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From Peak Gaps To Power Security: India's Path To Round-The-Clock Renewable Energy

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Abstract
India's transition to round-the-clock renewable energy (RTC RE) is pivotal for achieving its climate objectives and ensuring energy security. While the nation has made significant strides in expanding renewable energy capacity, several challenges impede the realization of uninterrupted clean energy supply. These include limited energy storage infrastructure, transmission constraints, policy and market design gaps, financial hurdles, and institutional coordination issues.

Comparative analyses of China's and Brazil's renewable energy strategies offer valuable insights. China's extensive investments in energy storage and grid infrastructure, alongside Brazil's utilization of dispatchable hydropower, demonstrate effective models for integrating variable renewable sources.

To overcome existing barriers, a multifaceted approach is essential. Key recommendations encompass accelerating the deployment of energy storage solutions, enhancing grid infrastructure, implementing supportive policies and market mechanisms, addressing financial constraints through innovative funding models, and strengthening institutional frameworks for better coordination.

By adopting these strategies, India can advance towards a resilient and sustainable energy future, aligning with global climate commitments and fostering economic growth.

Introduction
Renewable energy is generated from natural resources that are naturally replenished, such as sunlight, wind, flowing water, geothermal heat, and biomass. These sources do not deplete with use and are critical to reducing greenhouse gas emissions and ensuring a sustainable energy future.

Hydropower remains the largest renewable contributor, providing ~14% of total global electricity, followed by wind and solar at 5%–8% each. However, a major limitation of wind, solar, and to some extent hydropower, is that they are **not dispatchable**, i.e. their output depends on variable natural conditions and cannot be controlled or scaled up on demand. This intermittency makes it difficult to meet electricity needs consistently, particularly during peak hours or unfavourable weather. To maintain grid reliability, these sources must be complemented by energy storage, grid-balancing systems, or firm power sources.

This challenge has led to a growing global focus on **Round-the-Clock Renewable Energy (RTC RE)** is the ability to deliver renewable power 24×7, regardless of weather or time. RTC RE solutions **combine multiple renewable sources** with **storage technologies and flexible grid operations**.

India currently generates over 70% of its electricity from fossil fuels, with just 22% from non-nuclear renewables. To meet its clean energy targets (500 GW of non-fossil capacity by 2030) and move toward net-zero emissions, India must rapidly expand renewables and implement RTC RE at scale.

RTC RE will support energy-intensive sectors such as manufacturing, data centers, railways, and heavy industry in shifting to clean energy without compromising reliability. It will also allow Discoms (Distribution Companies) to provide 24x7 green power to commercial and industrial consumers increasingly committed to sustainability.

In short, RTC RE is central to achieving India's climate goals while ensuring secure and reliable electricity. The following sections explore India's electricity ecosystem, lessons from China and Brazil on RTC RE, key challenges to RTC RE, and potential solutions.

India's Electricity Ecosystem: Generation, Grid, And Demand

To understand the challenge of RTC renewables, it is important to grasp the structure of India's electricity ecosystem – from generation sources to the transmission grid and consumption patterns. India today is the world's third-largest electricity producer, generating about **1,949 terawatt-hours (TWh) in 2023–24.**

This power is supplied by a mix of generation sources. As of mid 2024, India's total installed generation capacity was ~442 GW, composed of roughly 55% fossil-fuel-based capacity and 43% non-fossil sources with the rest being Nuclear. Coal continues to dominate the mix, accounting for approximately **48%** of India's total installed generation capacity in 2023–24, followed by lignite at **1.5%** and natural gas at **5.6%**. Large hydroelectric projects contribute about **10.6%**, while renewable energy installations primarily solar and wind, together make up around **24.9%** of the capacity, with solar at **15.2%** and wind at **9.7%**. Nuclear power remains a smaller contributor, comprising about **1.8%** of total capacity.

On the **transmission and grid** side, India has developed a vast national power grid that connects virtually all states. A milestone was achieved in December 2013 when the Southern grid was synchronized with the rest of the country, creating a unified national grid operating at one frequency (50 Hz) This "One Nation, One Grid, One Frequency" system allows power to flow between regions, enabling surplus generation in one region to meet deficits elsewhere. Despite the existence of a national grid, **transmission limitations** remain in certain corridors, which can constrain the delivery of power from renewable-rich areas to high-demand centers. In fact, soon after achieving a unified grid, congestion issues were observed: surplus power in some regions could not always reach consumers in other regions due to inadequate transmission capacity. For instance, as of 2016, the southern states faced periods of high prices and shortages even while power plants in eastern/central India were underutilized, highlighting the need for further grid strengthening.

The government's Green Energy Corridor initiative has been implementing dedicated transmission lines and substations to evacuate renewable power from resource-rich states (Tamil Nadu, Karnataka, Gujarat, Rajasthan, etc.) and integrate it into the grid. Going forward, substantial expansion of interstate transmission will be required to support 24×7 renewable power flow across the country.

