RE-powering India's heavy industries: 20 GW today, 24/7 tomorrow

Indian heavy industries—steel, cement, and aluminium—despite their reliance on captive coal, can profitably integrate 20 GW of solar today. But how ready are they for a 24/7 renewable-powered future?

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About

This report explores how India's heavy industrial sectors—steel, cement, and aluminium—can leverage renewable energy to slash costs and emissions. It maps the sector-wise open-access renewable market potential across various states, examines evolving policies such as green taxonomy and carbon regulations for these sectors, and explains why renewables are emerging as the most strategic choice. As companies pledge ambitious 24/7 renewable energy targets, the report outlines a roadmap for the next era of corporate power procurement—one that makes round-the-clock clean electricity a reality.

Highlights

20GW	10%	₹9.5/kWh
Market size of open access solar which offers a cost advantage for steel, cement, and aluminium sectors	Reduction in production cost of electric arc furnace (EAF) based steelmaking by switching to open access solar	Estimate of the average per unit cost of sourcing 24/7 renewables

Executive Summary

Renewable power presents a massive opportunity for industries today

As industries strive for carbon neutrality, transitioning to renewable electricity is the most immediate lever for decarbonising operations. This shift currently presents a million-dollar cost-saving opportunity while also delivering several co-benefits.

India's evolving green energy open access regime has been a game-changer, enabling commercial and industrial consumers to wheel renewable power from distant locations directly to their doorsteps using the common grid infrastructure. The green energy open access market presents a 20 GW profitable opportunity for the steel, cement, and aluminium sectors across states, despite two key challenges: (1) electricity supply in these industrial facilities remains largely dominated by low-cost captive coal power, restricting the penetration of renewables, and (2) while a portion of electricity demand is met through the expensive grid, which could be cost-effectively replaced with renewables, multiple open access surcharges on renewable power erode potential gains.

With many corporations in these sectors pledging to achieve 100% renewable energy in the coming decades, this report also explores the pathway to a fully renewable-powered future with 24/7 demand matching. The discussion is specifically structured around large industrial consumers that have firm, round-the-clock electricity demand. It highlights how storage solutions—particularly batteries—will be indispensable in enabling the transition from partial renewable usage to meeting 24/7 targets.

> **States such as Odisha and Chhattisgarh have long been legacy industrial hubs, owing to their proximity to rich mineral reserves. By integrating renewable power, they are well-positioned to begin their transformation to green manufacturing hubs. The shift is already in motion — Odisha is now actively envisioning green industrial parks, setting the stage for an export-driven, low-carbon future in manufacturing.**

Duttatreya Das
Energy Analyst for India,
Ember

> **Cost-competitive, near-24/7 renewable energy will power the first wave of industrial decarbonisation and redefine the future of corporate power purchases.**

Neshwin Rodrigues
Senior Energy Analyst, Asia,
Ember

> India's industrial sector, one of the hardest to decarbonise, has significant financial incentives to transition through renewable-based electrification. However, policy and institutional barriers must be dismantled to maximise this shift.

Labanya Prakash Jena
Sustainable Finance Consultant,
Institute for Energy Economics and Financial Analysis (IEEFA)

> Renewables are already a cost-effective solution for Indian industry, and 24/7 clean power is the benchmark for the future of renewable procurement. This report highlights that companies can make significant progress toward round-the-clock renewable supply today, with further innovation in storage, flexible demand, and market design needed to achieve full 24/7 coverage at competitive rates.

Killian Daly
Executive Director,
EnergyTag

> As industries increasingly rely on variable renewable energy (VRE), they will expect high levels of reliability. High-quality VRE forecasting will be essential to optimise the use of storage, ensuring a dependable power supply while keeping costs in check. This “last mile” of decarbonisation will demand sophisticated predictive capabilities.

Dan Travers
Co-Founder, Open Climate Fix

Key takeaways

01 A 20 GW+ solar opportunity for heavy industries in India today

A 20 GW solar market opportunity exists under the green energy open access mode of power procurement for steel, cement, and aluminium across the top five producing states in India. Steel presents the largest opportunity at 9.4 GW, primarily due to its greater reliance on comparably expensive grid power which can be replaced with open access solar. Cement and aluminium, despite their dependence on inexpensive captive coal-based generation, collectively represent an 11 GW market. Seizing this opportunity could potentially eliminate 29 million tonnes of emissions annually.

02 Solar power, on average, could slash production costs by up to 10% for some steel makers

Solar power offers a significant opportunity to reduce operational costs for steel and cement plants across most Indian states. In certain cases, such as standalone electric arc furnaces (EAF) for steelmaking, these savings can account for up to 10% of operational costs. For direct reduced iron–arc furnace (DRI-EAF) based steelmaking, savings range between 2–5%, while for cement manufacturing, the potential is lower. aluminium, however, does not present a significant cost-saving opportunity due to the abundant captive coal-based generation in place.

03 Renewable power can transform mineral-rich states to green manufacturing hubs

From a regional standpoint, nearly 40% of the 20 GW open access solar power opportunity for heavy industries is concentrated in just two states—Odisha and Chhattisgarh. These states have long served as core industrial hubs for India's steel and aluminium production. Recent waivers on open access charges have further enhanced the appeal of renewable power in these regions, making it a commercially viable sourcing option for these industries. This shift has the potential to transform these regions into green manufacturing hubs, attracting international climate finance and corporate investments. More broadly, renewable power can also play a pivotal role in aligning steel production with India's emerging green steel taxonomy, enabling certain steel manufacturing routes to qualify for low emission intensity thresholds.

04 50% RE is cost-effective today while 80% may cost up to 1.4X

With many corporations pledging 24/7 renewable energy (RE) or 100% RE targets for the coming decades, it is important to assess what level of renewable integration is financially feasible today. Sourcing 50% variable RE is possible without integrating storage and is already cost-effective for heavy industries in India today. Increasing RE penetration from 50% to 80% leads to a moderate cost increase to up to 1.4X the cost of plain vanilla RE generation (~40% premium). This increase is primarily driven by the cost of storage and the challenge of managing surplus electricity.

05 24/7 RE can cost up to 3.5X

Achieving 24/7 RE today comes at a cost premium of 3.5X the cost of plain vanilla RE generation. The transition from 90% to 24/7 RE (round-the clock) demands massive oversizing of renewable capacity and significant battery deployment, which sharply drives up system costs. In fact, achieving 24/7 RE could cost up to 2X the per unit cost of electricity compared to the 90% RE case, making the final stretch the most cost-intensive phase of the transition. Batteries are expected to contribute up to 60% of the total cost of sourcing 24/7 RE.

Corporate renewable power procurement has gained significant attention in India

Industries are eager to switch to renewables to avoid expensive grid power while simultaneously fulfilling their renewable purchase obligations and climate commitments

Decarbonising the industrial sector is a complex challenge that demands technological advancements, backed by innovative policies and financing mechanisms. Industries rely on both electricity and heat as primary energy sources, with their shares varying across sectors. While long-term solutions like large-scale electrification and green hydrogen are being explored for heat decarbonisation, transitioning from fossil-based to renewable energy (RE) power is an immediate and practical step toward carbon neutrality.

India has committed to reducing the emission intensity of its economy by 45% from 2005 levels and ensuring that 50% of its total electricity capacity comes from non-fossil sources by 2030. Beyond national targets, major corporations in sectors such as steel, cement, and aluminium have carbon neutrality goals or pledged to source 24/7 RE within specific timelines.

India's industrial sector accounts for approximately 607 million tonnes (MT) of direct annual CO_2 emissions. It is also the largest electricity-consuming economic sector, accounting for 595 Terra Watt-hour (TWh), or 42% of the country's total electricity demand, primarily met through a combination of grid (through distribution companies) and captive (self-generated) power. Given this, two things are clear: decarbonising industries is essential for meeting national climate targets and switching to RE is a key lever in this transition. The good news is that this transition is already well underway.

A blend of carrots and sticks is driving RE growth in industries

India's commercial and industrial (C&I) sector has been seeing a significant increase in RE consumption. However, tracking this growth is challenging, as industries rely on both grid electricity—which includes a mix of fossil and non-fossil sources—as well as corporate RE procurement.

As of 2024, RE capacity for the C&I segment reached 35 GW, with solar contributing 66% and wind making up the rest. In 2024 alone, 6.9 GW of solar open access capacity was added for C&I consumers, representing a 77% increase from the previous year. While multiple factors have driven this surge, the primary catalyst has been the cost advantage of renewable energy and regulatory support from the government. These factors are explored in detail in the following section.

Cost advantage

Industrial electricity tariffs in India are higher than in many other countries in comparison to the cost of generation, with a 10-25% markup over the average cost of electricity supply. This is primarily due to a feature of the Indian electricity sector, where industries cross-subsidise residential and agricultural consumers through an additional levy known as the cross-subsidy surcharge to support social welfare. Despite efforts to regulate these subsidies, they often exceed prescribed limits, making grid electricity a costly option for industries.

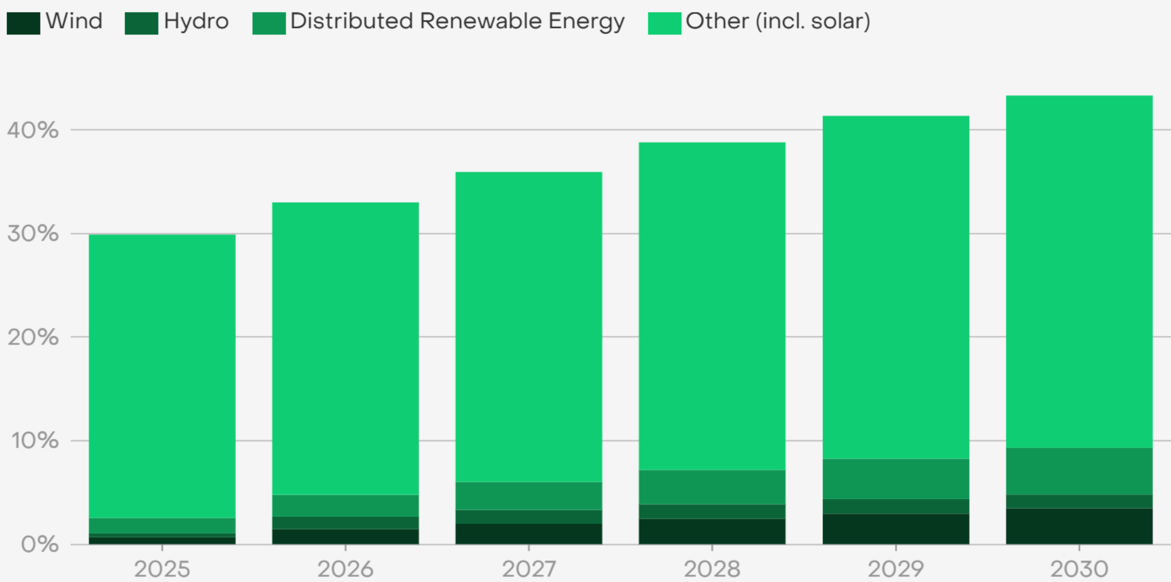
On the other hand, RE costs have declined significantly in recent years. Solar tariffs, for instance, have dropped by over 75%, from ₹10/kWh in 2014 to ₹2.5/kWh in 2024. However, private procurement of RE through open access (OA), either from third-party developers or captive generation, involves various additional charges, such as transmission and wheeling fees, various surcharges, and other levies (explored in detail in the mechanisms of RE procurement section). Despite these added costs, open access RE remains cost-competitive with respect to typical industrial electricity tariffs. This cost advantage has been an important driver of RE adoption among industrial consumers.

Regulatory push

Two key regulatory frameworks have played a significant role in accelerating RE adoption. The first is the Renewable Purchase Obligation (RPO) framework, which mandates a minimum share of RE consumption as a percentage of total electricity use for distribution companies (DISCOMs), captive power producers, and open-access consumers. Heavy industries such as steel, cement, and aluminium often rely on captive fossil-based power generation, making them subject to the RPO targets. Under this mandate, these industries must progressively increase the share of RE in their total captive consumption, with a target of 43% by 2030.

Indian industries are mandated to replace more than 40% of captive power with renewables by 2030

Share of captive power mix as mandated under the RPO



Source: RPO guidelines by Ministry of Power, India
RPO stands for Renewable Purchase Obligation. Distributed Renewable Energy includes projects of up to 10 MW

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There have been ongoing legal concerns for heavy industries like steel and cement whether co-generation and waste heat recovery (WHR)-based electricity generation can be qualified as RE power within the RPO framework. Courts have consistently ruled against this classification, reaffirming that WHR cannot be accounted for within RPO compliance. Consequently, companies are required to procure solar and wind power to meet their obligations, irrespective of their WHR-based generation.

The second key policy framework is the Green Energy Open Access (GEOA) Rules, 2022, which brought much-needed clarity to the procurement of RE through the non-discriminatory use of the transmission and distribution (T&D) infrastructure. These rules define eligibility criteria, streamline registration and permit processes, and rationalise associated charges and banking norms.

However, electricity is a concurrent subject in India, meaning both the central and state governments have jurisdiction. As a result, any central-level framework, including the RPO and GEOA rules, must be ratified and implemented at the state level to have a real impact. The extent of adoption has varied across states, with some not fully aligning with the spirit of these regulations, leading to inconsistencies in implementation.

Climate commitments

Several corporations have set their own carbon neutrality targets. Many have aligned with global initiatives such as RE100, which commits companies to sourcing 100% renewable electricity, and the Science-Based Targets initiative (SBTi), which provides a structured approach to gradually reducing all forms of emissions. Notably, major industry players like JSW Energy have committed to SBTi, while Dalmia Cement and Shree Cement have joined RE100, demonstrating their commitment to achieve 100% round the clock renewable power before 2050.

Many industrial commodities such as steel, aluminium, etc. are also subject to international carbon regulations, such as the Carbon Border Adjustment Mechanism (CBAM). These tariff barriers create strong incentives for industries to reduce their emission intensity in the near term to avoid financial penalties and maintain global competitiveness.

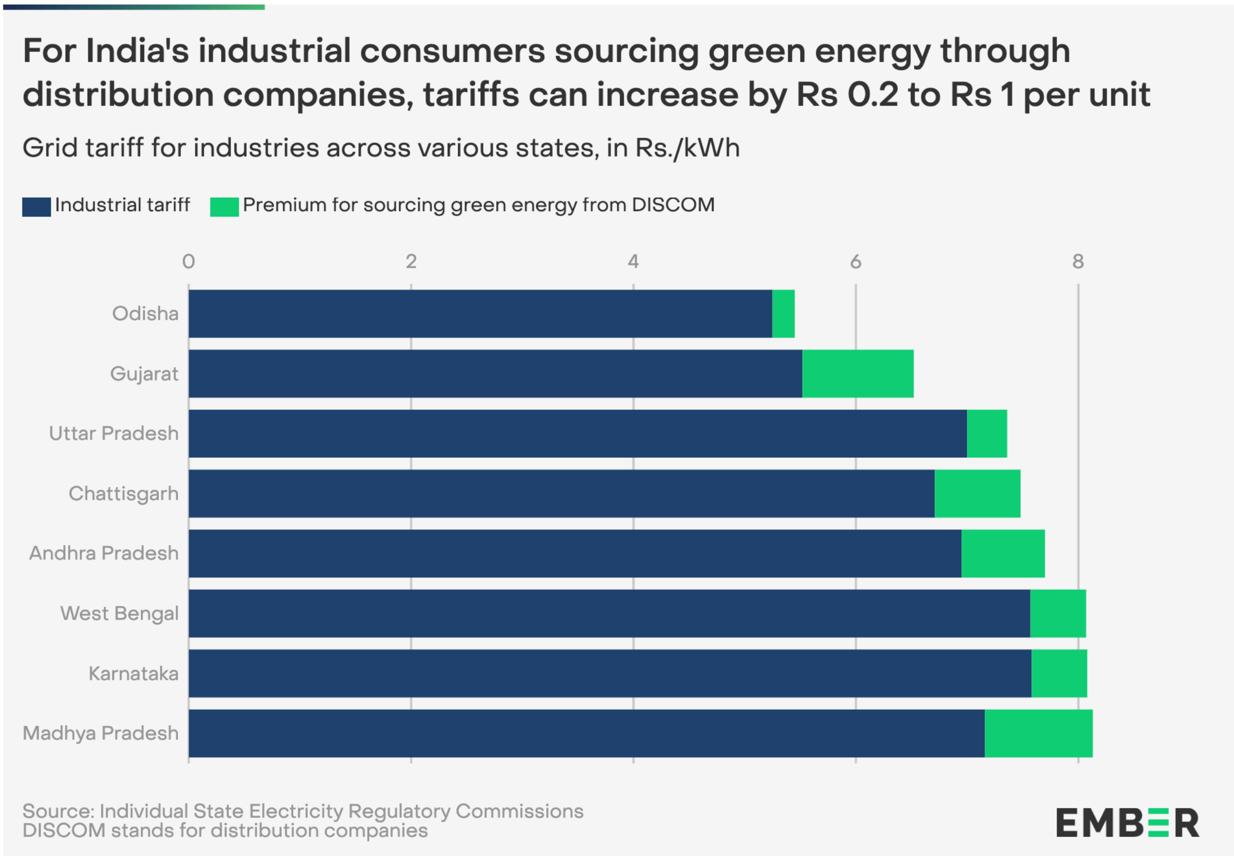
Multiple routes to green power procurement, each with their own set of challenges

There are multiple mechanisms for procuring RE in India for industrial operations. Some of the most common routes and associated challenges are explained in the following section.

