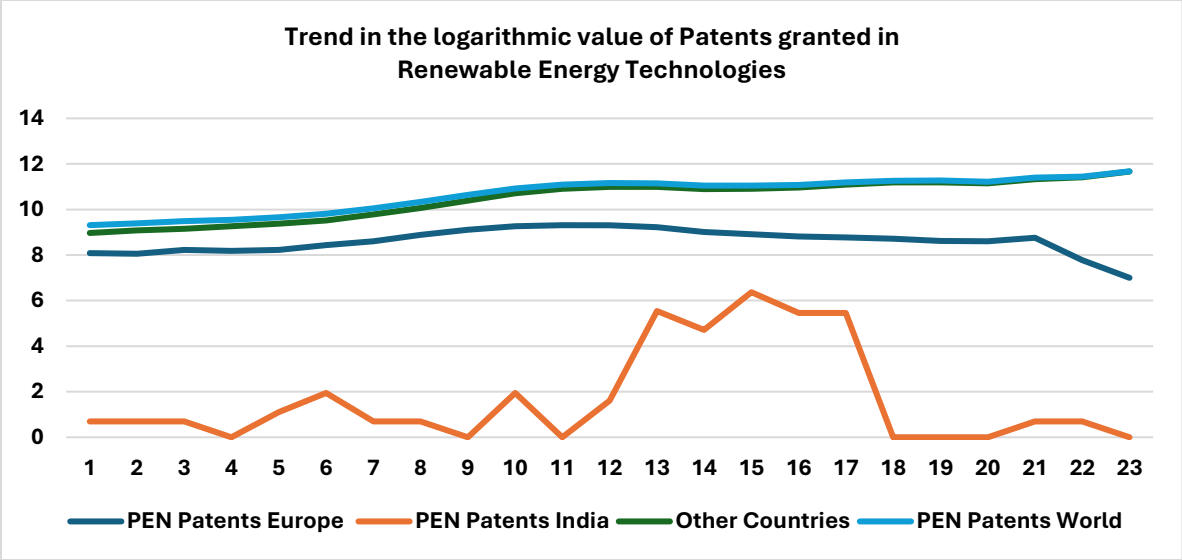
The mid-2010s has been marked as a watershed moment for European renewables structure; The share of hydroelectricity in the Europe's total renewable electricity generation has been declined significantly, from about around 92% in year 2000 to roughly 40% in year 2022, can be seen as a synergy of technology advancements, robust policy environments (notably the EU Renewable Energy Directive), and major investments in solar, wind, and biomass which sparked rapid growth. By the year 2017, non-hydro sources had surpassed hydro in total annual output. Crucially if we see, Europe's transition did not discard hydro; but it repositioned hydropower as a system stabilizer and the medium of storage facility. The pumped storage facilities in countries such as Austria, Norway, and Switzerland serve as renewable "batteries," storing surplus wind and solar for later use. This allows the EU to maintain the system reliability while phasing out fossil peaking plants and maintaining low carbon

emissions. Europe's experience shows that hydropower's contemporary value lies in its functionals of the transformation: from a primary generator to a strategic support asset for high-renewable grids structure.

Challenges, Implications for India and Opportunities for Collaboration

The comparative trends show across India as well as in Europe point to several pathways for India to enhance and adapt the hydropower's role as part of its energy transition. Europe begins in 2000 with a relatively high log value of 8.08, peaks near 9.31 by 2010, and then steadily declines to 6.99 by 2022, suggesting a relative slowdown in patent activity. India starts with very low log values (0 - 1.94), reflecting its modest patent base, but records sharp increases in 2012 (5.54) and 2014 (6.36) before levelling off in later years. Other countries display steady proportional growth, moving from 8.96 in 2000 to 11.66 in 2022. The global total follows a similar pattern, rising from 9.31 to 11.67 over the same period.

Figure 04: Trend in the logarithmic value of Patents granted in Renewable Energy Technologies



Source: International Renewable Energy Agency - INSPIRE Platform (2025)

It emphasized that India seeks a partner who actually contributes to the transfer of technology in the energy sector. In that sense, Europe can be a good trade partner for India. Other major Challenges the European partnership will improve our following sectors for a better hydro power generation:

- **Modernization of Infrastructure**: Europe has extensive experience upgrading ageing hydro plants with new turbines, digital automation, and operational optimization. Replicating these strategies could increase output and flexibility at Indian hydro facilities without large-scale new construction.
- **Climate Adaptation**: Both regions encounter increased hydrological variability. If we see Europe's advanced reservoir management, real-time forecasting, and integrated river basin planning the will feel that it could help India mitigate risks associated with the shifting of monsoon patterns and glacial melt.
- **Hybrid Systems**: Europe's move toward the hybrid systems that has combine hydro with wind and solar offers a template for Indian states with seasonal hydro generation, enabling the reliable renewable supply year-round.
- **Innovative Financing**: Models such as green bonds and community energy schemes if used in Europe could support the sustainable expansion of the Indian hydro within robust environmental and social frameworks.
- **Research & Innovation**: Joint efforts in exploring pumped hydro for long time duration and storage storage, micro-hydro for rural areas, and artificial intelligence for predictive maintenance could be able to maximize the value and reliability of India's hydropower resources.