On the **demand side**, India's power usage follows daily and seasonal patterns that pose challenges for renewables. Peak demand typically occurs in the evening hours after sunset, driven by residential lighting and cooling, which is a timing mismatch with solar availability. Peak loads are also higher during summer months due to air-conditioning and agricultural irrigation needs. In recent years, India's peak electricity demand has been rising rapidly – the record peak met reached ~240 GW in 2023 and about 250 GW in the summer of 2024. Notably, the **unmet demand** (load shedding or deficits) tends to occur in the late evenings or early mornings when solar generation is zero and wind may be low. For example, on a scorching day in May 2024 when a new peak of 246 GW was hit, the grid had no trouble during solar hours but faced a 13.25 GW supply shortfall during non-solar night hours.

This underscores why round-the-clock supply is essential – without storage or other firming capacity, a high-solar grid can experience energy shortages at night even if there is surplus solar power in the day. Similarly, seasonal variations affect demand and renewable output: monsoon months can reduce solar generation but also cool temperatures; winter evenings in northern India see high demand but minimal solar. The current **power mix and usage pattern** therefore demand flexibility. Traditionally, coal and large hydro have provided most of the load-following and peaking power. But as the share of inflexible solar/wind grows, the system must evolve to maintain reliability around the clock. In summary, India's electricity ecosystem is a complex interplay of a diverse generation mix, a sprawling but capacity-constrained grid, and dynamic demand patterns – all of which influence the pursuit of RTC renewable energy.

International Comparisons: Rtc Renewable Energy In China And Brazil

India can draw valuable lessons by examining how other large developing countries are integrating renewables and moving toward round-the-clock clean power. This section compares the electricity infrastructure and progress on RTC renewables in **China** and **Brazil**, two countries with significant renewable resources and ambitious energy goals, providing case studies in managing high RE penetration.

China

China has built the world's largest power system, with a total generation capacity of roughly 2,920 GW (as of 2023), nearly seven times India's capacity. Crucially, over half of China's capacity is now non-fossil (renewables + nuclear comprised ~53.9% in 2023) reflecting massive investments in solar, wind, and hydro.

However, coal-fired plants still supplied almost 60% of China's electricity in 2023, indicating that, like India, China faces the challenge of translating renewable capacity growth into year-round generation. China's approach to enabling RTC renewable supply centers on **scaling up energy storage and grid expansion** at an unprecedented scale. By the end of 2023, China had about 86 GW of energy storage capacity operational – including an astonishing ~51 GW of pumped hydro storage (the largest fleet in the world) and roughly 35 GW of battery storage. IIn comparison, India's installed storage is only a few gigawatts. This storage boom in China has been driven by deliberate policy: the government's plans target 62 GW pumped storage by 2025 and ~120 GW by 2030 alongside aggressive deployment of grid-scale lithium battery projects. The ample storage provides a buffer to smooth out the variability of China's ~1,200 GW of wind and solar capacity helping to deliver energy when the sun isn't shining or wind isn't blowing.

Another pillar of China's strategy is its **strong national grid** with ultra-high-voltage transmission lines that ship renewable power across vast distances. China has invested heavily in "West-to-East" transmission – for instance, sending wind and solar power from the sparsely populated northern and western regions (Inner Mongolia, Gansu, Xinjiang, etc.) to the high-demand eastern cities. This geographic dispersion means renewable generation in one region can often cover for a shortfall in another. A notable case study is the experience of **Qinghai province** in northwest China. Qinghai, endowed with expansive solar farms and hydropower, conducted a trial in 2017 where the entire province ran on 100% renewable energy for 7 consecutive days (168 hours). During that week, a mix of hydro (around 80% share) and solar/wind (20%) successfully met Qinghai's demand, demonstrating that round-the-clock renewable supply was possible at a regional scale with careful coordination. This experiment showcased the potential of combining different renewables (daytime solar, evening wind, and all-day hydro) to achieve continuous power. China is also piloting "renewable energy base" projects – giant complexes that integrate tens of GW of solar and wind with storage to provide stable output. In summary, China's progress on RTC RE is marked by large-scale **storage deployment** (both pumped hydro and batteries) to time-shift renewable energy, **grid infrastructure upgrades** (especially long-distance transmission) to balance regional resources, and **flexible operation** of its huge fleet of hydro and even thermal plants to fill gaps. While coal still plays a big role in ensuring 24/7 supply today, China's investments are steadily reducing the reliance on coal for balancing. The country's experience underlines the importance of proactively expanding storage and grid capacity alongside renewable generation – a lesson highly relevant for India.

Brazil

Brazil presents a different yet instructive example. Brazil's electricity system already obtains the **vast majority of its power from renewable sources**, thanks primarily to hydropower. In 2023, a remarkable 93.1% of Brazil's electricity generation came from renewables (chiefly hydro, along with growing wind and solar). The Brazilian power mix is dominated by large hydropower dams, which accounted for roughly 59% of installed capacity and an even larger share of actual generation in 2023. Hydropower's key advantage is its dispatchability – water can be stored in reservoirs and turbines ramped up or down to match demand, effectively providing round-the-clock renewable energy (as long as water is available).