Paying a green tariff to distribution companies

A green tariff refers to a pricing structure or rate plan offered by DISCOMs to supply electricity generated from RE to commercial and industrial consumers. This allows industries to access RE in a plug-and-play arrangement without navigating the complexities of corporate power procurement. For smaller consumers, whose electricity consumption may not be large enough to justify direct PPAs, this provides a more feasible and flexible alternative.

Introduced by the Ministry of Power (MoP), this mechanism was intended to leverage low-cost RE to bring down industrial electricity tariffs while providing industries with a pathway to meet their RPO targets. However, in practice, the determination of green tariffs and their alignment with RPO compliance varies across states. As of the present, 24 states have approved the green tariff mechanism.



Challenges with green tariffs:

- Unfavorable pricing structures: In most cases, green tariffs have effectively become a premium charged over the existing industrial electricity tariffs rather than states following a standard method as prescribed in the Green Energy Open Access (GEOA) Rules. These additional charges typically range from ₹0.2/kWh to ₹1/kWh for the states that we consider. The green tariffs, at instances, have been set significantly higher than the Average Power Purchase Cost (APPC) of RE procured by DISCOMs.

  Another issue is the uncertainty in green tariff pricing. Green tariffs are revised annually along with other electricity tariffs, making it difficult for consumers to have visibility on future costs. With mandates in place for energy storage in the electricity mix to improve flexibility, DISCOMs may charge higher tariffs in the near-term.

- Clarity on accounting mechanisms: Ensuring 24/7 green power supply is difficult, as many industrial consumers operate continuously with limited flexibility to shift demand. Additionally, green tariffs risk becoming mere accounting mechanisms that do not drive new renewable energy deployment but instead reallocate the renewable energy mix to industries at a premium.

  Secondly, future revisions to the GHG Protocol may impose stricter requirements for matching renewable generation with consumption, raising concerns about the recognition of green tariffs. If these tariffs lack granular time- and location-based verification, they may face challenges in being accepted as legitimate corporate emission reduction claims, potentially limiting their role to a great extent.

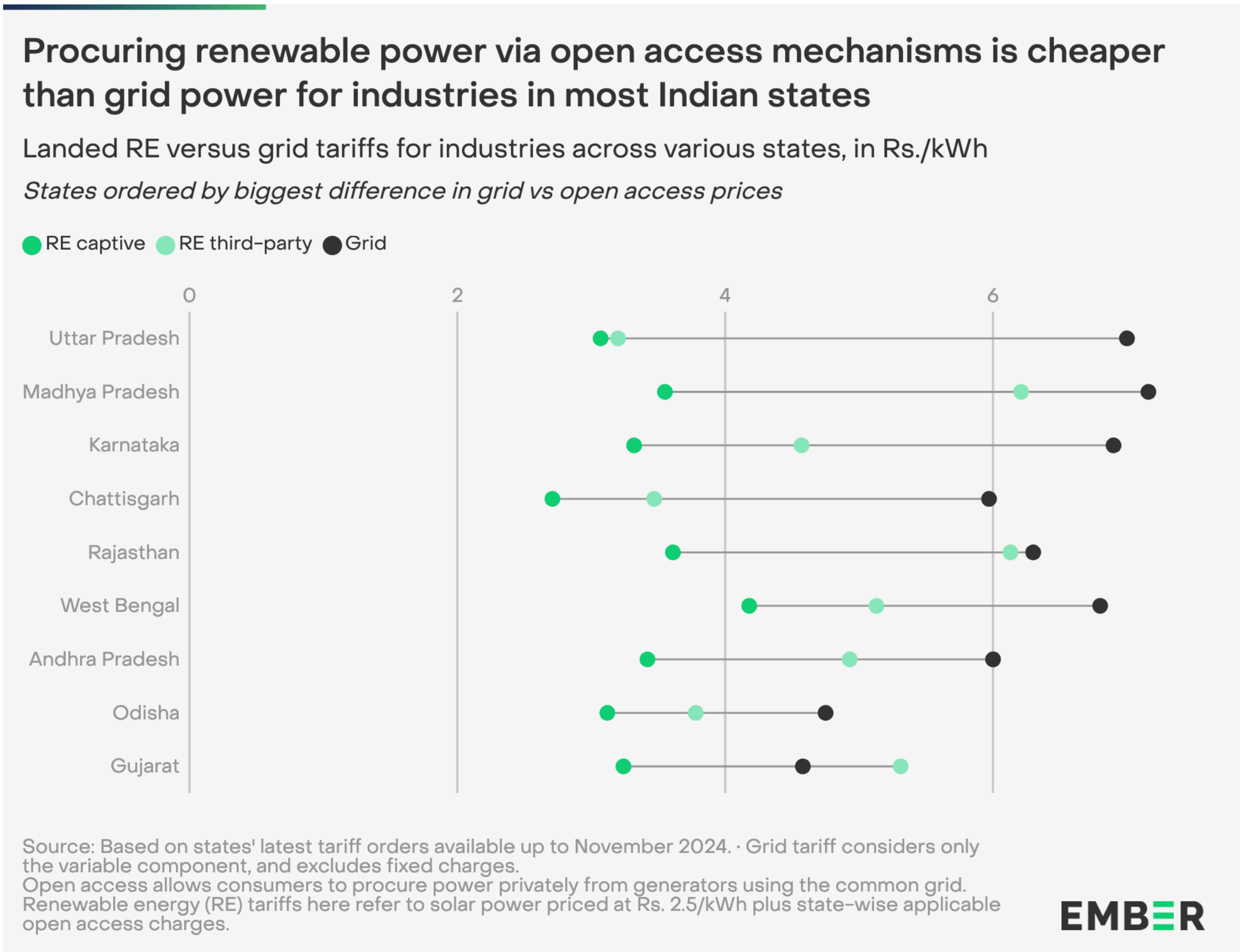
Green energy open access

This mechanism allows industrial consumers (above 100 kW) to procure RE directly from a RE generator using the transmission and distribution infrastructure under a non-discriminatory open access framework. The rules governing RE procurement through this mechanism are prescribed by the national government, which later must be adopted and implemented at the state level for effective execution.

Multiple open access (OA) charges are levied on top of the RE tariff, including transmission and wheeling charges, cross-subsidy surcharge (CSS), and additional surcharge (AS). Additionally, banking charges apply when industries store excess electricity generated during periods of low demand for later use. These charges are determined by state regulators based on the GEOA rules. The GEOA framework aims to rationalise these costs by imposing limits on arbitrary increases. For instance, the CSS cannot increase by more than 50% of the initial year's CSS for the first 12 years of a plant's operation. Furthermore, states can incentivise greater RE uptake by reducing or waiving these OA charges.

Under GEOA, industrial consumers can procure RE through three primary routes:

- Third-party – Buying power from a RE developer, all OA charges applicable.
- Captive – 100% ownership of an RE plant for self-consumption, CSS and AS are waived.
- Group-captive – Partnering with other entities to co-own a minimum 26% of an RE plant and consume at least 51% of the total electricity; CSS and AS are waived.



Despite various charges imposed on RE tariffs for open access power, it still offers significant cost advantage across most states. Based on data from multiple states, industrial consumers can achieve a cost saving of ₹1–4 per unit through open access renewable power, translating to an average tariff reduction of around 44% across states. The extent of this advantage depends on state-specific charges and their periodic revisions, but even with these variations, the business case for open access RE remains strong.

Challenges with open access RE procurement

- Regulatory variability across states: The Green Energy Open Access (GEOA) rules require state-level implementation for effective execution. However, there is significant variability across states in aspects such as applicable open access charges, energy banking norms, open access connectivity (General Network Access) rules, and other administrative processes. This fragmented regulatory landscape creates challenges for both buyers and sellers, requiring them to plan differently based on state-specific policies.

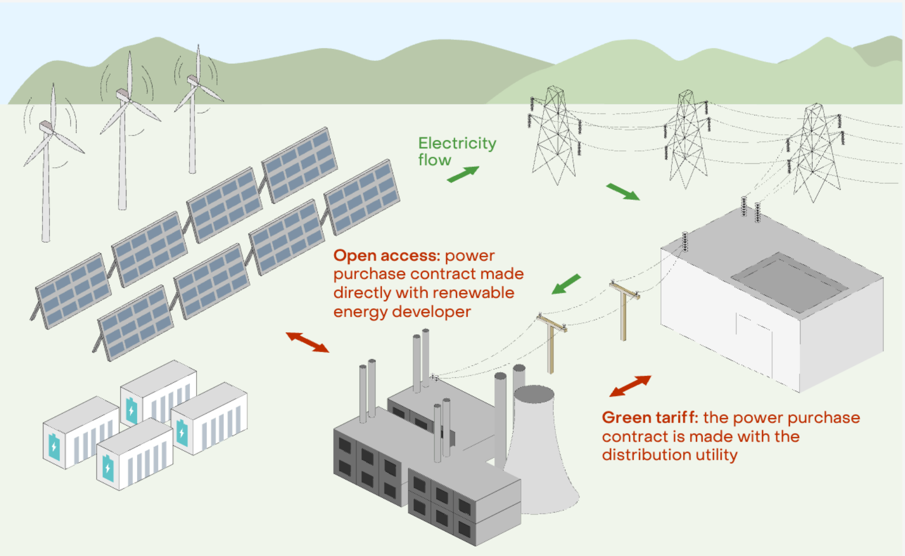
- Financial tradeoffs for small industries: The third-party model incurs additional charges such as CSS and AS, making it less cost-competitive and, at times, prohibitive. On the other hand, opting for a captive structure requires significant capital investment in an RE project, creating potential financial tradeoffs. Companies must weigh this investment against other priorities, such as expansion plans.

  This challenge is particularly pronounced for small businesses, especially arc furnaces in India, which often operate with high levels of informality and thin margins. For such industries, committing to captive RE can be a challenge.

  To address this, the government has introduced the group captive structure, allowing companies to invest 26% equity in an RE project while securing captive consumer benefits. This model helps mitigate financial tradeoffs to some extent. However, regulatory inconsistencies remain—certain states, like Gujarat, have yet to ratify the group captive structure, limiting its accessibility.

- Challenges posed by DISCOMs: C&I consumers play a crucial role in cross-subsidising various economically weaker consumer categories through surcharges. As a result, any policy that facilitates private RE procurement for industries is likely to face resistance from DISCOMs, as it poses a potential revenue loss for them. Research estimates that if 50% of C&I consumers shift to RE procurement through these mechanisms, the estimated increase in the average loss gap would be 53% per unit of electricity for third-party open access and 100% for captive projects. This highlights the financial pressure on DISCOMs due to RE procurement and political challenges that can lead to potential resistance by state governments.

For India's industrial consumers, Green tariffs and Open Access are the most promising renewable energy procurement options right now



Open access

Industrial consumers procure renewable energy directly from an RE generator using the transmission and distribution infrastructure under a non-discriminatory open access framework.

Third party – the industrial corportation buys power from a renewable energy developer

Captive – the renewable energy plant is owned by the industrial corporation for self-consumption

Green tariff

A rate plan offered by distribution companies – to supply electricity generated from renewable energy – allowing industries to access renewable energy via a plug-and-play arrangement, without navigating the complexities of corporate power procurement.

Source: Ember

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Other mechanisms

There are several other mechanisms for procuring RE, though they are not yet widely adopted in India. These include sourcing RE from green segments of the wholesale electricity market, such as the Green Day-Ahead Market (GDAM) and Green Term-Ahead Market (GTAM) or obtaining the Renewable Energy Certificates (REC). Additionally, concepts like the RE Virtual Power Purchase Agreement (VPPA)—which has been tested in advanced economies—have yet to gain traction in India due to regulatory challenges.

This discussion excludes rooftop and behind the meter solar, as industrial facilities often face challenges in co-locating RE generation within their premises due to space constraints.

Steel, Cement and Aluminium: The big three

This report examines RE procurement opportunities for India's heavy industries sector, with a focus on steel, cement, and aluminium. Together, these industries account for nearly 90% of electricity consumption within the heavy industries sector. Also, India is the world's second-largest producer of steel, cement, and aluminium by volume, behind China. They contribute approximately 580 million tonnes of CO_2, including both direct emissions and those from electricity consumption. Many of these industries are also part of large conglomerates with carbon neutrality commitments, making them likely candidates for near-term RE adoption.

Chapter 2 explores the cost dynamics of electricity consumption in steel, cement, and aluminium across different states, identifying potential market opportunities for RE deployment. Chapter 3 delves into the future of corporate power procurement, examining the mechanisms of ensuring 24/7 RE for industrial operations.

A 20 GW renewable opportunity lies in India’s steel, cement and aluminium sectors

The open access mechanism lets these industries slash costs and emissions with renewables

This chapter explores market opportunities for renewables in heavy industry sectors like steel, cement, and aluminium in India. It examines potential cost benefits of RE procurement for industries and how they can leverage RE to navigate carbon taxes and access green premium markets.

Steel: The most promising heavy industry market for renewables today

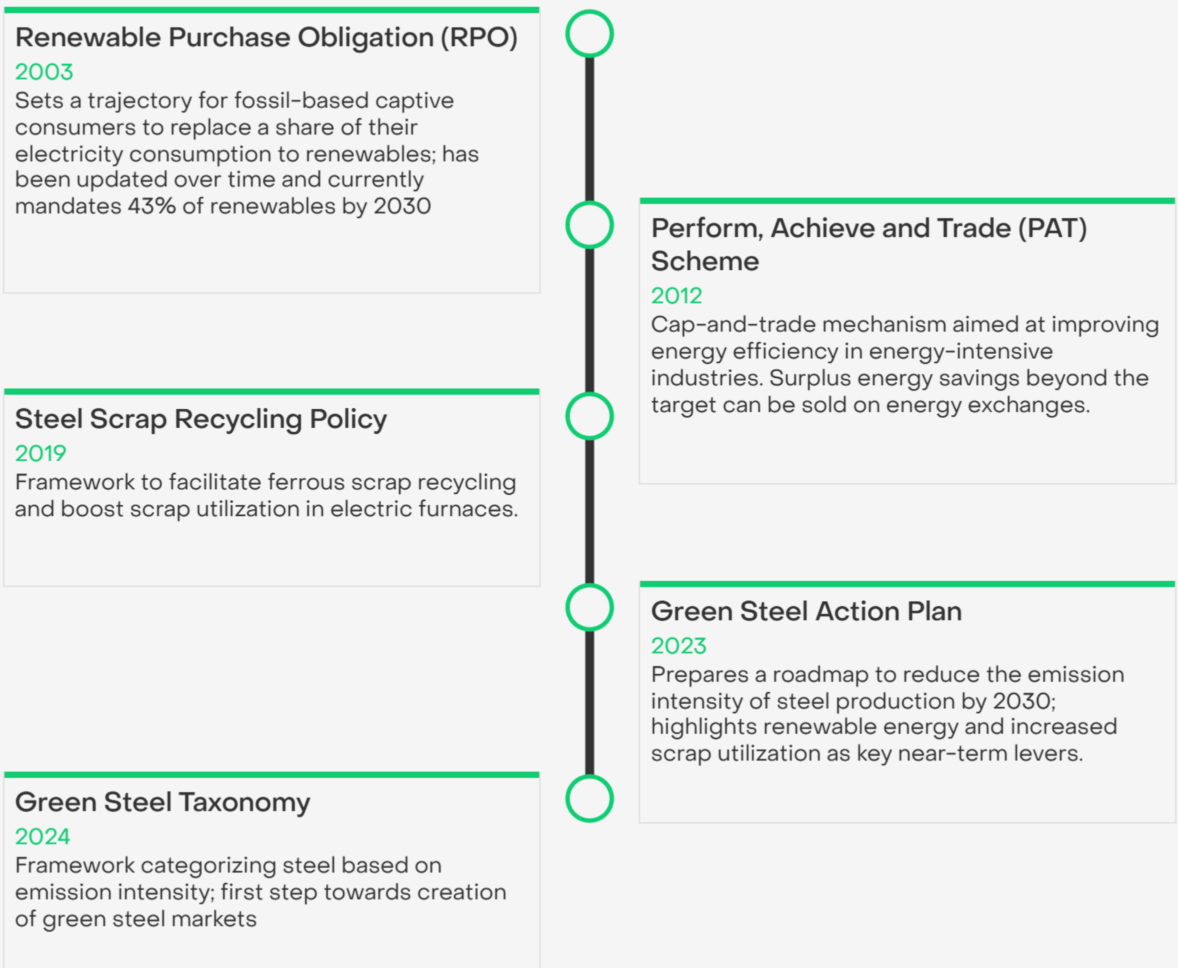
India stands as the second-largest producer of steel in the world, with an output of 144 million tonnes per annum (MTPA) in the Financial Year (FY) 2023-24, trailing China. Despite significant production volumes, India's per capita steel consumption lags at 97.7 kg per annum equivalent to one-third of the global average. The National Steel Policy (2017) projects India's steel production to rise to 255 MT by 2031, representing an estimated year-on-year (YoY) growth of 8.5%. This growth is expected to be primarily driven by the building and infrastructure sectors.

