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ELECTRIFYING INDUSTRIAL HEAT IN INDIA

Technologies and Policies to
Transform Indian Manufacturing

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April 2026

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ACKNOWLEDGEMENTS

The authors would like to thank Radhika Lalit (Climate Imperative) and Ali Hasanbeigi (Global Efficiency Intelligence) for their feedback on this report. The contents of this report are the responsibility of the authors alone and do not necessarily represent the views of the reviewers. The authors also thank Silvio Marcacci and Shannon Stirone for their assistance in preparing and editing this report.

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EXECUTIVE SUMMARY

India's industrial sector is an economic powerhouse, providing 19.5 million jobs¹ and 17 percent of the country's Gross Domestic Product (GDP).² The sector is rapidly becoming the backbone of the modern Indian economy, manufacturing everything from the steel and cement that propel industrialization to the cars and electronics that can lift millions out of poverty.

But that economic engine comes with massive energy and pollution costs. Industry accounts for almost half of India's final energy use.^{3,4} Over 40 percent of that energy is coal that manufacturers burn onsite, creating severe air pollution and public health impacts that the country is striving to mitigate.⁵ Another 27 percent is from petroleum and natural gas,⁴ heavily imported fuels that typically cost 4-4.5 times more than coal per unit energy^{6,7} and can soar even higher in price during global supply chain shocks, such as the COVID-19 pandemic and the early 2026 conflict in Iran.

Fortunately, the perfect solution sits right in India's lap: **solar-powered, electrified industry**. India has the lowest solar prices among major economies, with recent auctions clearing a levelized cost of electricity (LCOE) under ₹2.5 per kilowatt-hour (kWh),⁸ and electricity is used more efficiently than fossil fuels. Even when accounting for the costs of energy storage and grid fees for captive renewables, solar is often the cheapest option for Indian industry. By switching to solar energy, and to commercially available electric technologies like heat pumps and thermal batteries, Indian industry can slash its costs, cut its energy use, and deliver clean air.

Specifically, our analysis finds that electrifying industrial heat is already cheaper than producing heat with biomass, natural gas, or petroleum across all temperatures needed by industry. Electrified heat is also cheaper than coal-based heating (the cheapest fossil fuel in India) in three out of five temperature bands (<100°C, 100-200°C, and 1,000-1,800°C), which together account for 55 percent of India's combustion-based industrial heating.

Electrification can reduce industrial energy use by 22 percent and cut over half of the sector's CO₂ emissions when backed by clean energy. Industrial electrification can also reduce sector-wide emissions of non-GHG pollutants, cutting particulate matter (PM_{2.5}) by 38 percent, sulfur dioxide (SO₂) by 60 percent, and nitrogen oxide (NO_x) by 53 percent. By avoiding those air pollutants, electrifying all eligible industrial processes in India can save nearly 794,000 lives annually while also halving the incidence of numerous nonfatal health complications.

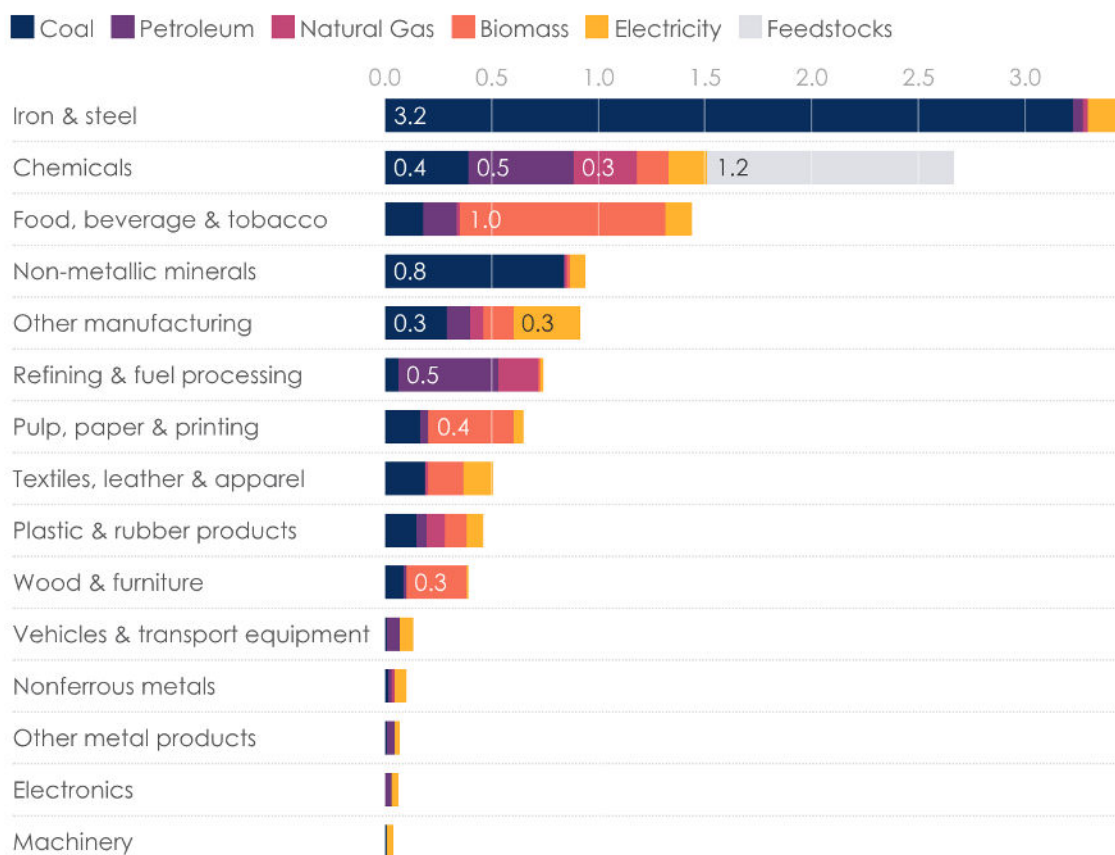
Effective policy can catalyze long-term, meaningful change through actions that increase industry's access to low-cost solar, drive adoption of clean industrial technologies, and enable the continued development of clean technologies and India's workforce.