In recent years, Brazil has significantly expanded **wind and solar** generation as well, reaching about 13% of generation from wind and 7% from solar in 2023. The integration of wind with Brazil's hydropower-dominated grid has been largely complementary: many of Brazil's wind farms are in the northeast region, where wind output tends to be strong at night and in drier months, allowing wind power to supplement hydropower (and conserve water in reservoirs). Brazil operates a nationally interconnected grid (excluding some remote Amazonian areas) with an independent system operator (ONS) that centrally dispatches generation to maintain supply 24/7.

A case in point of Brazil's progress is how it handled a severe drought in 2021–2022 that strained hydropower – the country accelerated contracting of wind, solar, and even battery projects to make the system more resilient. By 2023, with improved rains and ample new renewables, Brazil was able to drastically cut back fossil generation: gas-fired plants were used only as a last resort for peak loads, and gas fuel imports for electricity fell to their lowest levels in two decades

Essentially, Brazil leveraged **hydro as a giant storage battery**, and **wind/solar as additional energy sources**, to achieve near-RTC renewable supply nationally. It is not unusual on breezy nights for Brazil's entire electricity demand to be met with a combination of hydro and wind, with fossil plants completely idle.

Brazil's example highlights the importance of **flexible renewable resources** (like reservoir hydropower) and a **coordinated grid dispatch** in achieving RTC supply. While India does not have as high a proportion of hydro, certain regions (e.g. Himalayan states or the Northeast) have untapped hydro potential that could play a balancing role similar to Brazil's dams. Furthermore, Brazil's success with integrating wind at scale (now over 24 GW installed, often achieving capacity factors above 40%) demonstrates that renewables can become a reliable backbone of power supply with the right complementary mix.

For India, a takeaway is the value of diversity: Brazil's portfolio of hydro + wind + biomass + solar, managed by a unified national operator, provides inherent round-the-clock stability that solely solar or wind could not achieve. However, Brazil also underscores a challenge – dependence on one resource (hydro) can be risky under extreme weather (drought), so even Brazil is now investing in battery storage and additional non-hydro renewables to ensure firm power in dry years. Both China and Brazil illustrate different facets of enabling continuous renewable energy: China via massive **infrastructure build-out** (storage, transmission) and Brazil via **maximizing natural complementary resources and grid management**. These comparative insights inform the discussion on India's unique challenges and potential solutions for RTC renewables.

Key Challenges For Rtc Renewable Energy In India

Despite strong renewable energy growth, India faces several major challenges in realizing large-scale RTC renewable power. These challenges are technical, economic, and institutional in nature, cutting across the generation, grid, and policy domains. The most prominent issues include **insufficient storage capacity**, **grid constraints**, **policy and market limitations**, **financial hurdles** and **governance/institutional gaps**. This section examines the biggest obstacles in detail.

1) Limited Energy Storage Deployment:

Perhaps the foremost barrier to 24×7 renewable power is the lack of sufficient energy storage in India's grid. Solar and wind output is intermittent and cannot by themselves meet round-the-clock demand without storage or other balancing resources. Yet India's installed storage capacity today is minuscule relative to need. India has only about 4.75 GW of pumped hydro storage plants installed, and due to operational issues only ~3.3 GW of that is currently functional in pumping model. Grid-scale battery storage is in an even nascent stage. Current battery energy storage installations amount to only a few hundred megawatt-hours, largely in pilot projects. This is a **tiny fraction** of what is required to smooth renewable variability across India's ~200+ GW of variable renewables.

In contrast, China has already deployed tens of GW of storage for its grid. The scarcity of storage means India's grid has limited ability to bank surplus solar generation (e.g. from noon hours) for use during night peaks. Consequently, the system remains dependent on coal and gas plants for night-time power and ramping flexibility. The government has recognized this gap. For example, the Central Electricity Authority (CEA) estimates that about 73,900 MW of energy storage (pumped storage and batteries) may be needed by 2031–32 to support renewable integration. While pumped hydro is a proven large-scale solution, projects have long lead times and face environmental clearance and land acquisition hurdles. Battery costs, though falling, are still high and most batteries deployed globally are in more developed markets.

Thus, the **storage deficit** in India is a critical challenge: without a dramatic scale-up of storage (pumped hydro, lithium batteries, other emerging technologies), true round-the-clock renewable supply will remain difficult. Developers of RTC RE projects cite high storage costs and technology risk as a key difficulty – the upfront cost of battery systems makes purely RE + storage based RTC power currently expensive and hard to finance. Although India is now planning for ~50 GW of pumped storage and ~40+ GWh of batteries by 2030 these plans are just beginning to materialize. Bridging the storage gap is an urgent challenge to reliably meet demand with renewables.

2) Grid Infrastructure and Transmission Constraints

Delivering RTC renewable power requires a robust grid that can transmit electricity from wherever the wind blows or sun shines to wherever demand is, at any time. India's grid, despite being nationally synchronized, suffers from **capacity constraints and bottlenecks** in certain links. Renewable energy resources are often concentrated in specific regions (e.g. solar in Rajasthan and Gujarat, wind in Tamil Nadu and Gujarat, hydropower in the Northeast and North), far from some load centres.