The steel sector in India accounts for 10-12% of the country's total emissions, making its decarbonisation a national priority. With an emission intensity of 2.54 tonnes of CO_2 per tonne of crude steel—well above the global average of 1.91 tonnes—India faces significant challenges. This higher emission intensity in India is driven by three primary factors: greater energy consumption due to the use of lower-grade coal and iron, a heavy reliance on coal for steel making and captive power production, and limited scrap availability. In contrast, countries like the United States, with abundant natural gas and higher scrap availability, achieve much lower emission intensities in steel production.

The decarbonisation of India's steel sector has gained significant momentum in recent times, marked by the government's introduction of the Green Steel Roadmap and Action Plan in 2024. Several key initiatives have laid the foundation for a low-carbon steel sector.

Making the steel sector carbon lean in India – A work in progress

Major policies and mandates for reducing steel emissions



Source: Ember's analysis of key steel decarbonization policies

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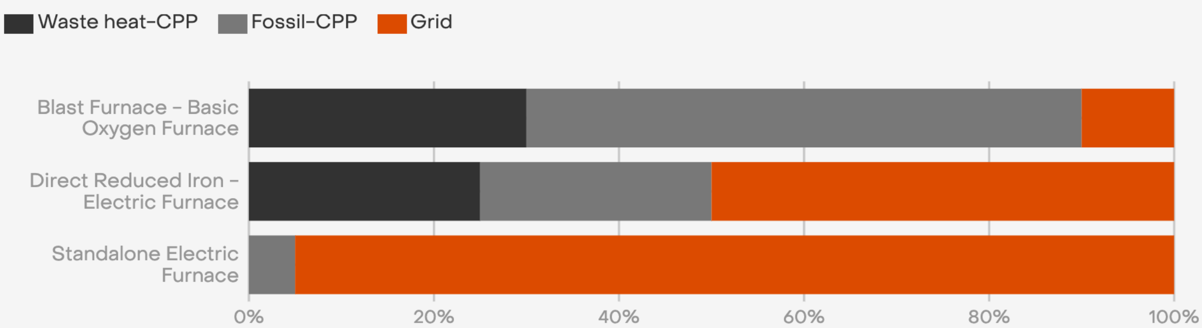
Electric furnaces for steel production are majorly powered by the grid

Steel production in India predominantly utilises three key routes: the Blast Furnace-Basic Oxygen Furnace (BF-BOF), the Direct Reduced Iron-Electric Arc Furnace/Induction Furnace (DRI-EAF/IF) and standalone scrap-based EAF/IF. Energy consumption varies significantly across these production pathways due to differing shares of thermal and electrical energy. A deeper understanding of these variations helps focus and streamline RE switching opportunities.

A survey of multiple steel manufacturing plants, based on project documents, provided valuable insights into electricity consumption patterns. While energy usage varies by production route and region, this analysis identifies average consumption trends across different steel production routes.

Electric furnaces rely heavily on grid power, offering a major market for open access renewables in India

Share of electricity sourced for various steel production routes in India



Source: Compiled from environmental clearance documents for industries, company websites, and Global Energy Monitor (GEM) · CPP stands for Captive Power Plant. Electric Furnaces include arc and induction furnaces. Induction furnaces often operate as standalone facilities.

The opportunity for RE adoption lies primarily with electric furnaces, which are the focus of this analysis. DRI-EAF and scrap-based standalone furnaces, with electricity consumption levels of approximately 664-825 kWh/ton of steel (roughly three to four times that of the BF-BOF route), rely significantly on grid-based electricity supplied by distribution companies. This dependence presents a significant opportunity to transition from grid power to cleaner and more cost-effective RE alternatives.

In contrast, the BF-BOF route, which involves primary steel production, is excluded from the analysis as its operations are predominantly powered by inexpensive captive power plants (CPPs) that utilise waste heat recovery (WHR) gases from blast furnaces and coke ovens, along with coal-based captive generation.

Some steelmakers are poised to unlock substantial cost savings

For understanding the cost benefits of open access solar in steel making, the focus is on the top steel-producing states with significant DRI-EAF/IF and standalone EAF/IF potential. The rationale is to prioritise steel manufacturing routes that are more reliant on grids. The top five states identified are Odisha (24%), Chhattisgarh (20%), Gujarat (15.4%), West Bengal (13%), and Karnataka (8.5%) accounting for more than 80% of arc furnace based steel production in India. This analysis excludes standalone EAF/IF clusters in Punjab and Haryana due to insufficient data, largely attributed to the high level of informality of arc furnaces in this region.

Geography of India's steel industry

India's steel manufacturing, particularly blast furnaces and direct reduced iron, are predominantly located in states which have access to ample iron ore deposits and coal mines. This has led to the concentration of steel production in resource-rich eastern states like Odisha, Chhattisgarh, and Jharkhand. Over time, the rise of urban conglomerates in western regions, such as Haryana, Gujarat, and Maharashtra, drove significant demand for steel in these regions. To meet this demand, mini steel mills—primarily in the form of standalone furnaces using steel scrap—were established in these regions. These developments occurred later in India's industrial history, reflecting the evolving geographic presence of steel manufacturing.

India has recorded some of the lowest RE tariffs globally, around ₹2.5/kWh (~USD 28.73/MWh) for solar and ₹3.2/kWh (~ USD 36.77/MWh) for solar-wind hybrid projects. While hybrids are more expensive than plain solar tenders, they generally tend to offer higher capacity utilisation factors (CUF). This modeling study assumes vanilla solar projects, aiming to replace grid-sourced electricity wherever it is economically viable.

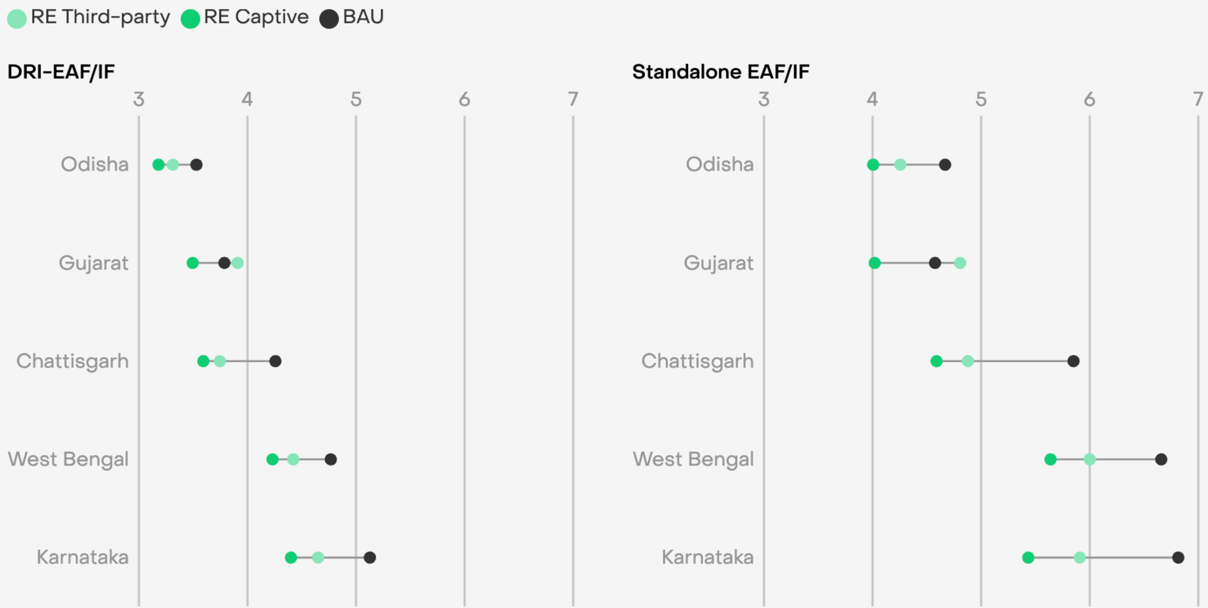
To evaluate the cost implications, three scenarios are constructed:

- Business-as-usual (BAU): Electricity sourced from a mix of captive generation (waste heat recovery and fossil fuel–based) and grid supply, reflecting state-specific coal-based captive costs and industrial tariffs.
- RE third-party: Grid electricity partially replaced with third-party solar during solar hours, accounting for open access charges under the latest tariff orders and states' Green Energy Open Access (GEOA) rules.
- RE captive: Grid electricity partially replaced with captive solar during solar hours, leveraging ownership benefits and tariff savings as per the GEOA rules.

Grid electricity is replaced first with open access solar because industries would prioritise substituting the most expensive electricity source—which, in this case, is grid electricity. This cost-optimisation approach —replacing the most expensive source first—is consistently applied across all sectoral analyses. The green tariff route, while also offering a cleaner alternative, is expected to increase costs above BAU and therefore is excluded.

Switching to renewable electricity reduces operational costs for steel manufacturers across most Indian states

Cost of electricity for steel plants: business as usual vs. renewable energy procurement (Rs./kWh)



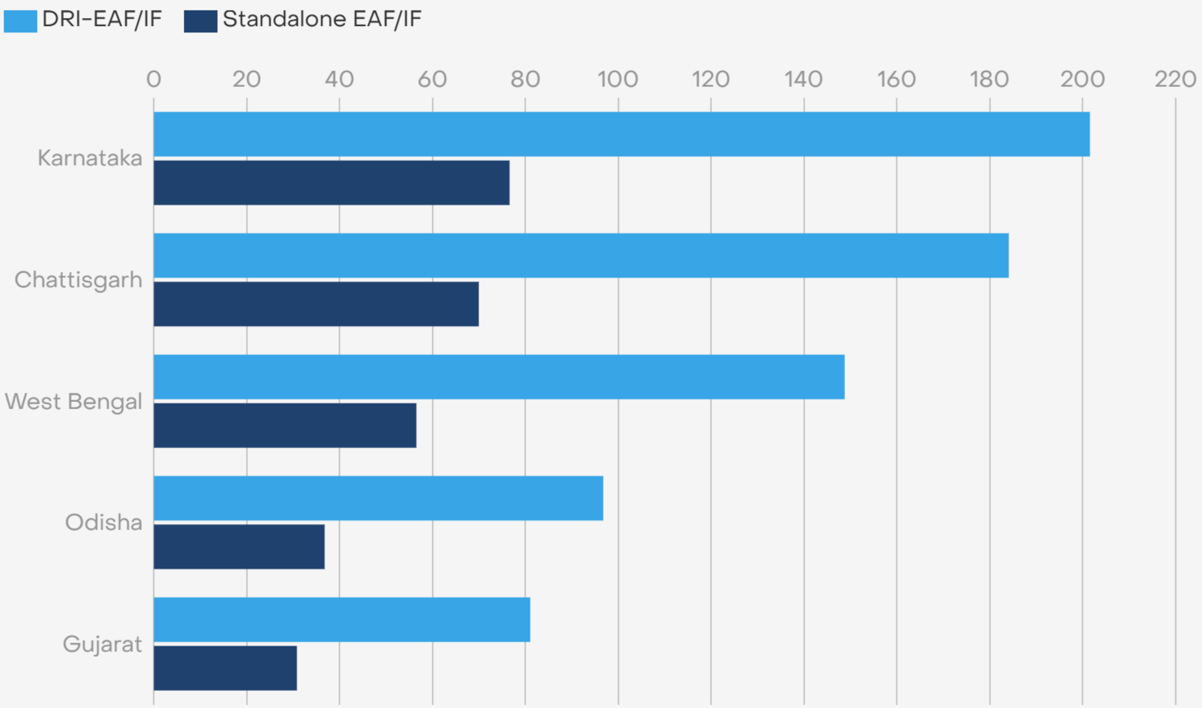
Source: Ember's analysis based on tariff orders upto November 2024. · Business-as-usual (BAU) refers to electricity procurement from a mix of captive and grid. Renewable (RE) scenarios consider replacing a portion of grid electricity with open access solar. States considered for analysis are the top DRI-EAF/IF producers in India.
DRI-EAF/IF stands for Direct Reduced Iron with Electric Arc or Induction Furnace.

States with high electricity prices can achieve significant savings through open access solar. For example, Chhattisgarh, West Bengal, and Karnataka, where electricity prices are high, achieve cost savings of ₹0.5 - 1.7/kWh through open access solar procurement. In contrast, states like Odisha and Gujarat, which have more competitive grid prices, offer limited cost advantages. Specifically, Gujarat offers no cost benefits under the RE third-party route. As a result, steel manufacturers in these states need to turn to captive RE to avoid cross-subsidy surcharge and improve cost-effectiveness.

Top steel-producing states like Chhattisgarh and Odisha have introduced attractive incentives by fully or partially waiving transmission, wheeling, and cross-subsidy surcharges under their respective green energy open access policies. Chhattisgarh, for instance, offers various incentives for the first 500 MW of open access consumption, including a waiver of transmission and wheeling charges and a 50% reduction in the cross-subsidy surcharge. Similarly, Odisha provides comparable discounts on these charges, with the condition that the RE projects are located within the state. Karnataka, on the other hand, introduced an open access policy offering a 50% waiver on the cross-subsidy surcharge. However, this policy has stalled after being struck down by the courts in early 2025 due to disputes over wheeling and banking regulations and issues related to the retrospective application of charges to projects.

India's steel makers can save millions annually by switching to solar

Annual cost savings for an average-sized steel plant from adopting solar energy (Rs. millions)



Source: Ember's industrial electrification model · Analysis based on tariff orders upto Nov 2024. DRI-EAF/IF stands for Direct Reduced Iron with Electric Arc or Induction Furnace.
Analysis assumes average plant sizes in tonnes per day (TPD) of 1,000 TPD for DRI-EAF/IF and 200 TPD for standalone EAF/IF; solar power in captive mode, with relevant state-wise open access charges applied.

Renewable energy procurement offers substantial cost savings for steel plants. The largest annual cost savings for a median sized DRI-EAF plant (~ 1000 tonnes per day (TPD)) can be achieved in states like Karnataka, Chhattisgarh, and West Bengal, amounting to approximately Rs. 200 million, Rs. 185 million, and Rs. 150 million, respectively. These savings could represent 2–5% of the total annual revenue. The savings for standalone furnaces (~ 200 TPD) can range between Rs. 50–100 million, ranging between 5–10% of their total revenue. The prospects of switching to RE by these steel companies would create a market for about 9.5 GW of open access solar, the largest ones being 2.9 GW and 2.4 GW in Odisha and Chhattisgarh, respectively.

This becomes particularly relevant in light of the challenges faced by the steel industry, such as high input raw material costs, elevated logistics expenses, including freight charges and the ongoing concerns of dumping. Indian manufacturers have lost domestic market share in certain steel categories due to cheap imports from China, Vietnam, and other trading partners, significantly suppressing domestic steel prices. The situation is expected to worsen with the looming threat of US tariffs, which could further divert a substantial volume of global steel supplies to India. By leveraging cost savings from RE procurement, Indian steel manufacturers can mitigate some cost pressures and improve their competitive positioning in national and foreign markets.

Benefits beyond cost savings

While RE procurement presents a compelling opportunity to reduce operational costs and enhance competitiveness, it also brings numerous co-benefits.

RE can reduce emissions in steel, profitably

India's steel sector emits approximately 300 million tonnes (MT) of CO_2 annually. Of this, the top five states, which contribute 80% of steel production from DRI-EAF and standalone furnaces, account for around 110 MT of CO_2 emissions and form a part of this analysis. RE holds significant potential to reduce emissions in standalone arc furnaces. Simply integrating solar power during daylight hours, without additional wind or battery storage, can lower the emission intensity of standalone furnaces from 0.61 tonne CO2 (t-CO2)/tonne of finished steel (tfs) to 0.38 t-CO2/tfs —a 40% reduction. If all DRI-EAF and standalone furnaces in the top steel-producing states transition to solar for their operations, this could result in annual emission savings of 15 million tonnes of CO_2.

Navigating the newly introduced Indian green steel standards with renewables

The Indian government introduced a Green Steel Taxonomy on 12th December 2024, a framework that categorises steel based on its emission intensity, measured as the tonnes of CO2 equivalent (t-CO2e) emitted per tonne of finished steel (tfs):

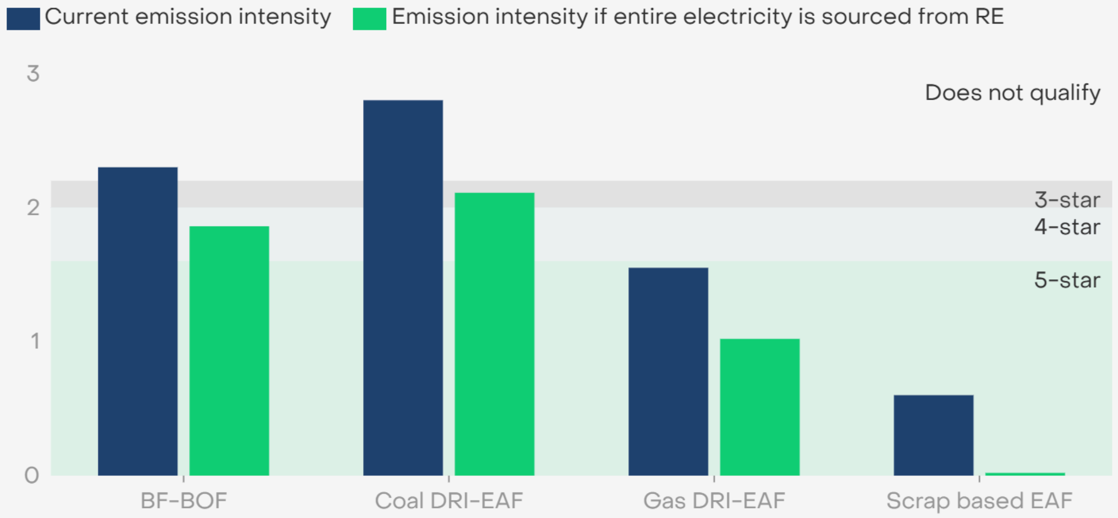
- 3-star green steel (2.0 - 2.2 t-CO2e/tfs)
- 4-star green steel (1.6-2.0 t-CO2e/tfs)
- 5-star green steel (below 1.6 t-CO2e/tfs)

The taxonomy acts as a soft mandate for steel companies, urging them to reduce their emission intensity to at least 2.2 t-CO2e/tfs as a minimum requirement to qualify for a green steel tag.