THE CASE FOR ELECTRIFYING INDIAN INDUSTRY

India is the 7th most vulnerable country to climate change⁹ and the 3rd largest emitter of climate-warming CO₂. Because of this, in 2021, India's government committed to reach net-zero emissions by 2070. Cleaning up India's vast and growing industrial sector will play a major role in achieving that goal. The sector was responsible for nearly half of India's CO₂ emissions in 2021, about 1.3 billion tonnes.⁴ While some of those emissions come from sources like purchased electricity and cement calcination, the majority come from burning fossil fuels to generate heat for industrial processes.¹⁰ Every year, Indian industry's process steam alone generates an estimated 182 million tonnes of CO₂ emissions and more particulate matter and NO_x emissions than the country's entire transportation sector.

Figure ES-1

India's Industrial Energy Use by Subsector in 2022 (EJ)



Data come from Rissman, et. al. (2026). *The Industrial Transformation Technology And Investment Model, version 1.1.0. Energy Innovation*. <https://energyinnovation.org/report/the-industrial-transformation-technology-and-investment-model/>

The largest industrial energy user in India is iron and steel, accounting for over a quarter of Indian industry's energy use in 2022 (Figure ES-1). Five other subsectors - chemicals; food, beverage, and tobacco; refining and fuel processing; non-metallic minerals; and pulp, paper and printing - also have high energy demands, collectively accounting for 40 percent of the industrial sector's energy use.

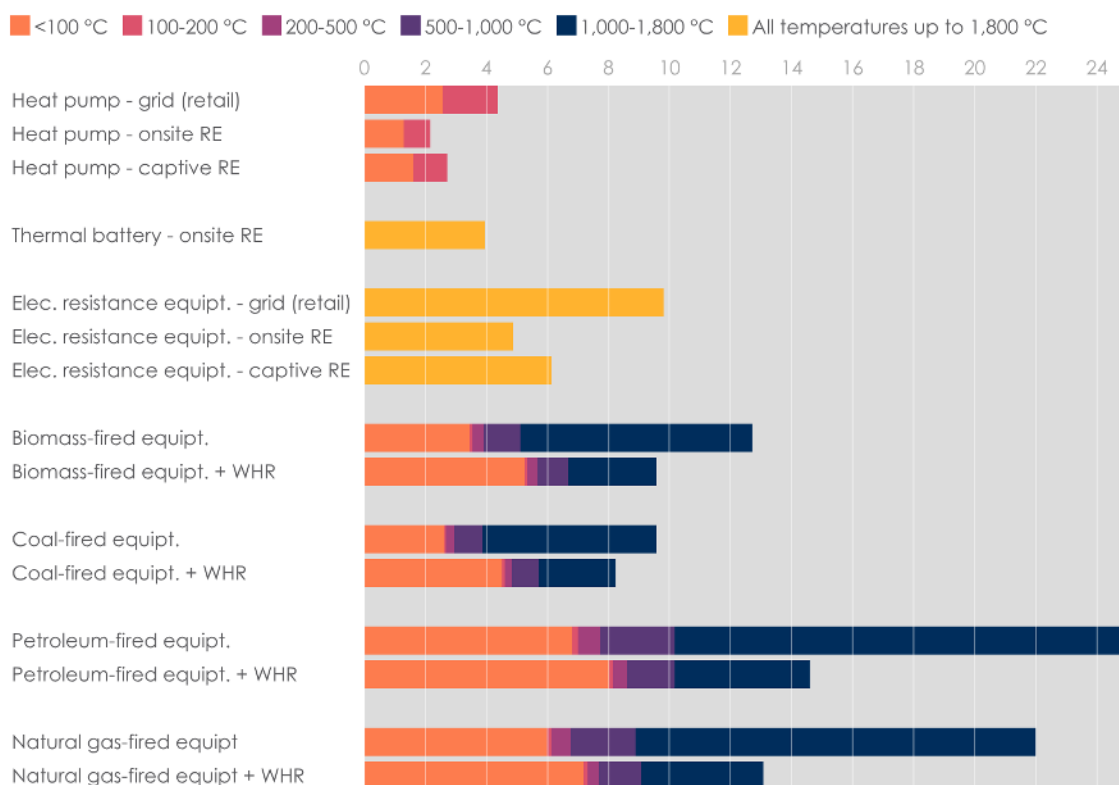
India has begun passing increasingly stringent air quality standards to stem the 2.5 million deaths caused annually by fossil fuels.¹¹ These rules have pushed some manufacturers off of coal and onto oil and natural gas, but relying on these heavily imported¹² fossil fuels exposes those manufacturers to high, volatile prices and supply risks. There is economic, public health, and environmental urgency to transition Indian industry from costly, polluting fossil fuels to clean electricity.