Inadequate transmission capacity causes curtailment of renewables and inability to serve distant demand. A notable issue has been the **north-south transmission bottleneck**: historically, the Southern Region grid had shortages and high prices while power surplus existed in Western/Central India, due to limited corridor capacity. Though new high-voltage lines have reduced this gap, further expansion is needed as RE capacity grows. Additionally, integrating a high share of renewables requires advanced grid management (for voltage/frequency control and stability). The current infrastructure is still catching up. Grid congestion occasionally forces grid operators to back down solar/wind plants to maintain stability. For instance, states like Tamil Nadu (with surplus wind in monsoon nights) have at times curtailed wind generation when local demand was low and export was limited.

Another aspect is **regional balancing**: to achieve RTC supply, renewable generation might need to be pooled from multiple states (e.g. solar from Rajasthan, wind from Tamil Nadu combined to serve a national RTC contract). However, arranging **open access and transmission for multi-state projects is complex**. Developers report challenges in obtaining long-term access to the interstate transmission system at multiple points and managing different state regulations. In summary, while India's national grid is a major asset, its **limitations in transmission capacity and smart grid capabilities** pose a challenge for RTC RE. Without significant upgrades – new transmission corridors (like the Green Energy Corridors), dynamic control systems, and possibly grid-scale storage at strategic nodes, renewable energy cannot freely flow on demand across the country. Thus, grid infrastructure is a critical bottleneck that needs to be overcome to support 24×7 renewables.

3) Policy and Market Design Issues

The policy and regulatory framework in India, until recently, did not specifically incentivize round-the-clock renewable supply. Renewable energy policies focused on capacity addition

(MW of solar/wind) and % share targets, but **not on firmness or time-of-day availability**. This led to a situation where discoms procured cheap solar power for daytime but relied on coal plants for evening power, with little obligation to ensure renewables could meet night peak.

There have been some changes: the government introduced **Renewable Purchase Obligations (RPO)** and has now added an **Energy Storage Obligation** – requiring that a portion of RPO be met by renewable energy stored for later use. Also, **RTC renewable tenders** initiated by Solar Energy Corporation of India (SECI) since 2019 signal a shift to demand firm power from renewables. However, various market design gaps remain. One issue is the lack of a full-fledged **ancillary services and capacity market**. In a power system with high renewables, resources like storage or peaking plants need compensation for just being available at critical times (capacity payments) and for providing services like frequency regulation. India's power market is still evolving on this front. The electricity spot market mainly deals in energy (kilowatt-hours), with nascent ancillary service mechanisms. Moreover, rigid long-term contracts for conventional power have sometimes reduced the flexibility to ramp down thermal generation and ramp up renewables.

Tariff structures are also a factor: retail electricity tariffs historically were flat or only mildly time-differentiated, giving consumers and discoms little economic signal to store cheap solar power for later. The regulator has now mandated Time-of-Day tariffs from 2024 onwards for large consumers, which should eventually encourage demand-shifting and storage usage. Additionally, **regulatory approval processes** for new technologies can lag. For example, standards for battery storage procurement, or rules for energy trading from hybrid/storage projects, have taken time to develop.

In summary, the policy environment is improving (with RTC bidding guidelines, storage mandates, etc.), but **market incentives are not yet fully aligned** to make RTC renewables the default choice. Policy uncertainty can also deter investment – developers need clarity on how storage will be treated in tariffs, whether there will be penalties or rewards for RTC performance, and how renewable integration costs (transmission, balancing) will be allocated. Addressing these policy and market design issues is essential to create the right conditions for RTC RE growth.

4) Financial and Economic Hurdles

The transition to round-the-clock renewables requires significant investment in generation, storage, and grid infrastructure and this faces financial constraints. A major challenge is the weak financial health of state distribution companies (discoms), which are the primary purchasers of electricity. Many Indian discoms are loss-making and carry heavy debt; cumulative losses of state discoms were approximately Rs 6.5 lakh crore (trillion) by 2022–23, about 2.4% of GDP. This puts them in a poor position to sign contracts for more expensive renewable + storage power or to invest in upgraded systems.

Discoms often prioritize least-cost short-term power purchases due to their financial stress, rather than long-term sustainability. While solar and wind are now very cheap per unit, adding storage for RTC supply raises the cost. Developers of RTC projects have noted that **financing such projects is difficult**: the high upfront capital cost and relatively unproven revenue model (for storage) make lenders cautious. Without concessional financing or guarantees, scaling up storage remains slow. Another financial hurdle is the **access to capital and technology** for newer solutions. Advanced batteries, smart grid tech, etc., often need international investment or partnerships. High interest rates or perceived risks in India can increase project costs.

On the consumer side, industrial users who might invest in RTC renewable contracts need assurance of cost-competitiveness. If coal power is subsidized or its external costs (pollution) not priced, RTC renewables could seem less attractive economically. Moreover, the power sector's structure sometimes leads to payment delays developers worry about payment security from discoms, which is why SECI's payment security mechanisms have been vital for renewable IPPs.

In summary, financial constraints discoms' poor finances, high capital costs for storage, and the need for viable business models are a significant challenge. Overcoming these will likely require policy support (subsidies, viability gap funding) and sector reforms (improving discom finances, perhaps through privatization or better tariff discipline.