The Green Steel Taxonomy aims to create new markets for green steel, encouraging procurement by governments and climate-prioritising corporations. Additionally, this framework can help address international carbon taxes, such as the Carbon Border Adjustment Mechanism (CBAM), by providing standardised and transparent emissions data for finished steel products.

Renewable power can help steel manufacturers achieve green steel certification in India

Emission intensity for various steel routes, in tonnes of CO2 per tonne of steel



Source: Ember's estimates based on Greening the Steel Sector in India · The main steel-making routes are BF-BOF (Blast Furnace-Basic Oxygen Furnace) and DRI-EAF (Direct Reduced Iron-Electric Arc Furnace). These routes consume varying proportions of thermal and electrical energy.
The green steel (3, 4 and 5-star) ratings are based on emission intensity ranges, as outlined in the Green Steel Taxonomy announced in December 2024.

Ember's modeling suggests that by sourcing the entirety (~100%) of the steel sector's power consumption from RE, the star rating for various steel-making routes can be significantly improved. In the scenario where the steel sector consumes 100% of RE power, the blast furnace-basic oxygen furnace (BF-BOF) route could achieve a 4-star rating, while the coal-based Direct Reduced Iron-Electric Arc Furnace (DRI-EAF) route could advance to a 3-star rating. RE thus can serve as an immediate lever to navigate the green steel taxonomy. Given the current cost challenges of achieving 100% renewable energy—primarily due to the high cost of storage—this pathway may come at a premium today (discussed further in Chapter 3).

Addressing domestic and international carbon compliance through renewables

The implementation of the EU's Carbon Border Adjustment Mechanism (CBAM) will significantly impact Indian steel exporters by increasing the cost of their shipments to the European market. Indian steel exporters will have to pay between €60 and €80 per tonne of carbon emissions over and above the standards mandated under CBAM. Currently, India exports around 30% (~ 3-4 MTPA annually) of its total steel exports to Europe. Imposition of CBAM could lead to an erosion of corporate profitability in steel exports by 20-35% on a case-by-case basis.

India has also introduced a domestic Carbon Credit Trading Scheme (CCTS) to incentivise industries to reduce carbon emissions and align with global climate commitments. Launched under the Energy Conservation Act, 2022, the scheme establishes a domestic carbon market where industries can earn and trade carbon credits based on emission reduction. Some of the initial challenges can be addressed by aggressively procuring renewable energy.

Cement: A promising yet challenging market for renewables

India is the second-largest producer of cement, with an installed capacity of 632 MTPA and an annual production volume of 433 MTPA, growing at an average rate of nearly 4%. The country's per capita cement consumption stands at around 195 kg annually, significantly lower than the global average of 500 kg. To meet rising demand, India's cement capacity is expected to reach 800 MTPA by 2030.

Cement production process

Cement production follows a fundamentally two-step process. First, an intermediate substance called clinker is produced in a kiln. This clinker is then transported to a grinding unit, where it is processed into cement. Clinker production is the most energy-intensive stage, accounting for approximately 95% of the total energy consumption. The process is primarily driven by thermal energy (~90%), sourced mainly from coal and petcoke, while electricity (~10%) comes from a mix of captive generation and the grid. With an emission intensity of 0.66 tonnes of CO_2 per tonne of cement produced, the Indian cement sector emits approximately 285 MT of CO2 annually.

Despite the lack of strong regulatory push compared to the steel sector, the cement industry has seen significant voluntary climate commitments. Three of the largest companies—UltraTech, Shree, and Dalmia Cement—have pledged to the RE100 initiative, committing to 100% renewable electricity by 2050, with some setting more aggressive near-term targets. Additionally, many cement companies have joined various global initiatives focused on carbon supply chains and trade sustainability, such as the Global Cement and Concrete Association.

Electricity comes from a mix of captive and grid for cement production

India's cement sector sources its electricity from both captive power plants and the grid, with larger plants generally having a higher share of captive consumption. On average, an integrated cement unit in India—comprising clinkerisation, grinding, and other pre- and post-processing stages—consumes around 80 kWh of electricity. India has one of the most electricity-efficient cement industries, with one of the lowest electricity consumption per unit of cement produced.

Due to the lack of exhaustive plant-level data, an average estimate has been derived based on multiple samples from environmental clearance reports from various plants. Our analysis indicates that, on average, the electricity mix across cement plants is supplied by:

- captive power plants (40%)
- waste heat recovery (WHR) systems (10%),
- the grid (50%).

While coal-based captive power plants (CPPs) dominate, cement manufacturers have also signed significant open access renewable energy deals. Currently, the sector is reported to be using roughly 6 GW of coal CPPs, which as per our estimates is significantly more than the total demand. Additionally, many cement manufacturers have committed to expand their WHR capacity and also their RE consumption by 4-5 GW 2030.

Cement plants must walk a tightrope to maximise gains from renewable energy

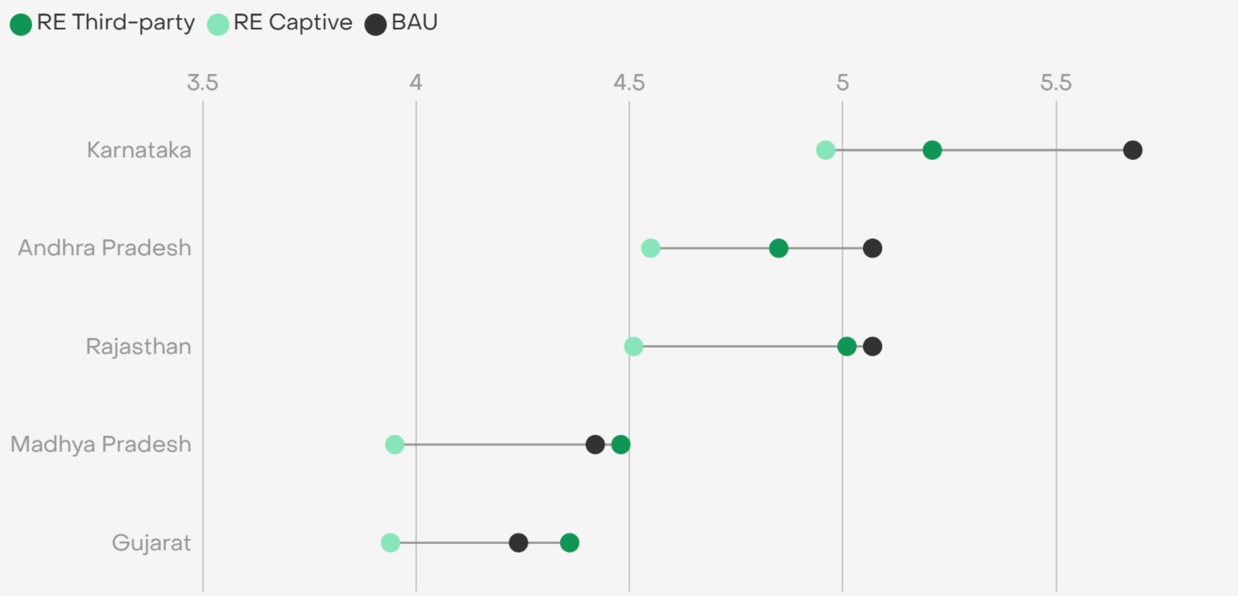
India's cement sector is geographically dispersed across multiple regions. The top five cement-producing states—Rajasthan (12.82%), Andhra Pradesh (12.03%), Karnataka (8.07%), Gujarat (7.28%), and Madhya Pradesh (6.80%)—account for approximately 50% of total production, while the remaining 50% is distributed across various other states.

Geography of cement production is highly dependent on raw material availability. On average, producing one tonne of cement requires approximately 1.5 tonnes of limestone and 0.2 tonnes of coal. As a result, cement plants are primarily concentrated in states with abundant limestone reserves, such as Rajasthan, Andhra Pradesh, and Karnataka.

This section follows the same scenario-building approach, beginning with a business-as-usual (BAU) case where electricity is sourced from CPP, WHR systems, and the grid. In the RE scenarios, a portion of costlier grid consumption is replaced by solar power during solar hours. Accordingly, we analyse three scenarios—BAU, RE Captive, and RE Third-Party—to assess the cost competitiveness of solar open access procurement for the cement sector across different states.

Captive renewables ownership is key to cost savings for India's cement plants, third-party sourcing may fall short

Cost of electricity for cement plants – BAU vs. RE procurement, in Rs./kWh

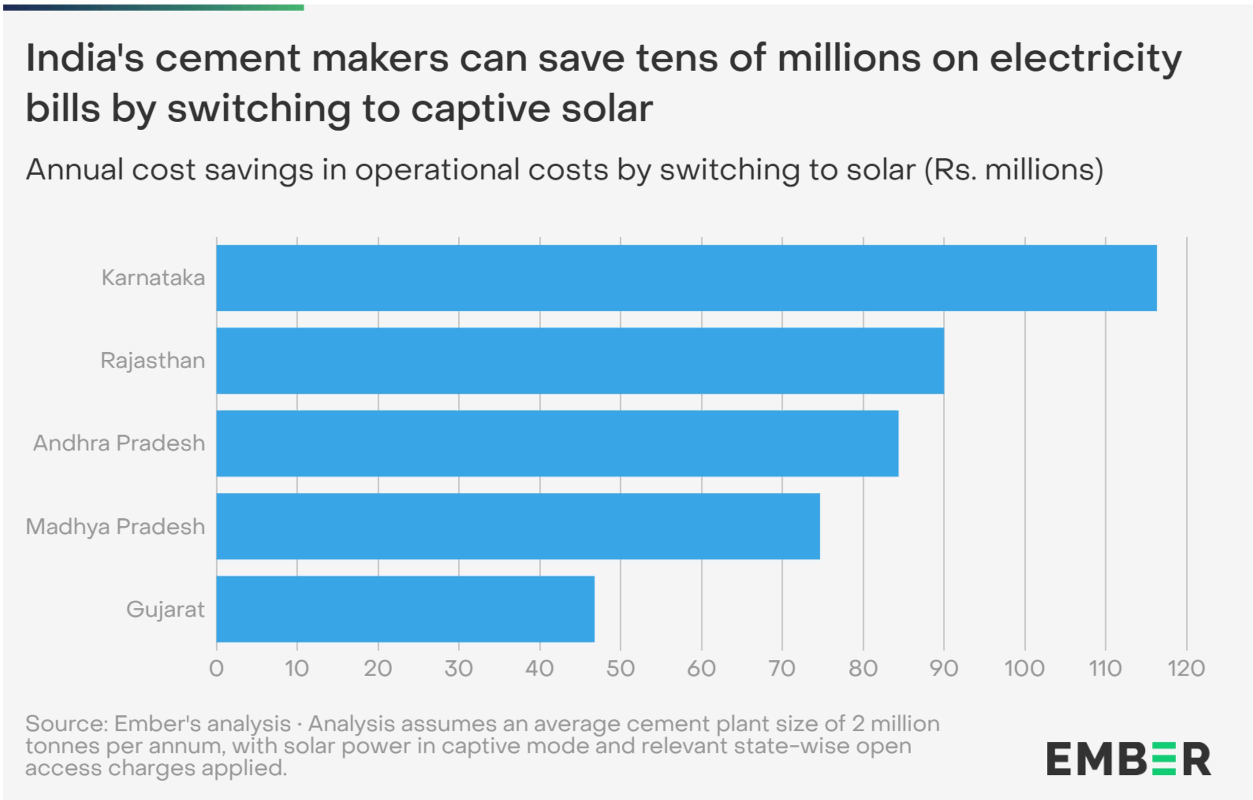


Source: Ember's analysis based on tariff orders upto Nov 2024.
Business-as-usual (BAU) refers to electricity procurement from a mix of captive and grid. Renewable (RE) scenarios consider replacing a portion of grid electricity with open access solar. States considered for the analysis are top cement producers.

The cement sector, like steel (DRI-EAF), is significantly exposed to the grid with high electricity tariffs. However, unlike steel, where RE procurement offers substantial cost advantages, the cost benefits for cement remain marginal compared to the BAU scenario. Third-party RE sourcing alone does not present a strong business case in most states. Instead, captive RE emerges as the more viable option, with potential savings of up to ₹0.5/kWh, as observed for Karnataka.

The key factor driving this price dynamic is the high cross-subsidy surcharge in most top cement-producing states. This contrasts with steel-producing states, which have lower cross-subsidy surcharges and, in some cases, waivers on these charges—such as in Odisha and Chhattisgarh—designed to promote open access RE.

Given this background, where margins are thin, we analyse the potential annual savings from captive RE sourcing. Based on a sample of cement plants, we find that assuming an average plant size of 2 MMTPA provides a reasonable benchmark for estimating savings.



Despite the small margins available for captive RE, the sheer scale of cement production translates these savings into substantial gains. Cement manufacturers in the top-producing states can save around ₹80–120 million per year. This comparative cost advantage can drive RE demand across the cement sector, with estimated requirements of 1.9 GW in Rajasthan and Andhra Pradesh and around 1.2 GW in Karnataka.

One of the key issues is that electricity costs account for only a fraction of total input costs, with potential savings reaching up to 1% of annual revenue. However, given the thin margins in general in the cement sector, even these savings can offer a competitive advantage if coupled with green brand equity. By positioning low-carbon cement as a premium product, companies could differentiate themselves in a highly commoditised market.

India's cement sector has recently seen a wave of acquisitions and consolidations, driven by a strong push for cost reduction. Leading players such as UltraTech Cement, Shree Cement, and Dalmia Bharat have also significantly increased per-tonne discounts in the last two years to reinforce distributor and dealer loyalty. In an industry where margins are razor-thin, scaling up production and leveraging shared infrastructure have become key competitive strategies. RE has already started playing a significant role in the cement sector in alleviating some cost pressures. If states relax surcharges to encourage RE procurement, it could lead to further improvement of competitiveness for cement manufacturers.

Aluminium: A steep climb for renewables

India is the world's second-largest aluminium producer, with a smelting capacity of 4.1 MTPA and production of 3.5 MTPA in FY 2022-23, contributing around 6% to global output. Despite this, per capita consumption in India is just 2.2 kg—far below the global average of 8 kg and 22-25 kg in developed nations. Aluminium demand is expected to rise in the coming years, driven by its growing use in power and electronics, especially in renewable energy (solar frames and mounts), as well as in consumer durables, aerospace, and infrastructure.

Aluminium production process

Aluminium production follows a two-step process. First, bauxite is refined into alumina via the Bayer process, which is highly thermal-intensive but consumes minimal electricity. The second step, the Hall-Héroult process, smelts alumina into aluminium through electrolysis, making it almost entirely dependent on electricity. Due to this high reliance on electrical energy (~ 14,361 kWh per tonne of aluminium on average) for smelting, securing cheap and reliable power is the top priority for aluminium producers, unlike primary steel and cement, where thermal energy dominates. The total CO2 emissions from aluminium production in India are estimated at 65 MT, based on an emission intensity of 18.5 tonnes of CO_2 per tonne of finished aluminium. Aluminium is the second most emission intensive metal after steel.

India lacks a strong regulatory framework for low-carbon aluminium, unlike steel, which has significant national policy support. However, aluminium production in India is concentrated among three major players—Vedanta Ltd., Aditya Birla Group (HINDALCO), and National Aluminium Company (NALCO)—unlike the steel sector, which has diverse ownership, including many smaller companies. Among them, Vedanta Aluminium and Hindalco have set 2050 carbon neutrality targets. Despite these commitments, a large-scale policy-driven push for decarbonisation in the aluminium sector is necessary for the near term action.