ECONOMIC VIABILITY OF INDUSTRIAL ELECTRIFICATION

Our technoeconomic analysis assessing the levelized cost of heating (LCOH) of 15 different heating configurations shows that industrial electrification is viable across all industrial temperature ranges (Figure ES-2, or see Table 2 for precise figures). Nearly all technologies powered by renewable electricity (RE) - whether using on-site solar with energy storage or electricity wheeled by the grid from captive solar plants with battery storage - were competitive with petroleum and natural gas combustion. The economics were most favorable at high temperatures, where combustion efficiency drops precipitously, and at low temperatures that can be served by highly efficient heat pumps. Many electric technologies outcompete biomass, which represents 17 percent of Indian industry's energy use today. And some electric technologies even out-compete coal: grid-powered heat pumps under 100°C, RE-powered heat pumps under 200 °C, and all RE-powered technologies above 1,000 °C. Neither the inclusion of waste heat recovery nor India's current carbon price (\$10/tonne CO₂ above an emissions intensity threshold) make a meaningful difference to these cost comparisons.

Figure ES-2

Levelized Cost of Heat by Technology Type Across Temperature Ranges (Rs/kWh_{th})



Notes: 1) In this figure, levelized cost of heat (LCOH) values include energy costs, annualized capital costs, and actual carbon costs, but not the social cost of carbon. 2) For heat pumps and combustion equipment, each stacked segment represents the incremental increase in the LCOH in that temperature range relative to the previous temperature range. For temperature ranges above 100 °C, bar segments do not themselves represent total LCOH. 3) "Onsite RE" refers to onsite solar plus battery storage to enable continuous use of heat. 4) "Captive RE" refers to consumer-owned and grid-delivered captive solar plus battery storage, where the consuming entity holds an equity stake of at least 26% in the plant, the plant provides over 51% of its energy to its owners, and the consuming entity pays transmission and distribution costs. 5) WHR stands for waste heat recovery.

Grid-powered electric technologies are more expensive, as retail electricity prices are 1.6-3.1 times higher than RE prices.^{13,8,14,15} And they only reduce CO₂ and non-GHG pollutant emissions if they are much more efficient than conventional equipment (e.g., low-temperature heat pumps or very high-temperature electric resistance equipment).

As India's grid phases out coal power plants in favor of renewable energy, the emissions associated with these grid-powered technologies will improve. In the meantime, firms can save money and reduce pollution by using onsite solar with thermal storage or battery storage, or wheeled captive solar with battery storage, which they can obtain via India's Green Energy Open Access (GEOA) Rules.¹⁶

IMPACTS OF INDUSTRIAL ELECTRIFICATION ON INDIA

The Industrial Transformation Technology and Investment Model (ITTIM)⁴ was used to model the impacts of electrifying Indian industry on energy use, CO₂ and non-GHG pollutant emissions, and public health. In a business-as-usual (BAU) scenario, by 2070, India's industrial energy use is forecast to more than triple from 2022 levels, from 12.5 exajoules (EJ) to 38.6 EJ. Scaling electrification to its full potential would reduce this energy usage by over 22 percent to 29.9 EJ.

Electrification would also cut the sector's future CO₂ emissions by 1,243 million metric tonnes - more than half (51 percent) of its BAU emissions - provided it is supported by clean electricity. Non-GHG pollutants exhibit similar reductions: PM_{2.5} falls by 38 percent, NO_x by 53 percent, and SO₂ by 60 percent. The public health benefits are significant, with around 794,000 lives saved annually when compared to the future BAU scenario. Adverse health impacts also drop 48 to 50 percent, averting 321,000 nonfatal heart attacks, over 1.73 million new asthma cases, nearly 32,000 new lung cancer cases, and more than 27,000 strokes annually.⁴

POLICIES TO SCALE INDUSTRIAL ELECTRIFICATION IN INDIA

Policy can make these staggering impacts a reality. For example, India can improve industrial access to low-cost solar by streamlining its recently updated GEOA rules,¹⁶ integrating industrial electrification with energy system planning, deploying more renewables, raising manufacturers' awareness of industrial electrification opportunities, and reforming electricity cross-subsidies that currently require industrial electricity customers to help offset residential and agricultural electricity costs.

In cases where RE-powered industry is still more expensive than powering industry with fossil fuels, India can promote electrification using production-linked incentives for clean commodities, standards on industrial energy consumption and emissions, policies that fairly price fossil fuels, and capital cost support.

Policymakers can also make more clean industrial technologies available by supporting technology research, development, and demonstration, and by incentivizing domestic manufacturing of electric industrial heating equipment. Workforce training and development can ensure that India has top-tier talent capable of manufacturing, deploying, and maintaining these cutting-edge technologies.

The right policies can unlock India's unique opportunity to be a leader in clean industrial technology, slash its dependence on expensive imported fuels, catapult economic growth, and safeguard the climate and public health. By harnessing this opportunity now, India could become a role model for middle-income countries worldwide, demonstrating how to leapfrog over dirty technologies and achieve industrial and human development goals profitably and sustainably.

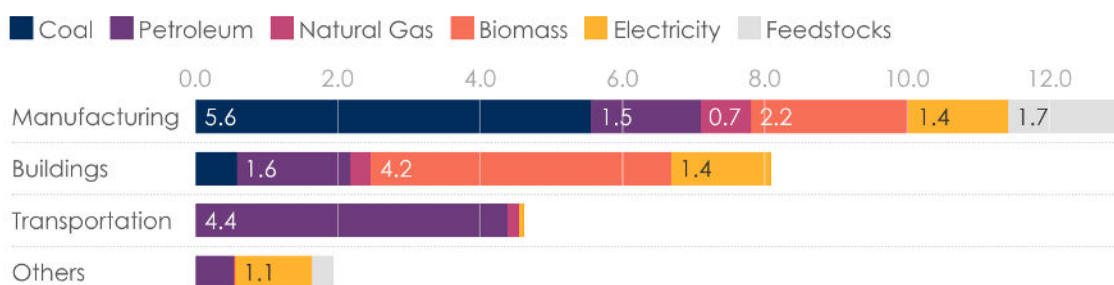
INTRODUCTION

INDUSTRY IN INDIA TODAY

Manufacturing is integral to India's economy, generating 17 percent of the country's Gross Domestic Product (GDP),² 19.5 million jobs,¹ and US\$451 billion in exports today.¹⁷ But this productivity comes at a high cost: the manufacturing sector (also referred to here as the industrial sector, or industry) consumed 47 percent of the country's final energy in 2022 (Figure 1), 83 percent of which relied on fossil fuels, including petroleum and natural gas that are typically imported at high cost.⁵