5) Institutional and Governance Gaps

Finally, governance issues and coordination challenges hinder the implementation of RTC renewable energy. The power sector in India is institutionally fragmented – generation, transmission, and distribution involve multiple entities (central PSUs, state utilities, regulators at center and state, etc.). Achieving something as cross-cutting as round-the-clock RE requires these entities to work in tandem, which is not always the case. For example, planning of generation and transmission is sometimes done in silos; renewable capacity might be added by one agency while transmission lags because coordination with the central transmission planner (CEA/POSOCO) was insufficient.

State-Center coordination is crucial since states ultimately distribute power. If some states are reluctant to buy RTC renewables or to allocate land for new transmission, national goals suffer. Additionally, each state regulator sets rules for grid connections, balancing charges, etc., which can differ and complicate inter-state RE projects. Another governance issue is **contracting and aggregation for RTC**: an optimal RTC RE supply may involve pooling resources from different owners and states, but there is no single authority that arranges such pooling outside of the tender process.

The first RTC tender had to allow developers to tie up multiple projects across states; doing this requires handling different land permits, PPA arrangements, and scheduling coordination, a complex undertaking. The lack of a streamlined framework for such multi-source projects is a governance gap. Moreover, while India has a national renewable energy ministry (MNRE) and a power ministry, their schemes need alignment – for instance, storage policy might fall between the two. **Regulatory delays** in adapting rules for energy storage, or in approving tariffs for hybrid projects, also reflect institutional learning curves for new concepts. Lastly, governance also extends to **grid operations**: the capabilities of load dispatch centers to forecast renewable output and manage variability are still being developed; investments in human resources and tools for grid operators are needed.

In summary, institutional gaps, whether in planning, inter-agency coordination, or regulatory agility, pose challenges to implementing RTC renewables smoothly. Addressing these will require strong policy direction and perhaps new institutional mechanisms (such as a nodal agency for energy storage or a better coordination forum between generation and transmission planners).

In conclusion, India's quest for round-the-clock renewable energy is impeded by a confluence of challenges: insufficient storage capacity, grid and transmission limitations, evolving policy frameworks, financial impediments, and multi-layered governance issues. These challenges are significant but not insurmountable. Recognizing them clearly, as above, is the first step toward formulating targeted solutions. The next section discusses how India can overcome these hurdles through strategic interventions and a coordinated roadmap.

Solutions And Roadmap For Rtc Re Expansion In India

Overcoming the challenges outlined requires a comprehensive and coordinated strategy. India's experience, together with lessons from countries like China and Brazil, suggests that a multipronged approach is needed – combining policy reforms, infrastructure upgrades, market mechanisms, and institutional development. Below, we propose actionable solutions and a possible roadmap to accelerate round-the-clock renewable energy deployment:

A) Accelerate Energy Storage Deployment (Pumped Hydro and Batteries)

A top priority is to vastly expand energy storage capacity, since storage is the linchpin of RTC renewable systems. The government should facilitate swift development of **pumped storage projects (PSPs)** by removing bottlenecks in approvals and providing financial incentives. Pumped hydro is cost-effective over its lifetime and offers large-scale storage (with no import dependency), but current projects face long delays. Recent steps such as treating PSPs as renewable, waiving transmission charges, fast-tracking environmental clearances for off-river sites, and directing states to provide land concessions must be implemented rigorously. CEA has identified 180+ GW of PSP potential. Even tapping a fraction (say 20–30 GW by 2030) would greatly enhance grid flexibility.

Concurrently, **battery energy storage systems (BESS)** need a boost through initiatives like production-linked incentives (to lower costs via local manufacturing of lithium-ion cells), viability gap funding for initial large projects, and mandated deployment. The government has already raised the ambition for BESS (targeting 4,000 MWh in initial tenders and 14,000 MWh under one scheme) and an SBI report projects up to 42 GWh of BESS by 2032. Achieving this will require making BESS projects bankable, possibly through 15-year assured capacity payments or permitting multiple revenue streams (peak energy sale, grid services). By 2030, a combination of, for example, 50 GW of pumped storage and 50 GWh of batteries would fundamentally transform India's ability to use renewables round-the-clock.
The roadmap could include interim targets (e.g. 10 GW storage by 2025, 20 GW by 2027, etc.) and periodic auctions for storage capacity. R&D into emerging storage tech (advanced chemistries, thermal storage, even green hydrogen for seasonal storage) should also be supported to ensure a pipeline of solutions. Simply put, **scaling storage is non-negotiable**. India needs to treat it as critical infrastructure, akin to how it treated highway construction or coal capacity in past decades, with urgent public and private investment.

B) Upgrade Transmission & Grid Infrastructure

In parallel with adding renewables and storage, India must strengthen and modernize the grid to handle flexible, distributed generation. This involves building new **transmission corridors** to renewable-rich areas and expanding the transfer capacity between regions. The

Green Energy Corridor projects (Phase I and II) which target thousands of circuit-km of new lines and substations for ~20 GW of RE evacuation should be expedited, and a Phase III (as being planned should aim for the 2030 horizon of 450–500 GW renewables. The national grid operator should continuously identify emerging congestion points and address them with network augmentation or FACTS (flexible AC transmission) devices. Additionally, the grid needs more **real-time monitoring and control** tools (PMU-based wide area monitoring, dynamic line rating, etc.) to safely integrate high renewables.