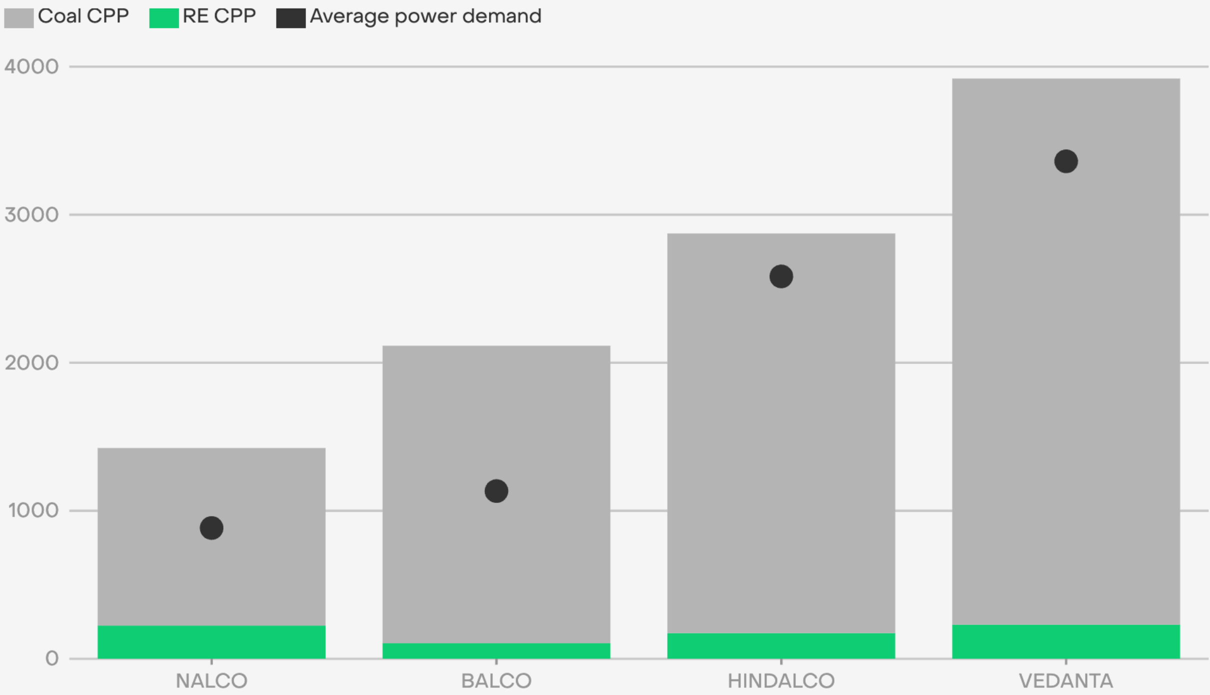
Entire electricity consumption is from captive coal power plants

India's aluminium sector has historically relied on captive coal-based captive power plants (CPP) to meet its electricity needs. All aluminium producers in India operate their own CPPs and often supply excess electricity to the state grid. While some RE integration has begun, its share remains limited due to the dominance of CPPs across industrial facilities.

Each tonne of aluminium consumes around 14,361 kWh on average in India, requiring an estimated 8 GW of coal power capacity, assuming a plant load factor of 85%. The sector's total captive coal capacity is currently estimated at 9.6 GW, with only a small share of RE. There is already excess coal CPP capacity available to meet any increased demand for aluminium.

Aluminium makers in India predominantly rely on captive coal power to meet demand, with excess available capacity

Comparison of power demand and supply (in MW) for aluminium companies



Source: Annual reports of companies, Global Energy Monitor (GEM) · CPP stands for Captive Power Plant. Power demand is estimated by using production data.
NALCO stands for National Aluminium Company, BALCO stands for Bharat Aluminium Company, and HINDALCO stands for Hindustan Aluminium Company. BALCO is a subsidiary of Vedanta.

With the RPO mandate, companies are required to follow a transition trajectory and replace 43% of their captive generation with renewables by 2030. However, weak enforcement has significantly slowed this process, with many companies still relying entirely on coal CPPs to meet their total demand.

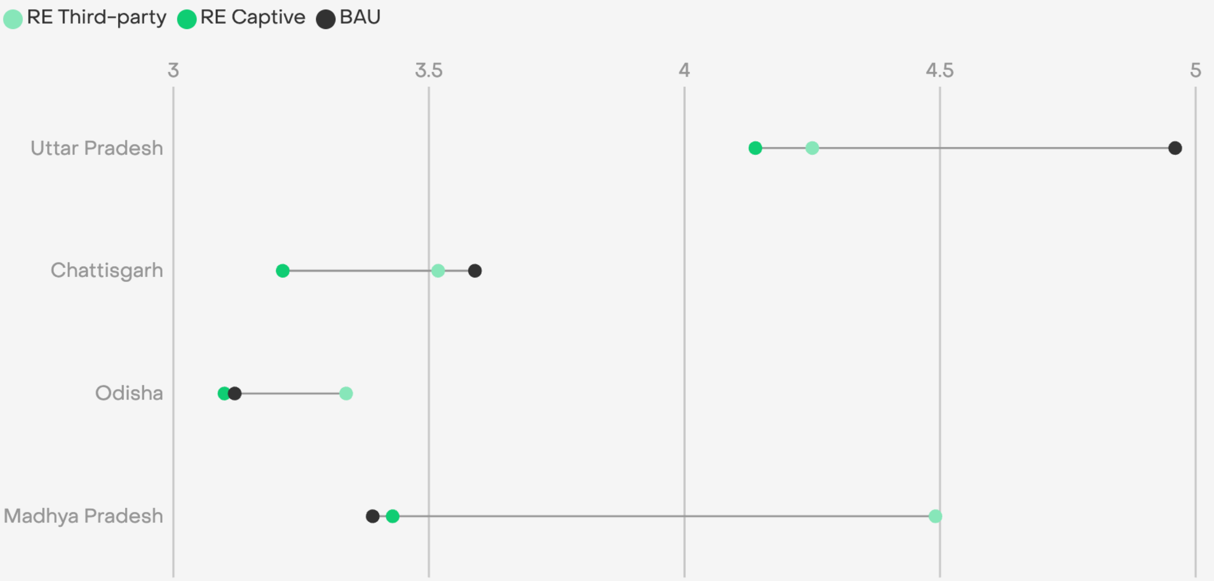
Transitioning to low-carbon aluminium would require sticks, not carrots

The aluminium sector in India is concentrated in the eastern region, primarily due to the proximity of key raw materials like bauxite and coal. Production is heavily clustered in a few states, with Odisha accounting for 67%, followed by Chhattisgarh at 15%, while the remaining 18% is split equally between Uttar Pradesh and Madhya Pradesh (9% each). The sector is dominated by a few major players, with Vedanta Aluminium leading at 2.34 MTPA—close to 60% of India's total aluminium production capacity.

This section follows the same scenario-building approach used previously, starting with a business-as-usual (BAU) case, where nearly 100% of electricity comes from coal-based CPPs. In the RE scenarios, a portion of CPP consumption is replaced by solar power during solar hours. Accordingly, we analyze three scenarios—BAU, RE Captive, and RE Third-Party—to assess the cost competitiveness of solar open access procurement for the aluminium sector, across states.

Profitable opportunity in some states for renewable use in aluminium production despite captive coal being dominant

Cost of electricity for aluminium plants – BAU vs. RE procurement, in Rs./kWh



Source: Ember's analysis · Business-as-usual (BAU) refers to electricity sourced entirely from coal captive power plants (CPPs). Renewable (RE) scenarios consider replacing a portion of coal CPP electricity with open access solar. States considered for the analysis are the top aluminium producers.

Aluminium plants are typically located near coal mines, benefiting from low-cost captive coal power and limiting the case for renewables. However, Uttar Pradesh, with high coal freight costs due to its distance from coal mines, and Chhattisgarh, with [supportive open access policies], stand out as exceptions—together offering potential for 1.8 GW and 2.5 GW of solar deployment, respectively.

However, stringent regulations, such as the enforcement of RPO obligations, will be necessary to drive the transition from coal CPPs to renewables in the aluminium sector. Additionally, the government could promote green aluminium standards, similar to green steel, to establish a regulatory framework for low-carbon aluminium. Given the entrenched presence of CPPs, it is unlikely that RE will replace them solely based on cost economics.

Case study for HINDALCO's aluminium plant in Uttar Pradesh

Aditya Birla Group-owned Hindustan Aluminium Corporation Ltd. (HINDALCO) operates a 0.41 MTPA aluminium smelting plant in Renukoot, Uttar Pradesh. The plant is powered by an 840 MW coal-based CPP with some co-generation, which primarily runs on imported coal, making it vulnerable to high prices and market fluctuations.

With domestic coal based CPP costs in Uttar Pradesh estimated at ~Rs. 5/kWh (actual cost can be higher given the dependence on imported coal) and solar available at ~Rs. 4.2/kWh, switching to solar can yield savings of at least ₹0.8/kWh. For HINDALCO's Renukoot plant, this translates to annual savings of ₹5 billion—about 4–6% of annual revenue from the plant. Meeting this shift would require 1.8 GW of solar capacity.

Uttar Pradesh's solar policy offers waivers on surcharges, wheeling, and transmission charges—making it attractive for third-party solar without requiring capital investment from industries. However, current policy limits these benefits to projects sited within Uttar Pradesh. Given the state's modest solar potential, this can result in low CUFs and inefficient use of solar assets. Instead of tying subsidies to in-state siting, the government should focus on enabling open access RE sourcing from optimal locations to strengthen its position as a cost-efficient green industrial hub.

Leveraging renewables to access climate conscious markets

The decarbonisation of India's aluminium sector presents a significant techno-economic opportunity, primarily due to two key factors:

- RE as the most influential abatement lever for aluminium: Approximately 80% of emissions in aluminium production come from captive coal-based CPPs. Unlike other heavy industries like steel and cement that rely on high-temperature heat, aluminium production can be largely decarbonised through RE alone.

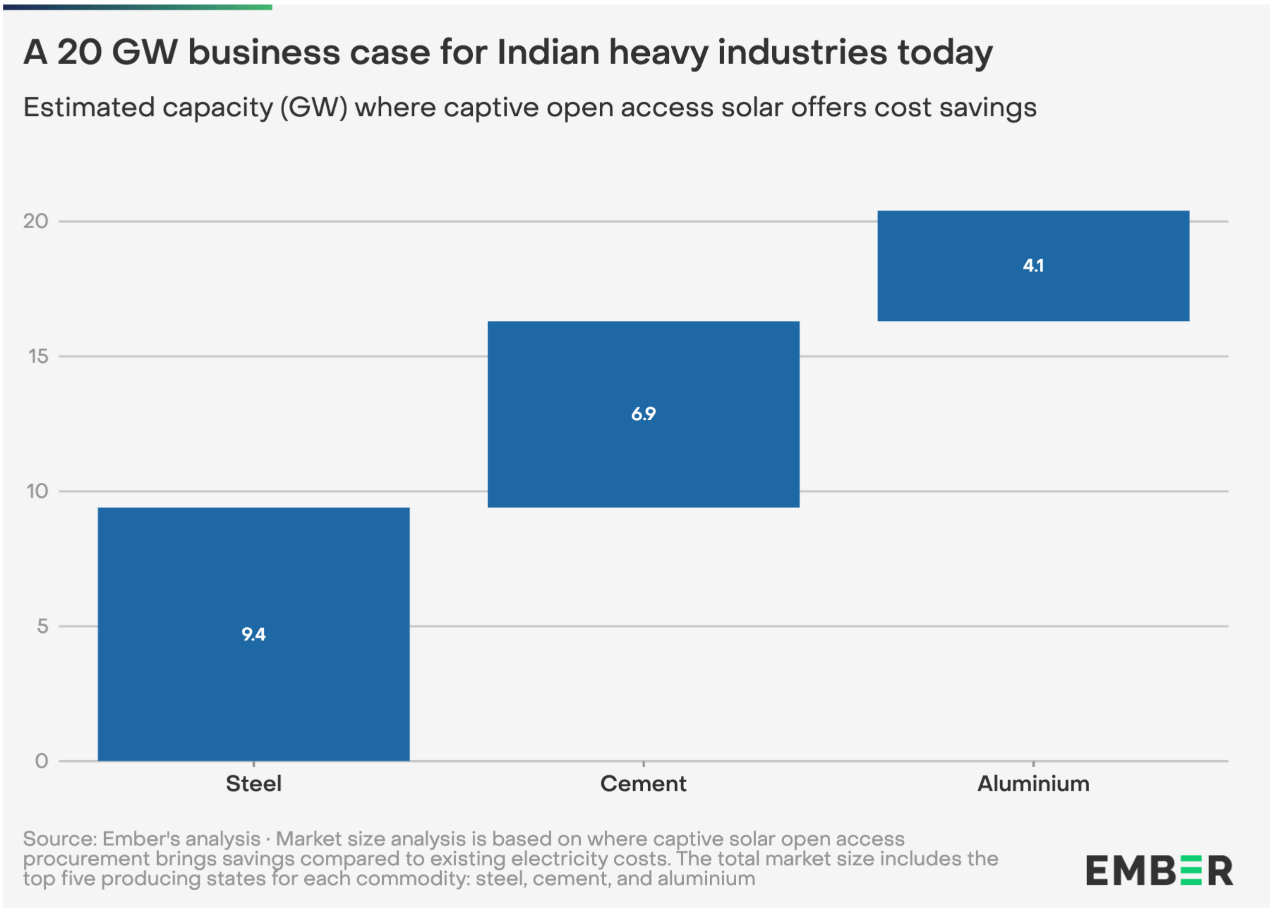
- Cost competitiveness: India has witnessed record-low tariffs for solar and solar-wind hybrid projects. This makes RE procurement for aluminium smelters in India more cost-competitive than in many other regions.

A shift to RE-powered aluminium can help companies navigate the EU Carbon Border Adjustment Mechanism (CBAM). With CBAM set for full implementation in 2026, India's aluminium exports—about 0.7 MMTPA to Europe—could face significant cost increases. This impact would be particularly significant for India's aluminium sector, given its heavy reliance on captive coal CPPs, which are classified as direct emissions under CBAM. As a result, aluminium prices could increase by up to 30% for European buyers. Transitioning to RE can ensure that Indian aluminium remains competitive in Europe while also expanding its footprint in climate conscious markets.

Summing up: A business case for 20 GW solar—today

While the industrial decarbonisation landscape is often dominated by high-tech solutions planned for 2030 or beyond, this analysis highlights what can be done today—profitably and at scale. Our study assesses the solar capacity that can be viably deployed under the open access model to decarbonise industrial operations in heavy industries like steel, cement, and aluminium, spanning various states of India.

- A 20 GW market opportunity: The total demand for open access renewables in the top-producing states of these commodities is 9.4 GW for steel, 6.9 GW for cement, and 4.1 GW for aluminium. The study focuses on DRI-EAF and standalone furnaces in steel, which present the biggest opportunity within the steel sector as they can replace a significant portion of grid power. The adoption of renewables in cement offers substantial savings, though not as high as in steel on average. Unfortunately, aluminium remains heavily reliant exclusively on captive coal, making it difficult for open access renewables to compete. For aluminium to transition, a regulatory-heavy approach will be necessary. Switching current production to 20 GW solar can reduce up to 29 MT CO_2.

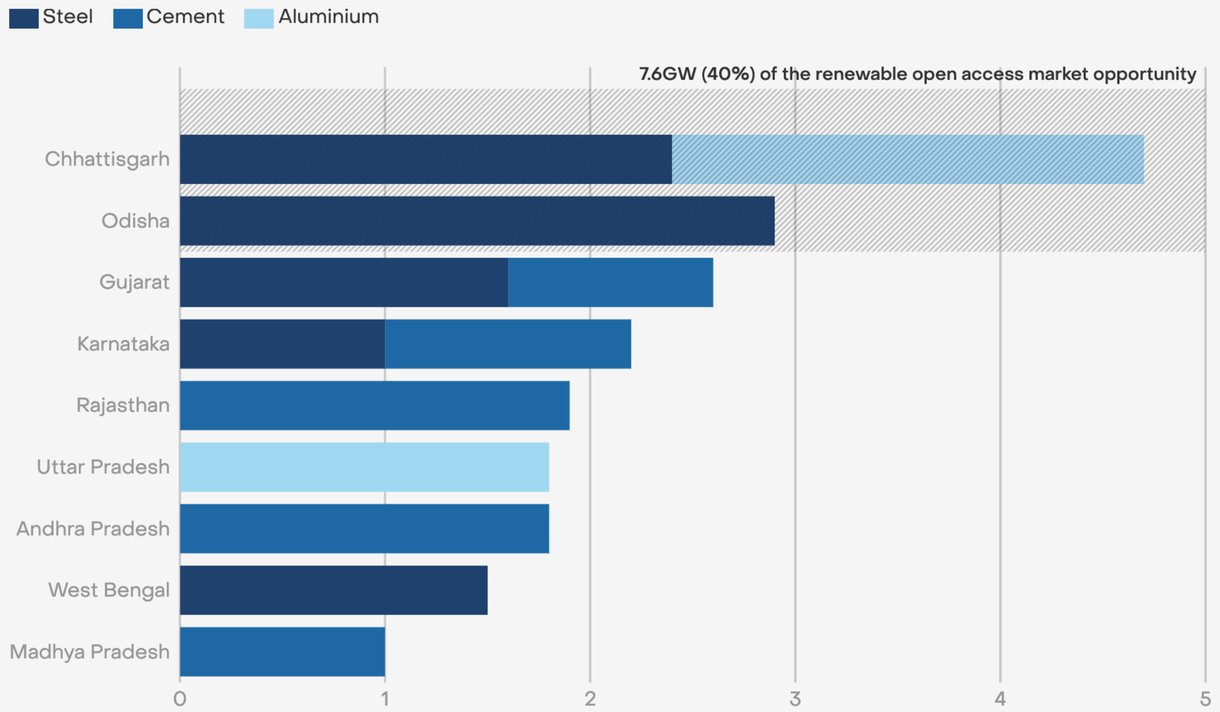


- Thin margins, big payouts: One of the distinguishing features of these sectors, which produce commodities, is that they operate with limited margins and a high degree of cyclicality in revenue generation. Long-term resilience is key, requiring these businesses to navigate market highs and lows strategically. Even marginal savings on electricity costs—ranging from ₹1–2 per unit—can have substantial financial gains that can be repurposed for other productive investments. Competitive pressures in India's steel and cement sectors have been well discussed in recent equity research, and renewable energy can provide some degree of respite.