Figure 1

India's Final Energy Use by Sector in 2022 (EJ)

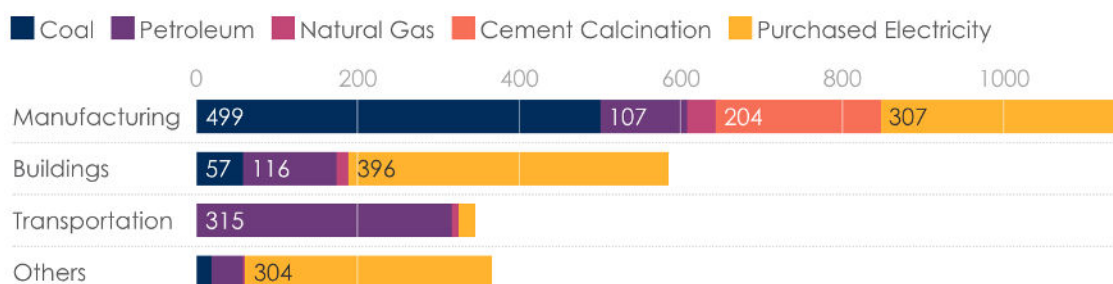


Notes: 1) The "Others" category includes agriculture, mining, and construction. 2) Manufacturing sector data come from Rissman et. al. (2026) *The Industrial Technology Transformation and Investment Model*, version 1.1.0. Energy Innovation. <https://energyinnovation.org/report/the-industrial-transformation-technology-and-investment-model/> 3) All other data come from Pacific Northwest National Laboratory. (2025). *Global Change Assessment Model*, version 8.2. <https://github.com/JGCRI/gcam-core>

This energy use generated almost 1.3 billion tonnes of carbon dioxide (CO₂) emissions in 2022, nearly half the country's total emissions, when accounting for emissions from purchased electricity and cement calcination (Figure 2). The manufacturing sector uses this immense volume of fossil fuels—23 percent, 17 percent, and 48 percent of India's total coal, oil, and gas consumption, respectively—to generate heat for a variety of industrial processes, from melting metal to catalyzing chemical reactions.¹⁰

Figure 2

India's CO₂ Emissions from Fossil Fuels and Cement in 2022 (MMT CO₂)



Notes: 1) The "Others" category includes agriculture, mining, and construction. 2) Manufacturing sector data come from Rissman et al. (2026) *The Industrial Technology Transformation and Investment Model*, version 1.1.0. Energy Innovation. <https://energyinnovation.org/report/the-industrial-transformation-technology-and-investment-model/> 3) All other data come from Pacific Northwest National Laboratory. (2025). *Global Change Assessment Model*, version 8.2. <https://github.com/JGCRI/gcam-core>

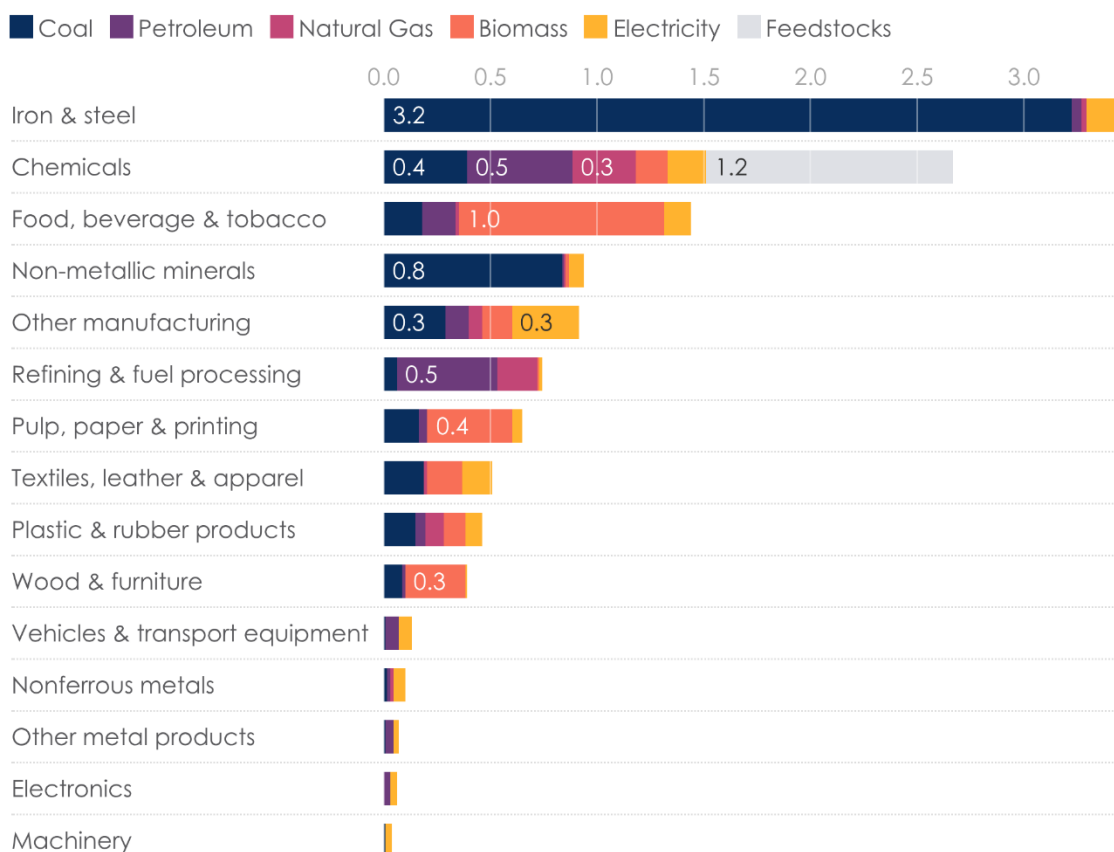
Among industrial subsectors, iron and steel is the single largest energy user, with its coal use alone accounting for nearly a quarter of Indian industry's energy use in 2022 (Figure 3). Five other subsectors—chemicals; food, beverage, and tobacco; refining and fuel processing; non-metallic minerals; and pulp, paper and printing—are also heavy energy users, collectively accounting for 40 percent of the industrial sector's energy use.