Another key aspect is implementing a **smart grid** at the distribution level. For example, automated demand response systems that can reduce loads when supply is tight, thereby aiding RTC balance. Investment in **regional balancing mechanisms** like HVDC links that can transfer power with minimal losses will also help (e.g. additional HVDC links between southern and northern regions to move surplus power quickly). The roadmap should align generation and transmission planning: every large renewable park or RTC project should come with a planned transmission expansion. Better **storage integration into the grid** is also needed, e.g., locating storage at strategic nodes to relieve transmission during peaks (storing energy when lines are full and releasing when lines are free).

Finally, strengthening the **interconnections with neighbouring countries** (Bangladesh, Nepal, Bhutan) can provide mutual support – Bhutan's hydropower, for instance, already helps India manage peak demand and could be further incorporated as RTC renewable import. To summarize, a robust, flexible grid underpins RTC RE – the plan must be to invest heavily in grid infrastructure over the next decade, ensuring that no renewable electron is wasted for lack of transmission and that power can reach every corner of India as needed.

C) Policy and Regulatory Reforms

Government policy will play a decisive role in shaping a favourable environment for RTC renewables. First, **long-term targets and mandates** for RTC RE should be established. Just as India has RPO targets for overall RE, it could introduce a requirement that a certain percentage of discom power procurement be RTC compliant (e.g. X% by 2030 must be firm renewable power with 24×7 availability). This would compel utilities to invest in or contract such solutions. The Ministry of Power's 2023 guidelines for procuring firm dispatchable RE with storage are a start. These need to be backed by enforcement through regulatory orders.

Second, **market reforms** should be deepened. The development of a **capacity market** or similar mechanism could ensure that developers of storage/RTC supply are compensated for maintaining firm capacity. An **ancillary services market** expansion (beyond frequency regulation into reserves, ramping services, etc.) can open revenue streams for storage and flexible generation, making RTC projects more economically viable. The electricity spot markets (power exchanges) could introduce longer-duration products or "shift" products that reward moving energy from off-peak to peak. Time-of-Day pricing at the retail level (with higher tariffs during peak evening hours) is set to roll out. This will encourage large consumers to either use stored solar power or reduce usage at high-cost times, aiding the overall balance.

Regulators should also simplify approval processes for hybrid renewable projects and energy storage adoption. For example, **simplified procedures for connecting storage** to the grid and clear methodologies for cost recovery will reduce uncertainty. On the policy side, **financial**

incentives may be needed initially: the government can consider interest subvention or credit guarantees for RTC RE projects to lower financing costs, or tax breaks (like accelerated depreciation) for storage assets. Also, ensuring **payment security** in contracts (perhaps via a national RTC power purchaser or guarantees) will attract private players. Another important policy reform is addressing discom finances – e.g., implementing the recommendations by the RBI and others to reduce losses, rationalize tariffs, and even consider privatization or franchise models for efficiency. A financially sound discom is more likely to procure innovative RTC solutions.

Finally, policies should encourage **diversification of the RTC resource mix**: for instance, incentivize adding a small percentage of **green hydrogen** or other storage in RTC bids, which can in the long run create new storage mediums. Overall, the policy roadmap should move from simply encouraging capacity addition to encouraging **reliability and flexibility**.
India's regulators and policymakers must treat energy storage and RTC supply as a public good and create mandates and markets that accelerate their adoption.

D) Financial and Market Incentives

Given the high capital cost of RTC renewable systems, creative financing and market incentives will be needed to mobilize investment. One approach is to set up a dedicated **"Renewable Energy Integration Fund"** that can provide viability gap funding (VGF) for RTC projects – essentially bridging the cost difference in initial years until storage costs decline. This fund could be financed through green bonds or multilateral loans (India has already issued sovereign green bonds that could be directed to such uses). Another idea is to use some proceeds from coal cess or carbon pricing (if introduced) to support storage deployment, effectively using fossil revenues to enable renewables.

On the market side, **long-term contracts tailored for RTC** should be promoted. Utilities could float tenders not just for capacity but for guaranteed energy at certain hours (for example, a contract guaranteeing supply from 5pm to 9am next day entirely from renewables/storage). These "time-specific" PPAs would explicitly demand firm output and pay a premium for it. Moreover, **corporate buyers** (commercial and industrial consumers) can be incentivized to procure RTC green power under open access – perhaps via credits or by certifying such supply as 24×7 green (beyond current renewable energy certificates which don't assure timing).

India might also explore **regional pooling** mechanisms, e.g., if one state has excess solar and another has wind, create a market exchange where states trade their renewable excesses in real-time. The existing real-time market on exchanges is a start; it has already enabled selling surplus renewable energy at attractive prices. Improving **forecasting** and scheduling will make more renewable energy available to the market, lowering costs. For instance, with better forecasting, any excess generation can be sold in day-ahead or real-time markets rather than curtailed, which provides extra revenue to renewable developers and helps balance supply.