- States in focus: States like Odisha and Chhattisgarh, located within India's mineral-rich regions, host a significant share of heavy industries. Their progressive green energy procurement policies, which offer discounts on cross-subsidy and various other charges, strengthen the business case for both third-party and captive renewable procurement by industries. Such policies are forward-looking and can position these regions as potential hubs for green steel and aluminium, developing a certain brand perception that can attract international finance and corporate action.

Chhattisgarh and Odisha's heavy industries account for 40% of India's renewable open access market opportunity

Renewable open access market size across states (GW)



Source: Ember's analysis · Market size analysis is based on where captive solar open access procurement brings savings compared to existing costs. The total market size includes the top five producing states for each commodity: steel, cement, and aluminium

On the other hand, states like Karnataka, Rajasthan and West Bengal present a more challenging environment for open access due to fewer incentives for green energy procurement and various regulatory hurdles. A rationalisation of green energy open access charges could provide much-needed relief for industries serious about transitioning. Also, a key concern is the potential elimination of transmission charge waivers, which could further stress the growth trajectory of renewable open access markets.

- Playing the global game: Reducing the carbon intensity of steel, cement, and aluminium can unlock access to new international markets. It can create new partnerships with climate clubs such as Responsible Steel and the aluminium Stewardship Initiative, as well as corporate buyer groups like big tech companies, automotive, and aviation sectors committed to green commodity markets. Besides opening up new revenue channels, this facilitates technology transfer, access to financing, and enhanced brand equity. Early movers like Kalyani FeRRESTA steel and Shree cement are case in point within Indian commodity markets. Additionally, decarbonisation efforts can help industries maintain competitiveness in regions implementing carbon tariff mechanisms, such as Europe's CBAM.

This chapter focuses on what is already feasible using standalone solar, without factoring in storage. The emerging opportunity of combining renewables with storage for 24/7 industrial supply—already under consideration in states like Gujarat—is explored in the next chapter.

Outlook for RE share in industries: 50% at competitive prices, 80% with a moderate premium, 24/7 RE is challenging

Balancing variable RE generation with firm industrial demand remains a challenge

As industrial consumers shift towards RE procurement, the fundamentals of balancing supply and demand undergo significant changes, introducing new challenges that make the act of balancing more expensive.

To explore the feasibility of balancing variable RE and industrial demand at different RE consumption levels, this chapter uses a PPA model for a renewable energy project designed to serve an industrial consumer, exploring scenarios from 50% variable RE to 24/7 variable RE supply (24/7 RE). It examines the optimal RE mix, storage requirements, and associated costs as industries inch closer toward 24/7 variable RE.

One of the main challenges in RE procurement for industries is the temporal mismatch between when RE is generated and when industries need power across different timescales—hourly, daily, and seasonally. Most industrial consumers operate on a 24/7 basis, but solar energy is only available during daylight hours, and wind energy fluctuates across seasons. This leads to periods where either RE supply exceeds demand or demand exceeds RE supply.

Key challenges in meeting demand through RE on a 24/7 basis occur during :

- Evening and night time: Industrial demand remains constant, but solar generation drops to zero, creating a shortfall in supply. This results in an hourly-level mismatch between generation and demand throughout the day.
- Low-wind months: Wind generation fluctuates and may be too low to meet industrial demand, leading to seasonal supply gaps. This causes a mismatch not only at an hourly level but also at a monthly level, where total generation over the month falls short of total demand.

To address this mismatch, consumers must either:

- Shift generation to times of higher demand (e.g., using grid banking or energy storage).
- Shift demand to align with RE generation (e.g., through demand response programs).
- Build a higher capacity of RE, which may lead to excess generation in non-lean RE generation blocks that has to be sold elsewhere.

What is Grid Banking?

In India, electricity banking is a mechanism that allows consumers sourcing electricity from renewable energy (RE) generators to inject surplus power into the grid when their generation exceeds demand and withdraw an equivalent amount when their generation falls short.

State Electricity Regulatory Commissions (SERCs) impose three key restrictions on electricity banking to ensure grid stability and financial viability for distribution companies (DISCOMs).

- Quantum of Banking: Caps the share of RE that can be banked to avoid overburdening DISCOMs. Green Energy Open Access Rules (GOAR) mandates at least 30% of monthly consumption to be eligible.
- Settlement Period: Sets the timeframe for using banked power, usually limited to intra-month use with time-of-day restrictions. GOAR requires at least monthly banking.
- Banking Charges: Fees for withdrawing banked energy, often ~8%, to cover DISCOMs' grid balancing costs.

However, since the type of industrial consumers we examine in this study require continuous power, the potential for demand-side flexibility is fairly limited. Instead, industries must rely on grid banking and storage mechanisms while also incorporating a much higher RE generation capacity in their RE procurement strategies for higher RE consumption levels.

Conceptualising the challenges of balancing RE supply and demand

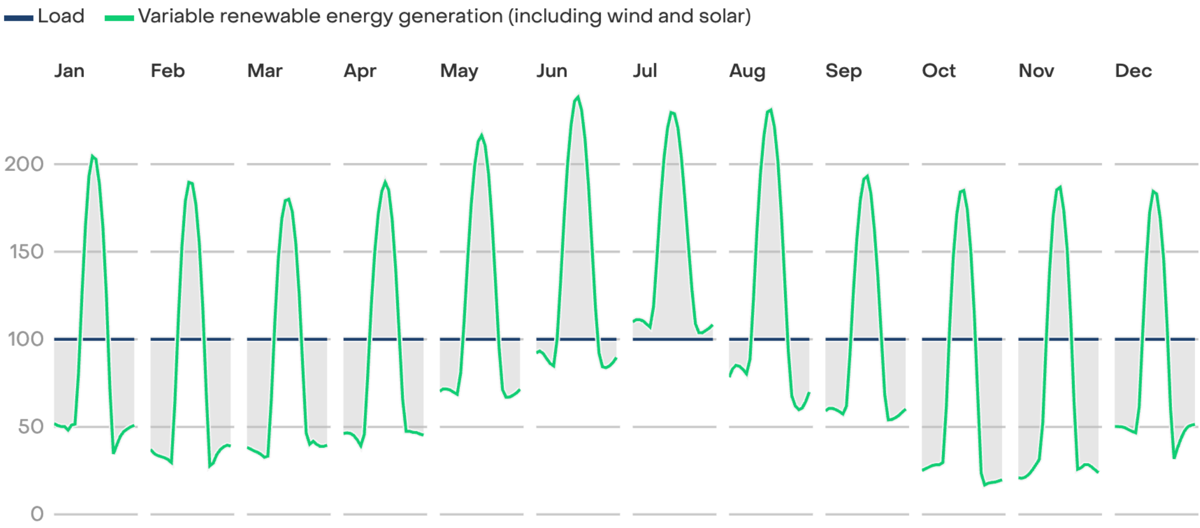
Balancing renewable energy (RE) supply with firm industrial demand presents two major challenges.

First, the monthly variation in RE generation (green curve) fluctuates across months, with higher generation in some periods and lower in others. This surplus often needs to be sold at lower prices, impacting revenue realisation. In the absence of cost-effective long-duration energy storage, industries must install higher RE capacity to maintain a steady RE share throughout the year, leading to surplus generation during high-resource months (e.g., May–July).

Second, daily variability in RE generation creates further mismatches, as RE generation peaks during the day while industrial load remains relatively stable. This results in surplus generation during peak RE hours (midday) and shortfalls during evening and nighttime hours. To address this, battery storage is necessary to shift excess generation to match demand.

An illustration of why perfectly balancing RE supply and demand for Indian industries may require both an hourly and seasonal shift

Hourly average generation and load (y-axis, MW), across a 24-hour period (x axis)



Shaded area represents supply deficit/surplus

The technical and financial viability of sourcing a certain share of RE is constrained by two key factors: surplus generation, which may need to be [sold at lower prices](), and the need for storage, which would increase costs. These challenges would intensify as the need for RE penetration rises, making balancing increasingly critical at higher RE procurement levels.

Sourcing half of the electricity from variable RE is viable for industries today

Sourcing half of an industry's electricity from variable renewables is viable today—marking the first stretch toward achieving 24/7 renewable energy

By 2030, various entities—including distribution companies (Discoms), open-access consumers, and captive power producers—will be required to source approximately 43% of their total electricity consumption from RE, including wind, solar, and hydro, as per the Renewable Purchase Obligation (RPO) norms. As industries work toward increasing RE procurement, understanding the practical implications of higher RE shares becomes essential.

This section explores the technical feasibility and financial viability of sourcing 50% of industrial electricity demand with RE in 2024. In this scenario, we model an industrial electricity consumer with peak demand reaching 500 MW and minimum demand rarely dropping below 350 MW throughout the day and across seasons.

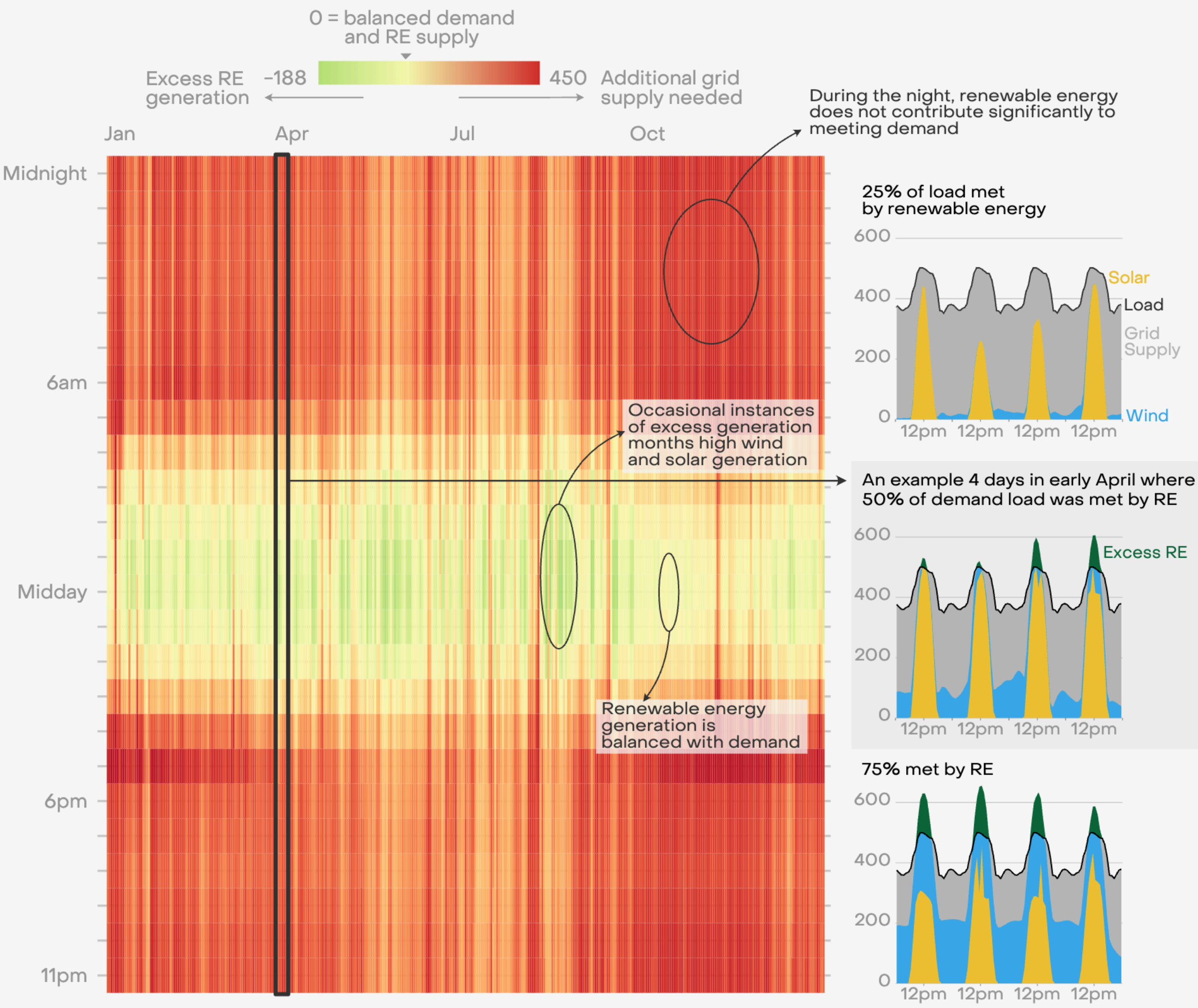
The analysis uses Ember's RE PPA model, which optimises the capacity of solar, wind and battery storage to match a given demand profile. About 571 MW from solar and 223 MW from wind would help meet 50% of an industrial consumer's electricity demand with RE, , without needing battery storage

With a peak demand of 500 MW and a load factor of over 80%, this demonstrates that achieving 50% RE does not require excessive oversizing. Particularly considering that the CUF of solar is below 25% and wind is slightly over 30%.

At this level of RE penetration, the key challenges of managing seasonal surplus and daily variability are minimal.

Using renewable energy when it's available and the grid when it's not, Indian industries can meet 50% of electricity demand with RE

Net load = demand load — renewable generation (MW, modelled data)



Source: Ember's renewable energy PPA model · Optimal solar and wind capacity for a 500 MW industrial consumer: 571 MW solar and 223 MW wind

The figure below illustrates the net load (load minus RE generation) for each hour in a year for an industrial consumer sourcing 50% of its annual electricity demand from RE on an annual basis. Additionally, it provides an hourly snapshot of demand-supply balancing during both high and low RE generation days, highlighting the variability in RE generation and its impact on industrial electricity consumption.

Banking is a viable strategy to absorb excess generation to reach the 50% RE mark

Since instances of excess generation are rare, the need to sell surplus electricity at lower prices is largely a non-issue. Instead, banking remains a viable option, as current regulations allow consumers to bank up to 30% of the electricity purchased from the grid.

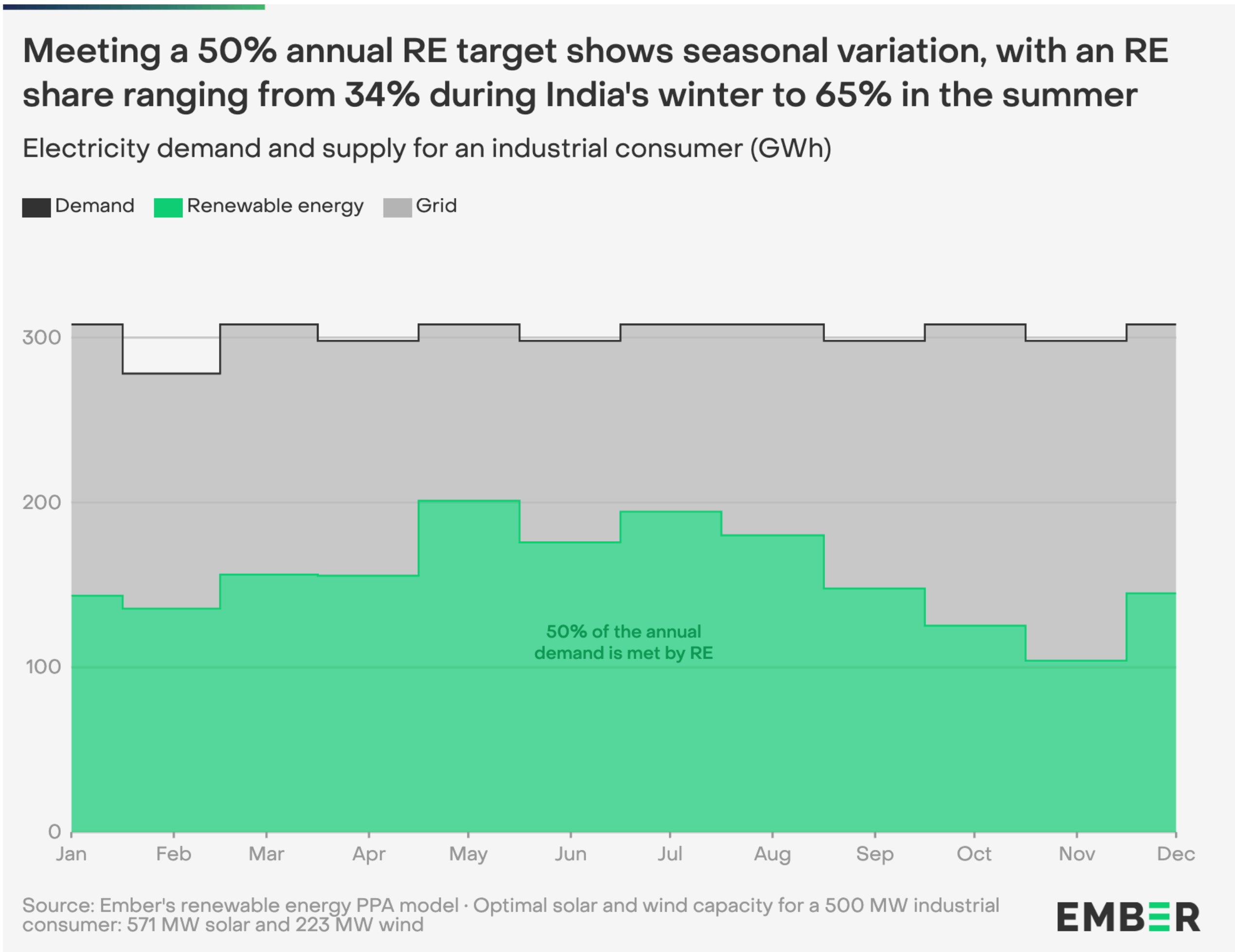
Given that 50% of total demand is sourced from RE, this means that equivalent of 15% of total demand (i.e., 30% of 50%) can be banked. This capacity is more than sufficient to absorb the occasional instances of over-generation, ensuring that excess electricity is efficiently utilised rather than sold at lower prices. For reference, the highest quantum of banking occurs in May, where less than 6% of the total electricity purchased from the Discom is banked in this scenario, demonstrating that banking remains well within allowable limits.