Among industrial firms, 80 percent are micro, small, and medium enterprises (MSME)—collectively the largest employers in the country outside of agriculture—that often use inefficient technologies and processes and contribute up to 70 percent of the country's industrial pollution load.¹⁰ This fragmentation of the industrial landscape complicates technology finance and rollout.

Industrial fossil fuel use contributes immensely to India's pollution. Every year, Indian industry's process steam alone is estimated to generate 182 million metric tons (MMT) of CO₂ emissions, 595 kilotonnes (kt) of sulfur dioxide (SO₂) emissions, and more particulate matter (PM) and nitrogen oxide (NO_x) emissions than the entire transportation sector, at 520 kt and 516 kt, respectively.¹⁸ Altogether, the industrial sector is estimated to account for almost 20 percent of India's PM_{2.5} emissions,¹⁹ and manufacturing and construction are estimated to make up 29 percent of anthropogenic SO₂ emissions.²⁰ Process boilers alone are estimated to contribute 9 percent of India's PM emissions (more than the transportation sector), 8 percent of SO₂ emissions, and 17 percent of NO_x emissions.

Figure 3

India's Industrial Energy Use by Subsector in 2022 (EJ)



Data come from Rissman, et. al. (2026). *The Industrial Transformation Technology And Investment Model, version 1.1.0. Energy Innovation*. <https://energyinnovation.org/report/the-industrial-transformation-technology-and-investment-model/>

At the same time, fossil fuel use exposes industry to volatile prices and supply risks. As stringent regulations limit coal use in India's cities, industries that switch to imported fossil fuels like petroleum and natural gas will not only see their day-to-day costs go up, but will also face large, periodic swings in the prices of globally traded energy. There is clear economic, public health, and environmental urgency to transition industrial heating away from costly, polluting fossil fuels.

Direct electrification of industrial processes is the most efficient and cost-effective way to transition much of India's manufacturing sector off fossil fuels. India is particularly well-positioned to provide its industries with low-cost process heat through a combination of inexpensive solar, thermal batteries, heat pumps that provide high efficiency gains, and other electrified technologies. In this report, we examine India's current policy landscape, electrified technology options, industrial

heating needs by subsector, and the factors that make India ideally situated for direct electrification. We also perform a detailed techno-economic analysis of potential industrial electrification configurations to identify the most cost-effective solutions and recommend policies that can facilitate their deployment.

INDIA'S MOTIVATION TO DECARBONIZE INDUSTRY

India is highly motivated to transition to clean energy and has made a commitment to reach net zero by 2070. In service of this target, India aims to deploy 500 gigawatts (GW) of non-fossil-fuel energy capacity²¹ to represent half of the country's installed generation capacity by 2030,²² with a pledge to build 50 GW of renewable energy every year between fiscal years 2023–24 and 2027–28.²³ Moreover, according to the Ministry of Finance's 2024–25 Economic Survey, India is the seventh-most vulnerable country to climate change, and therefore has increased climate adaptation and resilience expenditures from 3.7 percent of the country's GDP in 2016 to 5.6 percent in 2022.⁹ Many factors motivate India's climate ambition, including the air quality impacts of fossil fuel combustion, the economic risks of fossil fuel dependency, and pressure from carbon pricing at home and abroad.

The country's reliance on fossil fuels has resulted in major public health impacts due to poor air quality: combustion-related particulates are estimated to cause 2.5 million premature deaths annually,¹¹ with coal-fired power plants alone estimated to be responsible for 112,000 premature deaths each year.²⁴ In response, India has implemented a suite of air quality regulations, starting with the Air (Prevention and Control of Pollution) Act in 1981, and setting increasingly stringent national ambient air quality standards that cover pollutants such as NO_x, sulfur oxides (SO_x), PM₁₀, and PM_{2.5}. In 2019, the country implemented its National Clean Air Programme, which currently has a 2026 target to reduce PM₁₀ concentrations in 130 cities and urban areas by 40 percent from 2017 levels (though progress toward the target has varied by city).²⁵ In urban centers like Delhi National Capital Region, authorities have even banned coal use in industries to combat smog, forcing a switch to cleaner alternatives.²⁶

In addition to air quality impacts, fossil fuel dependency presents economic difficulties. India relies heavily on fuel imports—89 percent of its crude oil, almost half its natural gas, and over a quarter of its coal (primarily high-grade coking coal)¹²—and demand shows no signs of slowing, with the nation's natural gas consumption expected to increase 60 percent by 2030.²⁷ By depending so heavily on foreign supply chains, India is exposed to energy supply risk, price volatility, and geopolitical pressure. The early 2026 war in Iran is one example of India's energy vulnerability, spiking global oil prices 50 percent²⁸ and Asia's liquified natural gas prices 143 percent²⁹ within the first few weeks of the conflict alone.