Tariff design is another lever: regulators could allow a slightly higher tariff for RTC renewable supply contracts, recognizing the added value of reliability, much as they did for peak power contracts in the past. International climate finance can also be tapped – India could seek lines of credit from development banks specifically for large battery storage parks or pumped storage, reducing the cost of capital. By aligning financial incentives (both in the market and via policy support) to reward reliability and flexibility, India can attract the enormous investment required for RTC renewables.

E) Strengthening Institutional Coordination and Governance

Institutional reforms and better coordination will ensure the above measures are implemented effectively. A possible step is to establish a dedicated **"National Renewable Energy Integration Mission"** or task force that brings together the Power Ministry, MNRE, CEA, POSOCO, state representatives, and experts. This body would monitor progress on storage, grid upgrades, and RTC projects, and troubleshoot inter-agency issues. It could, for example, help synchronize transmission build-out with renewable commissioning and ensure uniform standards across states for things like energy storage procurement.

The **regulatory commissions** (CERC and SERCs) should also enhance coordination perhaps through a forum on grid integration, so that regulations are harmonized where needed (e.g., a standard framework for energy storage contracts that states can adopt). Improving **SLDC capabilities** is an institutional solution as well: providing training and modern tools to state grid operators so they can handle higher RE and execute measures like demand response or scheduling of storage optimally. On the distribution side, governance reforms such as **utility privatization or PPPs** in distribution (already ongoing in some Union Territories) could indirectly aid RTC adoption by bringing in efficiency and accountability. a privatized discom might be more willing to invest in smart meters, demand response, etc., that facilitate 24×7 renewable use.

The government can also encourage **public-private partnerships** in building storage or grid projects (for instance, inviting private investment in transmission lines through tariff-based competitive bidding, which is already happening). Moreover, learning from global best practices is part of the roadmap: Indian institutions can collaborate with counterparts in countries that have integrated renewables heavily (e.g., grid operators in Europe or the US for managing high wind/solar scenarios, Brazilian ONS for hydro-wind coordination, Chinese agencies for large-scale storage implementation). Finally, transparency and data-sharing improvements – such as publishing granular renewable generation and curtailment data, storage utilization data, etc., can help identify problem areas and build confidence among stakeholders. In essence, **good governance** (clear roles, accountability, and cooperation,) will be the glue that binds together the technological and economic solutions for RTC renewables. The roadmap should thus include institutional milestones (for example, creation of a Storage Mission, or adoption of model regulations by all states by a certain date) in addition to capacity targets.

By executing these strategies in concert, India can develop a robust ecosystem for RTC renewable energy over the next decade. A high-level timeline could be envisioned as: by 2025, establish the necessary policies and initial projects (pilot RTC tenders, a few GW of storage); by 2030, scale up to tens of GW of storage and have a significant fraction of renewables delivered as firm power; and by 2035 and beyond, approach a stage where new coal capacity is unnecessary and existing fossil plants play only a minor, backup role as most demand is met by round-the-clock clean energy.

The solutions are within reach. Many are already identified in government reports and expert studies but require political will and coordination to implement swiftly. The benefits in terms of emissions avoided, improved energy security, and a modernized power sector will be well worth the effort.

Conclusion

India's pursuit of round-the-clock renewable energy (RTC RE) is both essential and challenging. This research has explored the definition of RTC RE and its significance for India's decarbonization and energy security goals. By enabling 24×7 clean power, India can reduce coal dependency while meeting growing electricity demand.

India's electricity ecosystem comprises a diverse yet fossil-heavy generation mix, a nationally integrated grid requiring further reinforcement, and demand patterns that often peak when solar and wind energy alone cannot suffice. Comparisons with China and Brazil demonstrate the feasibility of achieving RTC renewables: China through substantial investments in storage and grid infrastructure, and Brazil by leveraging flexible hydro resources.

However, India faces several challenges on this path: limited storage capacity, transmission constraints, policy and market design gaps, financial struggles of utilities, and coordination issues. Addressing these requires a comprehensive approach, including expanding energy storage (both pumped hydro and batteries), upgrading the grid, reforming policies to support firm renewable supply, creating financial mechanisms to offset higher upfront costs, and enhancing institutional coordination.

Implementing these measures demands concerted efforts from all stakeholders i.e. central and state governments, regulators, grid operators, generators, and financiers. The reward is a transformed power sector where renewable energy reliably powers the nation around the clock, aligning with global climate commitments and enhancing domestic energy self-sufficiency.

In conclusion, scaling up RTC renewable energy is crucial for India's sustainable energy transition. It requires an integrated strategy encompassing technology, policy, economics, and governance. While the challenges are significant, India's track record of achieving ambitious energy targets suggests that, with strong resolve and strategic planning, the nation can overcome these hurdles and lead in the global shift towards sustainable energy.