As seen in the figure, even during months of higher generation from solar and wind, the total generation does not exceed demand on a monthly aggregate level. The net load curve remains mostly positive, indicating that generation rarely surpasses consumption.

Rare instances of excess generation while sourcing 50% RE after banking

One major concern to meet RE share is that there may be instances of overgeneration. Which has to be sold elsewhere and can potentially impact the LCOE of the useful electricity supplied. But in this scenario, instances of over-generation after banking are rare. Moreover, the net load curve remains mostly positive, indicating that generation exceeds demand only for a few instances in a year. Even when over-generation does occur, it is infrequent and limited in magnitude. On rare occasions when generation exceeds demand, the excess electricity can be banked and utilised within the same month, ensuring utilisation in other time periods.

For most of the time—especially during months of low wind and solar generation—the shortfall in RE supply is met by the grid.



Batteries aren't a necessary to reach 50% RE

Meeting up to 50% of demand from variable RE allows industrial consumers to optimise variable RE consumption while maintaining flexibility to source the remaining electricity from other suppliers, such as DISCOMs. This flexibility is particularly valuable during periods when RE procurement is costly, such as night-time or months with lower wind generation. Consequently, optimising the mix of solar and wind may be an important consideration for industrial consumers.

Industrial consumers can meet around 50% of their total electricity consumption from RE without requiring battery storage. Having an optimal mix of solar and wind manages the variability of RE generation.

Since 50% of electricity must be met by variable RE on an annual level, both intra- and inter-annual variations can be fairly managed to maintain this target from year to year. If solar or wind output falls short at certain periods of times, these shortfalls can be offset by periods of higher-than-expected generation. This balancing effect ensures that, on an annual basis, approximately 50% of electricity can be sourced from RE without the added cost of storage infrastructure. Similarly, while years with low wind and solar generation may impact the ability to meet the target, the RE mix ensures that years where both solar and wind are low will be relatively rare, helping to maintain overall RE contribution.

Why balancing 50% renewable energy isn't an issue

- Over-generation concerns are minimal as the net load curve remains mostly positive, meaning variable RE generation rarely exceeds demand, reducing the need to sell surplus electricity at lower prices.
- When over-generation occurs, it is infrequent and limited in magnitude.
    - Excess electricity can be banked and utilised within the same month, ensuring effective use.
    - Current regulations allow banking of up to 30% of grid-purchased electricity and since 50% of demand is purchased from the grid (Discom), 15% of total demand can be banked

- During low wind and solar months, shortfalls are met by the grid, ensuring reliability.
- On a monthly aggregate level, total generation does not exceed demand
- There are days when RE meets a significant portion of demand (up to 80%) and days when it meets far less (<25%), but on an annual aggregate level, it accounts for 50% of total demand.

Balancing gets harder closer to 24/7 RE, with steep challenges only beyond 80% RE

When referring to 24/7 RE supply, we define it as a scenario where every kilowatt-hour (kWh) of electricity consumption is met exclusively through a combination of solar, wind, and storage. While hydro is a renewable source, it is not considered in this report. The overall framework is broadly similar to the principles of the 24/7 Carbon-Free Energy (CFE) procurement framework.The mechanism we model for achieving this is 24/7 clean power purchase agreements (PPAs) for renewable energy procurement.

While achieving 24/7 RE procurement is technically feasible, two key challenges limit its financial viability. The first is the seasonality of solar and wind generation, which requires oversized RE capacity to ensure that demand is met even in low-resource months. This leads to excess generation during high-resource months, where the surplus energy often has to be sold at a lower price, reducing financial returns. The second challenge is the daily variability of renewable energy, where variable generation throughout the day may not align with industrial demand. The overlap between generation and demand observed earlier is insufficient to achieve 24/7 RE supply. This misalignment necessitates storage solutions to balance supply and demand, increasing the overall cost of electricity procurement. As RE penetration increases, these constraints become more significant, making financial viability a key concern.

Seasonal variation remains a significant technology constraint that cannot be fully addressed with existing solutions. Lithium-ion battery energy storage systems (BESS) are effective for short-duration balancing but are unsuitable for seasonal storage due to high costs and limited energy capacity. Addressing this challenge requires storage technologies that can decouple energy capacity from power capacity, enabling cost-effective, long-duration storage. Among emerging solutions, flow batteries present a promising alternative to lithium-ion systems, offering scalable storage that can better support the seasonal and daily balancing required for 24/7 RE procurement.

Understanding and addressing these challenges is crucial to making 24/7 RE a viable and cost-effective alternative in the near future.

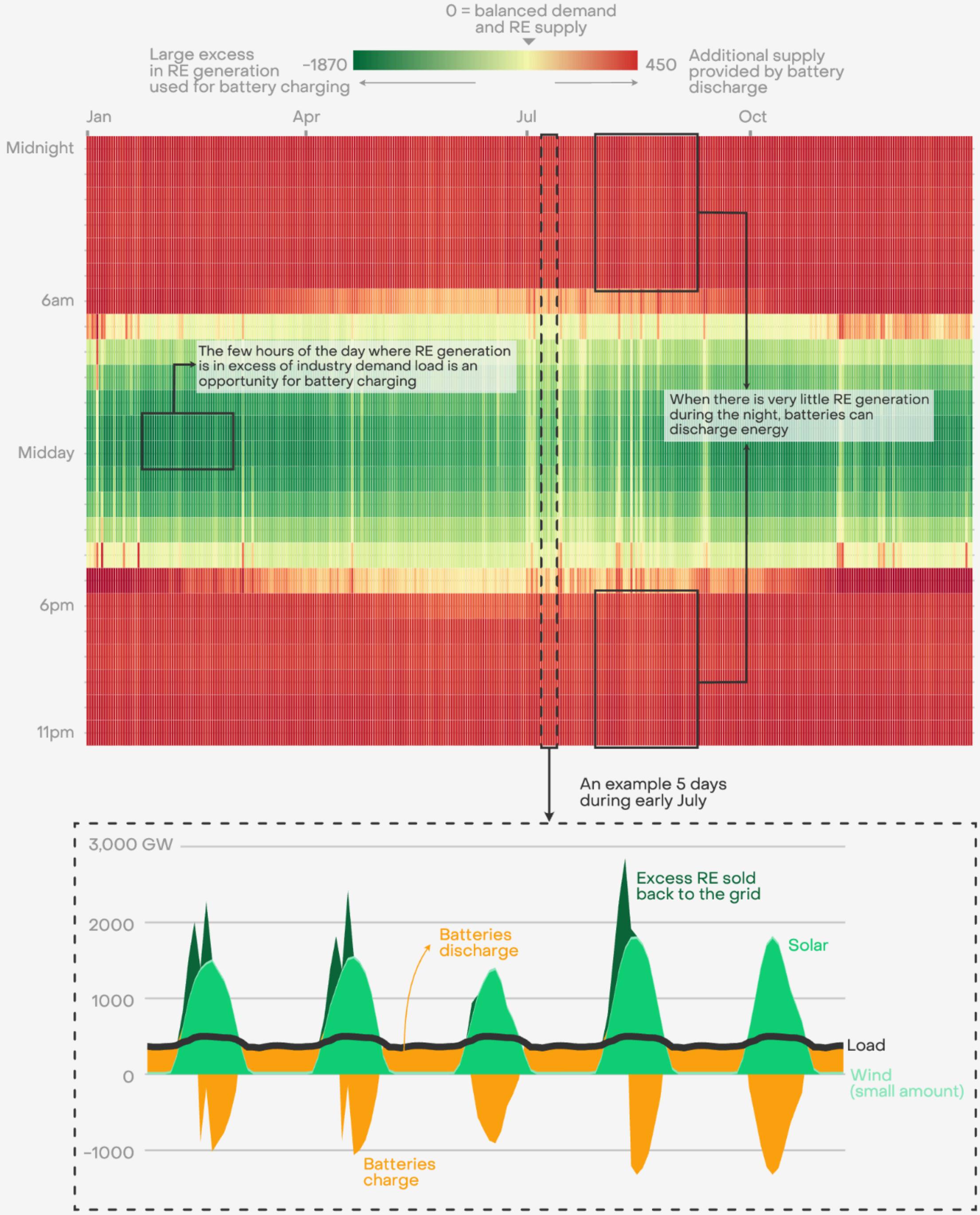
24/7 variable RE is technically achievable but requires significant storage addition and RE oversizing

This section examines a strategy to procure 24/7 renewable energy (RE) and assesses its financial viability for an industrial consumer. We consider the same case as discussed earlier, where electricity demand remains relatively stable, peaking at 500 MW and not dropping below 350 MW throughout the day and across seasons. Given this consistent load profile, an optimised supply mix has been identified to efficiently meet the 24/7 RE requirement while minimising cost implications.

When we look at the net surplus and net deficit in generation across different timescales, we find that the scale of surplus generation is significant—while peak demand is 500 MW, solar generation can reach around 3 GW, meaning generation is occasionally up to 6 times higher than demand. This highlights the challenges of balancing supply and demand on both high and low renewable generation days.

24/7 renewable energy in Indian industries requires batteries to supply about half of the total demand

Net load = demand load — renewable generation (MW, modelled data)



Source: Ember's renewable energy PPA model · Optimal solar, wind, and storage capacity for a 500 MW industrial consumer: Solar: 2,443 MW, Wind: 37 MW , Battery Storage: 2,753 MW (4-hour)
The top figure shows the net load, while the bottom figure illustrates how RE and storage are dispatched to balance supply and demand

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In the 50% RE procurement scenario, the capacity mix consisted of 572 MW of solar and 224 MW of wind, with wind contributing approximately 30% of total RE generation. However, in the 24/7 RE procurement scenario, the mix and overall capacity changes significantly:

- Solar capacity increases to 2,443 MW,
- Wind capacity drops to just 37 MW, reducing wind's share to around 1% (in capacity terms),
- A significant portion of demand is met through battery storage, which increases to a massive 2,753 GW-4hr capacity.

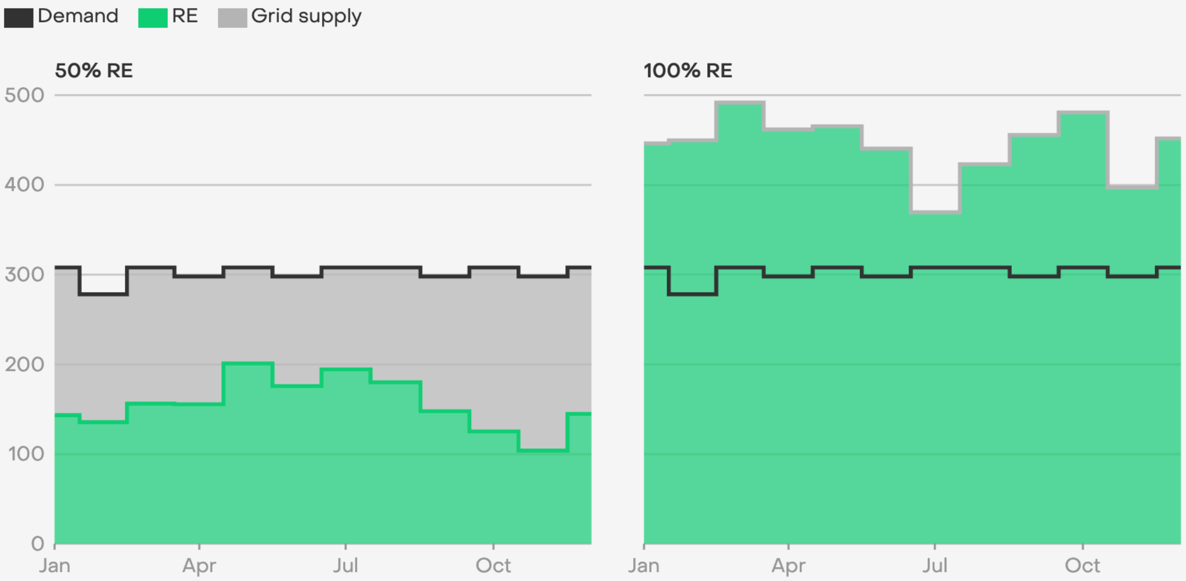
This shift underscores the heavy reliance on solar generation and storage to ensure continuous renewable energy supply in a 24/7 framework.The current strategy for achieving 24/7 RE procurement relies on oversizing solar capacity, generating substantially more electricity than is needed on both a daily, monthly and annual basis.

While in the 50% RE procurement scenario, instances where RE generation exceeded demand were relatively rare in the 24/7 RE procurement scenario, there is consistent overgeneration during solar hours.

As shown in the figure, even during months with lower solar generation, monthly aggregated solar generation frequently exceeds monthly aggregated demand. This overgeneration ensures that there is sufficient energy availability to optimally manage intra-day variability, and supply storage losses.

A 50% RE system for Indian industrial consumers avoids surpluses, but a 24/7 RE system may face surplus even after battery use

Electricity demand and supply for an industrial consumer (GWh)



Source: Ember's renewable energy PPA model

As RE penetration increases, balancing supply and demand becomes progressively more challenging due to the variability of solar and wind generation. Different balancing mechanisms—such as banking, battery storage, and selling surplus electricity—play varying roles depending on the share of RE in total consumption. This section explores how these mechanisms function at different penetration levels and highlights key constraints that impact their effectiveness.

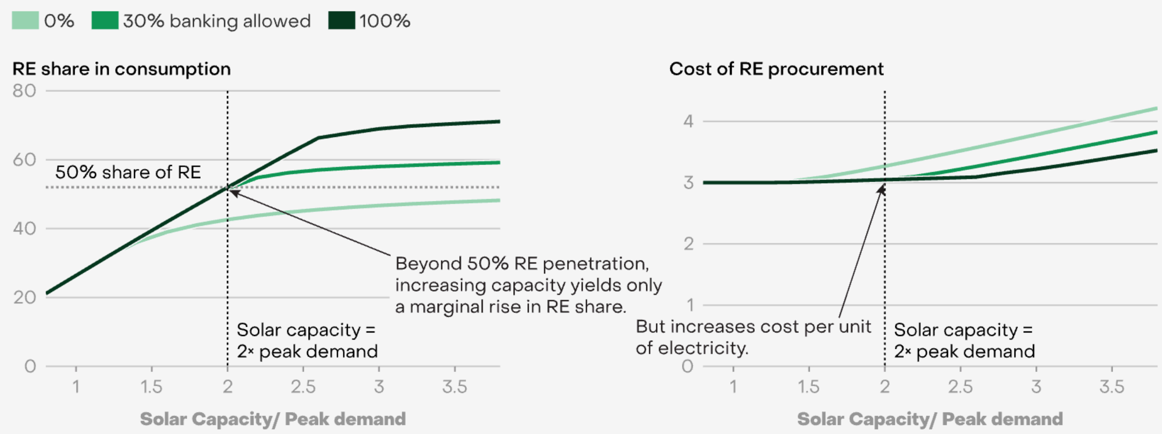
Managing the integration of higher shares of variable RE requires addressing several important factors. One challenge arises when electricity production exceeds demand, leading to surplus energy that must either be curtailed or redirected elsewhere. Storage solutions, while helpful, introduce efficiency losses during charging and discharging cycles, reducing the overall available energy. The extent to which renewable energy is effectively utilised depends on the ability to align generation with demand, either in real-time or through stored reserves, making these variables critical in ensuring a stable and cost-effective transition to higher RE adoption.

As RE share increases, balancing becomes harder. Banking is instrumental in reaching a certain RE share; storage necessary beyond that.