Carbon pricing at home and abroad will also create pressure for firms to decarbonize. India has begun implementing the Carbon Credit Trading Scheme (CCTS), a carbon-

intensity-based market that will phase in industries like cement, steel, aluminum, and fertilizers this year.³⁰ (For more on the CCTS, see the “Forthcoming Policies” section below.) Increasing international demand for cleanly produced goods will also create incentives for India’s industrial sector to reduce emissions. Carbon border adjustment mechanisms (CBAMs) like the one the European Union (EU) adopted in 2023 place a fee on imported goods based on their “embodied carbon,” or the CO₂ emitted during their manufacture. The United Kingdom, Norway, Canada, Australia, and Taiwan are exploring CBAMs of their own.³¹ As more countries and subnational regions adopt carbon pricing and use CBAMs to protect their domestic firms from foreign competition, Indian manufacturers will need to reduce their emissions in order to access export markets.

MEETING CLIMATE TARGETS WITH INDUSTRIAL ELECTRIFICATION

One impactful and cost-effective pathway for India to meet its climate targets, reduce local air pollution, and secure long-term economic resilience is to electrify industrial process heat, the single greatest source of industrial emissions, with renewable energy. Industrial electrification is feasible today with proven technologies, is far more energy efficient than burning low-carbon fuels (especially green hydrogen) and, when powered by clean energy, is the only decarbonization solution that eliminates both GHGs and non-GHG pollutants.

India may be the best-positioned region in the world to reap the benefits of electrified industry. For one, many of its industrial firms have been pushed away from coal by air quality regulations and instead rely on imported petroleum and natural gas, which are expensive, volatile in price, and subject to supply risks. Second, utility-scale solar has reached record-low prices in India, and open-access rules enable industry to obtain this low-cost electricity directly from power plants. Onshore wind energy is also inexpensive and accessible via the same rules, but it is not as cheap as solar, nor is it consistently available year-round, making solar the better option for many industrial firms.

Whereas industrial electrification is prohibitively expensive in most regions of the world, when powered by low-cost solar, it can actually save Indian industry money while also delivering benefits like improved workplace safety, better process control, and reduced liability and insurance premiums. In later sections, we explore this opportunity in detail, including the benefits of electrification, key electrification technologies, and industrial electricity prices in India.

EXISTING POLICIES TO SUPPORT CLEAN INDUSTRY IN INDIA

Fortunately, India is already home to a variety of policies that can support industrial electrification, though some are still under development (e.g., India’s carbon market).

The Government of India (GoI) has actively supported industrial decarbonization since 2008, when it launched the National Action Plan on Climate Change. Until recently, this support focused mainly on energy efficiency, one of the most technologically mature and cost-effective industrial decarbonization solutions. In recent years, with the formal establishment of India's net-zero target and increasing global demand for low-carbon products, India has begun exploring more ambitious support for low-carbon industry. This includes major national missions to scale up the production of green hydrogen and low-carbon steel, as well as a carbon market that could accelerate adoption of a broad range of industrial decarbonization technologies.

Energy Efficiency Standards

Historically, India's most far-reaching policy to reduce industrial emissions has been the Perform, Achieve, and Trade (PAT) mechanism. Established in 2012 by the Bureau of Energy Efficiency, PAT set binding targets for facilities in energy-intensive industries to reduce their energy consumption and created tradable certificates for over- or under-performance.³² While ambitious in intent, the policy failed to achieve the sweeping emissions reductions it aimed for, due in part to conservative targets and the subsequent oversupply and then price crash of certificates on the market. Moreover, the policy was not strictly enforced, with inconsistent and opaque auditing. This year, the PAT mechanism will be phased out in favor of India's CCTS, described in the "Forthcoming Policies" section below.

India's Bureau of Energy Efficiency also runs a Standards & Labeling program that rates the energy efficiency of a range of appliances and "endorses" appliances that meet minimum energy performance standards. Labeling is mandatory for some appliances and voluntary for others. The program currently covers only one type of industrial heating equipment, small packaged boilers (classified by fuel type), as well as non-heating equipment like motors and air compressors, all on a voluntary basis.^{33,34}

Financial Incentives

Incentives for the production of clean industrial goods are important in most parts of the world, where electricity is much more expensive than conventional fuels, but they may be less vital in India. Currently, the only clean industrial production incentive available in India is for the production of ammonia using renewable energy.³⁵

Policies that help firms purchase industrial equipment, whether by buying down equipment costs or providing low-cost financing, may be a more important driver of industrial electrification in India. Currently, GoI offers incentives for the "modernization" of industrial equipment in MSMEs and in the textile industry.^{36,37} These incentives, which cover up to 15 percent of the capital cost of equipment, do not directly target decarbonization but could in theory be used for the purchase of

efficient or electrified equipment. However, they are limited to a small subset of industrial firms.