References

1. Central Electricity Authority. Techno-Economic Analysis of Renewable Energy-Round the Clock (RE-RTC) Supply for Achieving India's 500 GW Non-Fossil Fuel Based Capacity Target by 2030. Feb. 2024. https://cea.nic.in/wp-content/uploads/irp/2024/02/Techno_Economic_Analysis_of_Renewable_Energy_Round_the_Clock_RE_RTC_Supply_for_Achieving_Indias_500_GW_Non_Fossil_Fuel_Based_Capacity_Target_by_2030.pdf.Central Electricity Authority+1Central Electricity Authority+1
2. Institute for Energy Economics and Financial Analysis. Understanding Round-the-Clock Tenders in India. Nov. 2021. https://ieefa.org/wp-content/uploads/2021/11/Understanding-Round-the-Clock-Tenders-in-India_November-2021.pdf.IEEFA
3. ICRA Limited. "Round-the-Clock Renewable Energy Critical for Grid Stability, However, Remains Exposed to Cost and Execution Challenges." Press Release, 23 Feb.

2024. https://www.icra.in/CommonService/OpenMedia?Key=45c29084-1d0d-4215-a263-e8baa1695549.ICRA Limited
4. The Energy and Resources Institute. "India's Energy Transition: The Challenge with Decision-Making in a Time of Rapid Change." 2019. https://www.teriin.org/article/indias-energy-transition-challenge-decision-making-time-rapid-change.TERI
5. EY India. India: Energy Sector at Crossroads. Feb. 2024. https://www.ey.com/content/dam/ey-unified-site/ey-com/en-in/insights/energy-resources/documents/2024/ey-india-energy-sector-at-cross-roads.pdf.EY
6. World Bank. More Power to India: The Challenge of Electricity Distribution. 2014. https://documents.worldbank.org/curated/en/815021468042283537/pdf/More-power-to-India-the-challenge-of-electricity-distribution.pdf.World Bank
7. NITI Aayog. Towards a Clean Energy Economy: Post-COVID-19 Opportunities for India’s Energy and Mobility Sectors. June 2020. https://www.niti.gov.in/sites/default/files/2023-02/India_Green_Stimulus_Report_NITI_VF_June_29.pdf.NITI Aayog
8. International Energy Agency. India Energy Outlook 2021. 2021. https://www.iea.org/reports/india-energy-outlook-2021.IEA
9. Energy Transitions Commission. Roadmap to India's 2030 Decarbonization Target. 2024. https://www.energy-transitions.org/publications/roadmap-to-indias-2030-decarbonization-target/.Energy Transitions Commission
10. Goldman Sachs. India Clean Energy: Balancing Growth with Decarbonisation. 2023. https://www.goldmansachs.com/pdfs/insights/pages/gs-research/balancing-growth-with-decarbonisation/report.pdf.Goldman Sachs
11. Tongia, Rahul. "Balancing India's 2030 Electricity Grid Needs: Management of Time Granularity and Uncertainty." arXiv, 1 July 2022. https://arxiv.org/abs/2207.02151.arXiv
12. ResearchGate. "Renewable Energy Sectors in India: Growth, Challenges, Initiatives and Awareness—A Brief Review." 2021. https://www.researchgate.net/publication/348327494_RENEWABLE_ENERGY_SECTORS_IN_INDIA_GROWTH_CHALLENGES_INITIATIVES_AND_AWARENESS-A_BRIEF_REVIEW.ResearchGate
13. ResearchGate. "Ensuring Sustainable Energy Security: Challenges and Opportunities for India." 2014. https://www.researchgate.net/publication/264396654_Ensuring_Sustainable_Energy_Security_Challenges_and_Opportunities_for_India.ResearchGate
14. SolarQuarter. "Overcoming Cost and Execution Challenges: The Crucial Role of Round-the-Clock Renewable Energy for Grid Stability." 23 Feb. 2024. https://solarquarter.com/2024/02/23/overcoming-cost-and-execution-challenges-the-crucial-role-of-round-the-clock-renewable-energy-for-grid-stability/.SolarQuarter
15. Ember. "RE-powering India's Heavy Industries: 20 GW Today, 24/7 Tomorrow." April 2025. https://ember-energy.org/latest-insights/re-powering-indias-heavy-industries-20-gw-today-24-7-tomorrow/.Ember Energy
16. International Institute for Sustainable Development. "Round-The-Clock Renewable Energy Projects with Battery Storage Are the Future." 2024. https://www.iisd.org/articles/iisd-news/round-clock-renewable-energy-projects-battery-storage-are-future.IISD
17. Princeton University. "Unlocking India's Energy Transition: Opportunities, Challenges, and the Role of Cross-Subsidies." 2025. https://jpia.princeton.edu/news/unlocking-

india%E2%80%99s-energy-transition-opportunities-challenges-and-role-cross-subsidies.JPIA

18. Reuters. "India Eases Coal Supply Rules to Ramp Up Power Generation Capacity." 7 May 2025. https://www.reuters.com/world/india/india-eases-coal-supply-rules-ramp-up-power-generation-capacity-2025-05-07/.Reuters
19. Economic Times EnergyWorld. "India Faces Clean Energy Challenges Despite Renewable Growth." April 2025. https://energy.economictimes.indiatimes.com/news/renewable/india-faces-clean-energy-challenges-despite-renewable-growth-sunita-narain/119452304.ETEnergyworld.com+1ETEnergyworld.com+1
20. Times of India. "Holistic Policy Needed to Realise Renewable Energy Targets." 11 May 2025. https://timesofindia.indiatimes.com/city/lucknow/holistic-policy-needed-to-realise-renewable-energy-targets/articleshow/121065119.c