Beyond 50% variable RE, the utility of banking declines — Energy banking cannot be a substitute for storage

Due to grid banking restrictions, particularly around the quantum that can be banked, banking as a mechanism to balance demand and variable renewable energy (VRE) supply cost-effectively is limited for RE procurement beyond 50%. The quantum of banking allowed is directly linked to the consumption from DISCOMs, as banking is typically permitted for at least 30% of the total monthly consumption from the distribution licensee. As VRE consumption increases, the proportion of electricity sourced from DISCOMs decreases, thereby reducing the quantum of energy that can be banked. This limitation restricts the ability of industrial consumers to use banking as a mechanism to shift generation effectively, as the share of their consumption/sourcing from RE increases.

Monthly banking restrictions limit India's industrial consumers to cost-effectively procure up to 50% RE



Source: Ember's estimates for a 500 MW industrial consumer with an 82% load factor · As per the Green Energy Open Access norms, consumers are allowed to bank at least 30% of their total monthly electricity consumption from the distribution licensee.
These estimates only include solar.

Additionally, beyond a certain threshold, costs mainly start increasing due to two reasons.

1. Limited compensation for excess banked energy, typically 75% of the last discovered solar tariff by DISCOMs. This could be 45% lower than the tariff the consumer is paying to the generator for electricity.
2. Banking charges, often 8% of banked energy or additional per-unit withdrawal fees.

Assuming that the 30% quantum limit on monthly banking applies, the feasible size of solar capacity to meet a peak demand of 500 MW is up to 1 GW. This results in a solar capacity-to-peak demand ratio of 2.

Beyond this point, further increases in RE capacity result in only marginal increase in RE penetration while significantly increasing costs due to banking challenges in managing surplus energy. Excess generation beyond the banking limit must either be curtailed or sold at lower prices, reducing the cost-effectiveness of additional RE capacity.

Our analysis indicates that increasing the banking quantum limit would have the greatest impact on raising RE's share in consumption. However, it is unlikely that DISCOMs will permit this, given the potential financial impact of this.

Additionally, any excess electricity that surpasses the banking limit is typically purchased by DISCOMs at 75% of the tariff at which they have recently signed a solar power purchase agreement (PPA). This means that the financial loss on each unit of surplus electricity sold could be as high as 40%, further diminishing the financial viability of expanding RE capacity beyond a certain threshold.

While banking helps manage excess generation, it should not be considered a replacement for storage. Banking is most effective for balancing uncertainties in solar and wind generation, allowing for adjustments within a monthly cycle by offsetting excess generation. Energy banking would not be very effective in balancing monthly variations in demand and supply mismatch.

Oversizing of solar and large-scale storage deployment becomes the primary strategy for achieving 24/7 RE

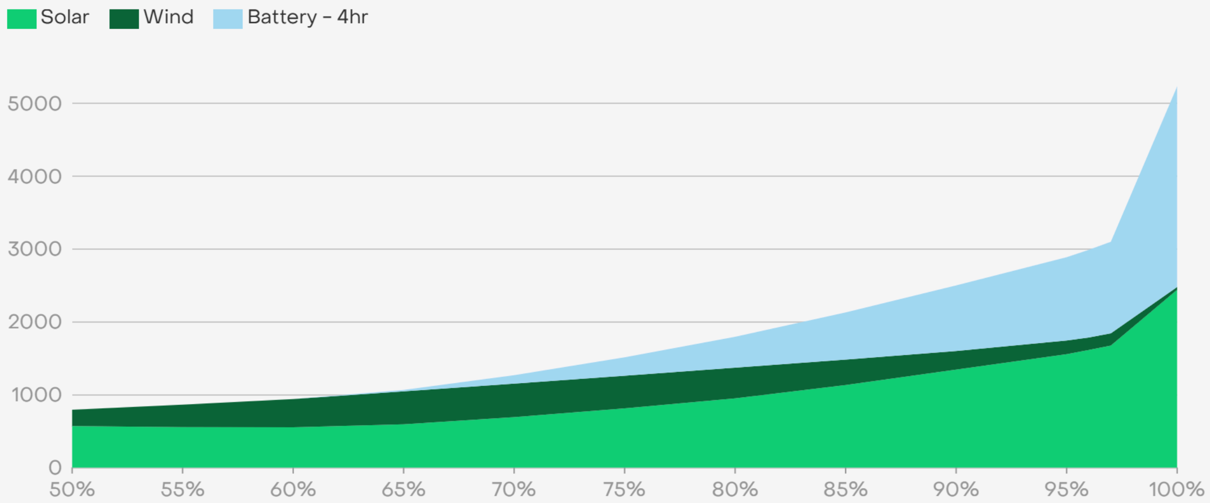
As the renewable energy share rises beyond 65%, storage requirements begin to grow rapidly. Up to this point, minimal or no battery capacity is needed, with zero storage required below 65% RE share. However, beyond 75%, battery capacity expands significantly—from 252 MW (4hr) at 75% RE to 899 MW at 90%, and then surges to 1,256 MW at 97%. To achieve 24/7 RE, storage requirements reach 2,753 MW, nearly matching the solar capacity, which also increases to 2,443 MW, while wind drops to just 37 MW.

Moderate oversizing and small battery capacity can enable up to 75%-80% renewable energy penetration for industries

As renewable energy penetration increases beyond 50%, the optimal share of wind in the generation mix initially rises, peaking around 65% RE share. Beyond this point, wind's role begins to decline. By the time the system reaches 90% RE, wind contributes only marginally. In a conservative scenario, a balanced mix of solar and wind can supply up to 65% of electricity demand without the need for storage. However, beyond this level, storage becomes necessary to manage variability and ensure reliability. Battery capacity grows steadily after 65%, increases significantly beyond 90%, and rises sharply after 97%, as the system relies heavily on solar oversizing and storage to deliver a stable 24/7 renewable energy supply.

Beyond a 65% RE share, storage becomes essential and must scale significantly to enable the final stretch toward 24/7 RE

Capacity for different RE penetration levels for India's industrial sector (MW)



Source: Results for optimal solar, wind and battery storage capacity from Ember's RE PPA model for an industrial consumer with a 500 MW peak demand

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50% RE Penetration

- The overlap between generation and demand is sufficient with an optimal mix of solar and wind (estimated at 30% of total RE capacity).
- Minimal excess generation occurs, as supply rarely exceeds demand.
- Banking serves as a useful mechanism to manage minor mismatches between generation and demand without requiring significant storage.

75% RE Penetration

- Excess generation becomes more frequent, necessitating the sale of surplus electricity.
- Limited use of banking due to regulatory constraints

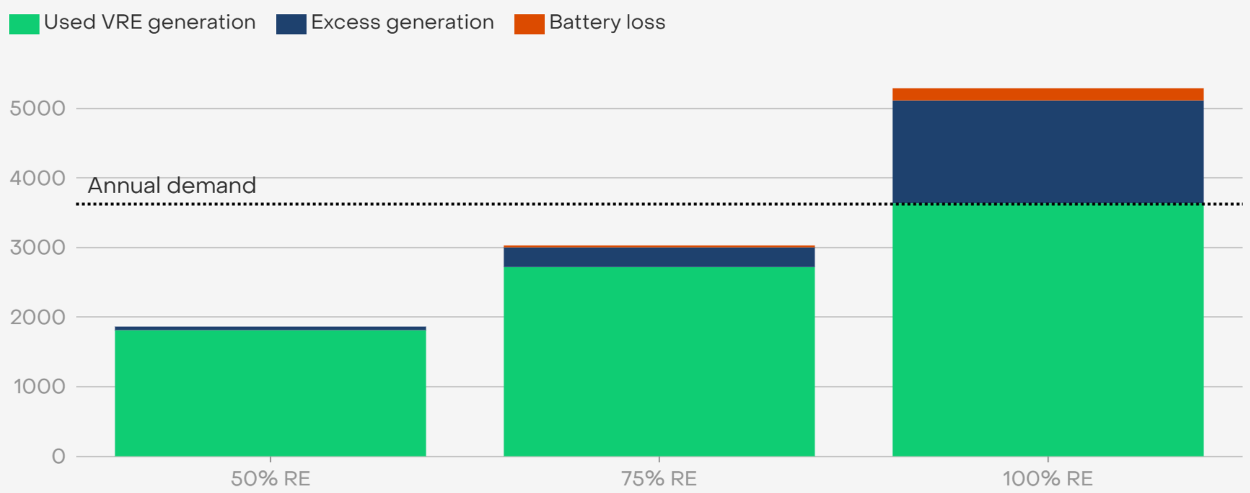
- Battery storage begins to play a larger role, now comprising 20% of total system power capacity, though storage losses remain minimal in the overall balancing mix.

100% RE Penetration (24/7 RE Supply)

- Massive oversizing of solar and storage is required to ensure continuous supply.
- Wind capacity becomes less useful beyond 50% RE penetration, as solar dominates the mix at higher RE levels.
- A significant scale-up in RE capacity is necessary—almost 3× the capacity required for just a 2× increase in RE supply (from 50% to 24/7 RE).
- Storage capacity requirements grow exponentially, reaching nearly 2,800 MW, to manage intermittency and ensure reliability.
- The final 3% of demand is the hardest to meet, requiring disproportionately high storage investments, making cost and efficiency critical challenges in achieving 24/7 renewable energy.
- Banking cannot be availed at 100% RE penetration

Excess generation and battery losses stay modest for Indian industries for up to 75% RE penetration but rise sharply to achieve 24/7 RE

Used VRE generation, Battery losses and Excess generation in GWh



Source: Results on generation balancing from Ember's RE PPA model for an industrial consumer with a 500 MW peak demand

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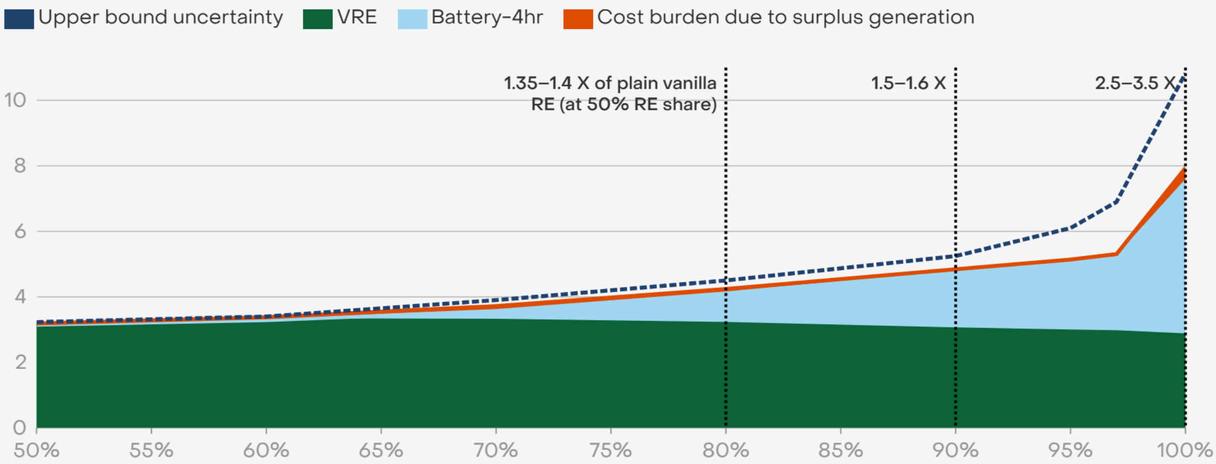
Increasing RE share from 50% to 80% comes at a moderate premium, while achieving 24/7 RE can cost up to 3.5x the cost of RE generation

Sourcing 50% renewable energy is already cost-effective for heavy industries in India. Scaling up to 80% RE penetration leads to a modest cost increase of up to 1.4X the cost of RE generation, primarily driven by storage requirements and the challenge of managing surplus electricity, which is often sold back to the grid at prices lower than the cost of generation. Increasing RE penetration to 90% raises costs to around 1.6X the cost of RE generation. At this stage, the system becomes increasingly reliant on battery storage, though the cost premium may still be manageable for some consumers. However, reaching 24/7 RE poses a significant financial hurdle—achieving just the final 1% of RE penetration increases the cost of supply by at least ₹2.5/kWh, a 41% jump. While losses from selling excess electricity are not a major concern at assumed market prices (₹1.8/kWh), they could become more significant if prices fall—or provide cost relief if prices rise. The cost of 24/7 renewable energy ranges from ₹8 to ₹11 per kWh, with an average estimate of ₹9.5 per kWh.

Increasing RE consumption from 50% to 80% comes at a moderate premium for Indian heavy industries, but achieving 24/7 RE could cost upto 3.5X

Component-wise levelised cost of supply for different shares of RE (Rs/kWh)



Source: Ember's RE PPA model · In the model, surplus electricity is assumed to be sold at ₹1.8/kWh, while the cost of generation ranges from ₹2.6 to ₹3.2/kWh. This loss per unit of surplus energy sold is reflected in the overall cost burden of the RE PPA.

Green tariffs have the potential to transform Discoms' role

Green tariffs can complement open-access RE procurement, particularly in achieving 24/7 RE. While industries can source up to 70% of their RE needs through open access at competitive rates, the remaining 30% often comes at a higher cost due to storage expenses and losses associated with selling excess power. Using green tariffs to meet this last portion of demand offers a cost-effective solution, eliminating the complexities of balancing demand with variable RE supply.

However, if electricity consumption is concentrated in high-cost periods—such as seasonal lows in generation or night hours—discoms may increase premiums on green tariffs. While the combination of open-access RE and green tariffs is currently the most cost-effective approach for industries to achieve 24/7 RE procurement, this strategy may become less effective over time. As discoms move toward cost-reflective pricing, green tariff charges may more accurately reflect the actual cost of supply, making it unsustainable to rely solely on buying power during hours when RE PPAs don't supply.

Despite this, green tariffs have the potential to become a dominant mechanism for RE sourcing and redefine the role of DISCOMS in the process in the future due to the following advantages:

- Addressing Discoms' pushback – Discoms often resist open-access RE as they risk losing high-paying industrial consumers. Green tariffs provide an alternative mechanism that allows industries to procure RE without bypassing discoms, mitigating revenue losses for utilities while enabling a smoother transition to higher RE adoption.
- Cost reduction through aggregation – Large-scale aggregated green tariff programs—where multiple consumers and RE generators (including storage) participate—help lower costs. A single buyer relying on a PPA with limited generators must oversize capacity for reliability, increasing costs and leaving surplus power that is hard to monetise. Aggregation, however,

balances diverse demand profiles with a mix of RE sources, reducing the need for oversizing, optimising procurement, and minimising excess generation risks. Moreover, Discoms can procure RE from multiple locations, enhancing the geographical spread of generation and improving supply reliability.

- Simplified procurement for industries – Open-access RE purchases require significant administrative and technical expertise, which is not a core function for most companies. Discoms, however, already possess these capabilities, making green tariffs a simpler option for industrial consumers.

What can be a realistic target for maximising RE consumption today

Sourcing 50% of electricity from RE is already cost-competitive for industrial consumers in India. A noticeable cost premium begins to emerge only after 65% RE share, when storage becomes necessary to maintain supply reliability. Even so, a moderate premium—up to 80%—may be acceptable for many industries committed to decarbonisation, offering a realistic near-term target for heavy industry. Costs remain relatively manageable up to 90% renewable energy, but reaching the final 5% becomes prohibitively expensive due to steep increases in storage requirements and generation overcapacity.

Supporting materials

Methodology

Cost benefit analysis for renewable energy procurement by industries

The analysis evaluates the current cost structure (BAU) for heavy industries by compiling HT industrial electricity tariffs across states and considering captive coal-based generation and waste heat recovery costs, assumed at ₹1.5/kWh for fixed and variable expenses. In the renewable energy (RE) scenario, a solar tariff of ₹2.5/kWh is used, incorporating state-wise charges such as transmission, wheeling, cross-subsidy, and additional surcharges, while also factoring in applicable waivers under green energy open access rules. The data for state-specific tariffs and open access charges are updated until December 2024.

The RE open access model follows a cost optimisation logic, replacing grid or captive power with the cheapest available option. By comparing variable electricity costs, the analysis estimates cost savings per unit, which is then used to assess the profitability improvement for industries transitioning to renewable power.

Power purchase agreement (PPA) Optimisation Model

The PPA optimisation model determines the least-cost mix of solar, wind, and battery storage to meet industrial demand while ensuring reliability. It considers a 500 MW peak load with an 82% load factor, incorporating the costs of solar, wind, and battery storage. Generation profiles are derived from historical weather data (2017–2023) to account for variability in renewable resource availability.

Using PyPSA, the model optimises the capacity of solar, wind, and battery storage to meet the demand profile while achieving renewable energy consumption targets ranging from 50% to 100%. The optimisation is performed across all weather years to ensure robustness. Finally, the model estimates the cost of meeting different RE targets under a PPA framework.

The model incorporates banking provisions, allowing excess renewable energy generated during high-output periods to be credited and used when generation falls below demand. The banked units are limited to 30% of the electricity purchased from the grid each month and incur a banking charge of 8% on the units banked. Any excess generation beyond this limit is assumed to be sold to the discom at ₹1.8/kWh, which is 75% of the lowest solar tariff (approximately ₹2.5/kWh). This framework ensures a realistic assessment of surplus energy utilisation and valuation under prevailing market conditions.

Acknowledgement

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Cover image

Gas plant with flare stack and industrial equipment overlooking the foothills near Cochrane Alberta Canada.

Credit: Ramon Cliff / Alamy Stock Photo