India's financing support for industrial decarbonization is more comprehensive but still mainly focused on energy efficiency. Concessional financing is available through the Indian Renewable Energy Development Agency (IREDA) for industrial energy efficiency projects³⁸ and through the Small Industries Development Bank of India (SIDBI) for industrial MSMEs adopting energy-efficient equipment, cleaner fuels, or on-site solar.³⁹ SIDBI often pools its financing support with lines of credit from a range of domestic and international financing institutions, from India's Bureau of Energy Efficiency and Technology Information Forecasting and Assessment Council to the World Bank, Japan International Cooperation Agency, and KfW Development Bank.⁴⁰ Moreover, through the Assistance for Deployment of Energy Efficient Technologies in Industries and Establishments Scheme, India's Ministry of Power subsidizes interest rates for the adoption of energy-efficient technologies among MSMEs across 14 industrial subsectors.⁴¹ Finally, an Energy Efficiency Financing Platform connects firms with energy-efficiency financiers like IREDA and SIDBI.⁴¹

Enabling Policies

Despite the now-widespread deployment of low-cost solar in India, grid electricity is typically expensive for industrial firms, which partially cross-subsidize residential and agricultural electricity tariffs. As a result, firms may be best positioned to access the low costs of solar by directly procuring it, as India's Green Energy Open Access Rules allow for industrial customers with loads of at least 100 kilowatts.¹⁶ Firms can directly purchase renewables by signing third-party power purchase agreements or investing in a captive solar plant, whether on their own or in partnership with other firms (group-captive solar). Moreover, in many states, regulators offer "green tariffs" that allow industrial firms to purchase a bundled supply of renewable energy directly from their utilities.⁴²

Under the National Steel Policy of 2017, India has also implemented policies to specifically support decarbonization, including electrification, of the steel industry. The Steel Scrap Recycling Policy aims to increase the availability of scrap steel for the production of secondary steel, which leverages electric furnaces and creates far fewer emissions than coal-based primary steelmaking. Furthermore, the Steel Research and Technology Mission of India is a public-private partnership offering around ₹2 billion (US\$24 million) to support steel-related technology and workforce development.⁴³

Forthcoming Policies

As noted above, GoI is in the process of transitioning the PAT scheme to the CCTS, India's first-ever carbon market, covering nine energy-intensive industries like cement, aluminum, and textiles.³² The government has indicated a gradual transition from PAT

to CCTS, with sectoral coverage and compliance timelines being phased in starting this year. The CCTS, authorized by the Energy Conservation (Amendment) Act of 2022, is unlike traditional cap-and-trade programs in that instead of establishing an overall emissions cap, it is an emissions-intensity-based credit trading mechanism. It will limit firms' emissions of CO₂ and perfluorocarbons (a group of potent GHGs) per unit of product they produce, offering tradable certificates to facilities that overperform. The government is aiming for an initial credit price of around US\$10 per metric ton of CO₂-equivalent emissions (tCO₂e),³⁰ though the social cost of carbon for India was estimated to be much higher, at US\$86 per tCO₂e in 2018.⁴⁴ Only facilities emitting above the intensity threshold will need to buy permits, so ensuring that the threshold is ambitious and becomes tighter every year or two, driving continued improvement, will be important in ensuring the policy is a meaningful catalyst for industrial electrification.

The Energy Conservation (Amendment) Act also authorizes GoI to set standards requiring industry to consume a minimum share of non-fossil energy,⁴⁵ but the government has so far only used this authority for power sector decarbonization.⁴⁶

ELECTRIFICATION OF INDUSTRIAL HEAT

ELECTRIFICATION COMPARED TO OTHER DECARBONIZATION STRATEGIES

Direct electrification is the best solution for most industrial process heat, as it avoids many of the downsides of other major clean energy options: green hydrogen combustion, bioenergy combustion, and carbon capture and sequestration (CCS). An open-source interactive tool by Energy Innovation, the Industrial Zero Emissions Calculator (IZEC), demonstrates the benefits of electrification relative to those alternative solutions by modeling the resource requirements of decarbonization scenarios that lean heavily on each of the different technologies.⁴⁷ India-specific results are summarized below, and more detail can be found in the IZEC's accompanying report.⁴⁸

Green hydrogen combustion is half as efficient as direct electrification per unit of useful heat created, losing energy through electrolysis and combustion.^{49,50} Per the IZEC, heavy use of green hydrogen for India's industrial decarbonization—mainly as a substitute for coal combustion—would increase India's current electricity demand by a factor of 6 and require the grid to grow annually by 3.4 percent to meet India's 2070 target.⁴⁷ Green hydrogen is also capital intensive, requiring expensive electrolyzers and extensive pipelines, and burning it produces harmful NO_x gases.⁵¹

Bioenergy (solid biomass or biogas) also wastes energy when it is combusted, and its production is highly resource intensive unless derived from waste, of which only a finite quantity is available. Dedicated bioenergy crops require land, water, fertilizer,

and other resources. In the IZEC's modeling, meeting three-quarters of Indian industry's process heating needs with bioenergy would require reallocating almost 24 percent of India's present agricultural land.⁴⁷ This pivot is simply not feasible given that India's agricultural yields are already sustaining losses from climate change.⁹ At a global scale, overreliance on bioenergy can also drive deforestation, ecosystem decline, and water quality issues, especially in vulnerable locales with poor land use protections. Lastly, biomass combustion in India emits more fine particulates than coal as well as a comparable amount of NO_x.⁵²

CCS carries its own problems, including upstream emissions from fossil fuel production (e.g., methane leakage from wellheads and coal mines) and point-source emissions from the residual CO₂ (around 10 percent) that CCS cannot capture.⁴⁹ The capital costs for capturing, injecting, and storing CO₂ are considerable, too: the IZEC estimates that in a CCS-heavy decarbonization scenario, India would need to spend about US\$2.9 trillion on CCS equipment,⁴⁷ which would represent an immense expenditure on a strategy that locks India into continued fossil fuel use.