The study shows, to begin with, the high capital intensity of the hydropower remains a critical obstacle. Larger upfront in investment requirements, coupling with long gestation periods, make such projects less appealing to commercial financiers and developers in India and across the Global South. This financing burden slows down both the new capacity additions and modernization efforts. Secondly, for important complex clearance processes may hinder timely project implementation. Hydropower schemes must be navigated multiple environmental and the land related approvals, often intertwined with sensitive issues such as the resettlement and the community opposition. These procedural and social hurdles can significantly extend project timelines and heighten execution risks in India's regulatory environment. A further challenge that may lies in tariff competitiveness. Due to prevailing of the financing structures and the frequent cost that overruns, hydropower tariffs in much of India remain higher than those for wind or solar, reducing its attractiveness in an increasingly price-sensitive renewable market. Finally, the technological gaps which persist. India may continue to depend heavily on imported expertise for advanced turbine technology, digital monitoring systems, and the pumped storage solutions capabilities essential for integrating hydropower as a flexible, grid-balancing resource.

Policy Interventions, Changes, and Innovations

It is important for India to accelerate sustainable hydropower by integrating EU best practices with domestic priorities. Like a single-window clearance system may speed approvals while safeguarding the environment, which is complemented by performance-linked incentives to reward timely project completion. The blended finance tools like green bonds, concessional loans, and risk guarantees can lower costs and may attract the investment. Then comes the Indo EU innovation hubs which should make advancement of turbine efficiency, digital plant control, and hydro informatics. With this, stronger ESG frameworks with the benefit-sharing and fair resettlement must be made mandatory. An annual Indo-EU Hydro Forum may be helpful to drive collaboration, monitor the progress, and refine strategies, making the hydropower a key pillar of India's clean, equitable, and resilient energy future.

Conclusion and Recommendations

This study finds that India and EU's hydropower partnership shows a significant opportunity to accelerate India's renewable energy transition through providing the adoption of advanced technologies, sustainable design practices, and the climate-resilient solutions. Even if the hydropower's which have the share in the global renewable mix has reduced, its role in making and ensuring grid stability, providing the storage capacity, and meeting peak-demand needs remains indispensable. By leveraging and looking at the EU's strengths and ability in the modernization, pumped-storage development, and hybrid renewable integration, India can overcome long-standing challenges such as financing gaps, regulatory delays, and ecological constraints. A phased strategy that emphasizes the institutional collaboration, demonstration projects, skill development, and nationwide scaling can position hydropower as a dependable low-carbon pillar of India's energy system, while simultaneously strengthening the energy security, fostering domestic innovation, and promoting inclusive growth through community engagement.

By realizing this potential, a well-funded Indo-EU Hydro Task Force may provide the strategic oversight, and can also prioritizing the expansion of pilot initiatives in pumped storage and advanced hydropower supported by EU technical expertise and financing. Another important thing is modernizing India's permitting framework through a streamlined single-window mechanism inspired by the EU models, along with the joint ventures and innovation hubs, that can boost local manufacturing capability and build a skilled workforce. Integrating the strong environmental safeguards as well as ensuring equitable community benefit-sharing must remain central to all

project designs. Optimum financial help and concessional funding can mitigate tariff and risk barriers, reinforced by continuous platforms for knowledge exchange and policy alignment.

Limitations

The study shows that India–EU hydropower partnership faces notable constraints, for example possible political and policy divergences arising from changing governmental priorities in both regions. The environmental sensitivities and local community resistance necessitate continuous, adaptive engagement to maintain trust as well as acceptance. Technology transfer efforts may navigate the balance between the accessibility and intellectual property rights, adding layers of complexity, but should be backed by the social capital. Furthermore, apart from this all, climate-driven hydrological uncertainties threaten long-term operational reliability. These all challenges, though significant, can be addressed through strong governance, participatory planning, and flexible strategies to sustain the hydropower's role in India's clean energy transition.

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