For all these reasons, green hydrogen, bioenergy, and CCS are best reserved for industrial uses that cannot be electrified, like high-temperature heat in steel and cement, and feedstock uses in the ammonia, petrochemical, and refining subsectors.⁵³ Biomass may be particularly well-suited for these difficult-to-electrify operations given the high availability of crop residues in India relative to other countries. Biomass is already commonly used in Indian industry, accounting for around 17 percent of final energy use in manufacturing. However, other end-uses like aviation and heavy-duty shipping will likely compete for those resources in the future, driving up prices (Figure 1).

The IZEC does not model direct use of geothermal heat, a low-carbon heating option that tops out at around 300°C (compared to industrial bulk heating temperatures of up to 1,800°C) and is not widely available in the absence of advanced drilling techniques, which are currently nascent and expensive in India. However, geothermal may be a suitable decarbonization option for certain industrial facilities with favorable temperature requirements and optimal geographic locations, especially as the technology improves.

Despite being much more efficient than low-carbon fuels, direct electrification of industry could increase India's electricity demand four-fold if it is not paired with energy and materials efficiency improvements, according to the IZEC.⁴⁷ This would require an annual electricity growth rate of 3 percent from 2025 to 2070.⁴⁷ While this is well below the historical averages—the annual growth rate of India's grid from 2009 to 2023 was 5.7 percent⁵⁴—grid growth comes with all the challenges of creating new generation, transmission, and distribution infrastructure. However, even modest efficiency improvements—25 percent in energy efficiency for industrial heating and 15 percent in materials efficiency—can reduce industrial electricity demand by 28

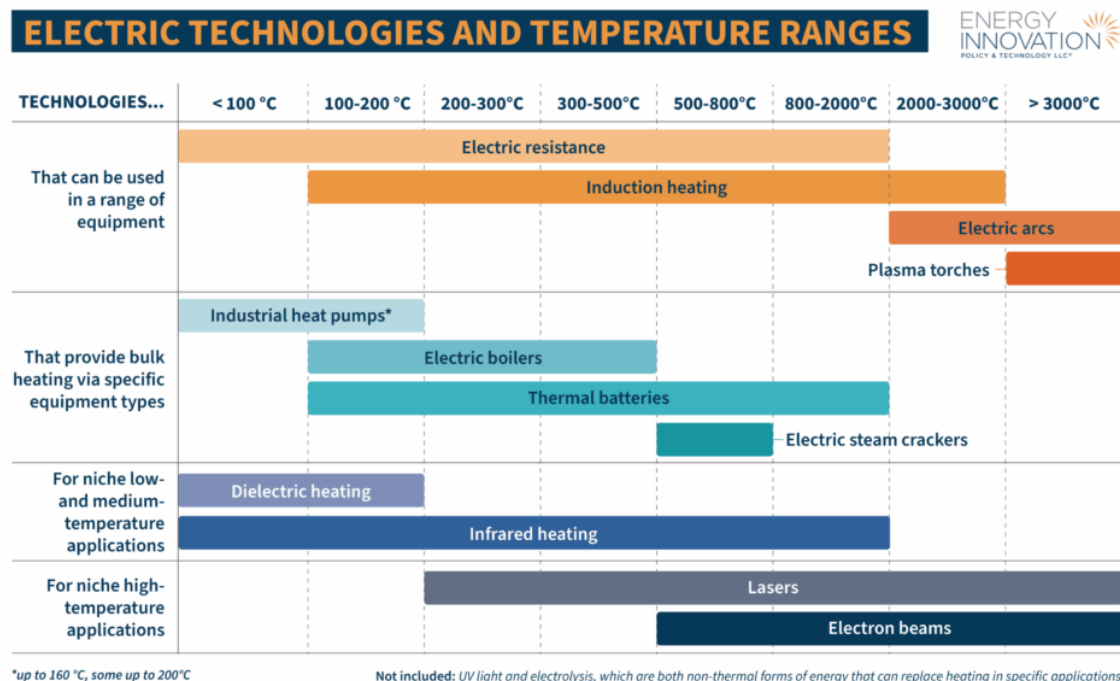
percent.⁴⁷ This would require the grid to grow only 2.4 percent annually between 2025 and 2070.⁴⁷

A 25 percent energy efficiency gain by 2070 is conservative. By way of comparison, the International Energy Agency's net-zero scenario includes a 25 percent improvement over just ten years (2020 to 2030).⁵⁵ Additionally, the International Energy Agency forecasts that readily available energy-efficiency measures could lower global industrial energy intensity 44 percent from 2018 to 2040.⁵⁶ Studies estimate that industries central to India's economy have untapped efficiency potentials: 19 percent in the case of iron and steel (shown in China)⁵⁷ and 30 percent for textiles.⁵⁸ Materials use can also be significantly conserved, with 30 percent less metal being usable in most applications without compromising integrity,⁵⁹ and studies in cement and other primary materials displaying the viability of significant potential reductions.⁶⁰

ELECTRIFICATION TECHNOLOGIES

To be an effective substitute for conventional technologies, clean industrial technologies must output heat at the same temperatures (and sometimes pressures) used in industry today. Fortunately, an array of electric technologies can provide process heat across the temperature spectrum (Figure 4). Most technologies that electrify low and medium heat (e.g., under 400 degrees Celsius) are commercially available, though they may need facility- and process-specific adaptations to meet other process requirements (e.g., pressure) depending on their level of adoption in a given industry.

Figure 4



*up to 160 °C, some up to 200 °C

Not included: UV light and electrolysis, which are both non-thermal forms of energy that can replace heating in specific applications

Source: Baldwin et al. (2025). Overcoming All Barriers to Industrial Electrification. Energy Innovation. <https://energyinnovation.org/report/overcoming-all-barriers-to-industrial-electrification/>

Industrial Heat Pumps

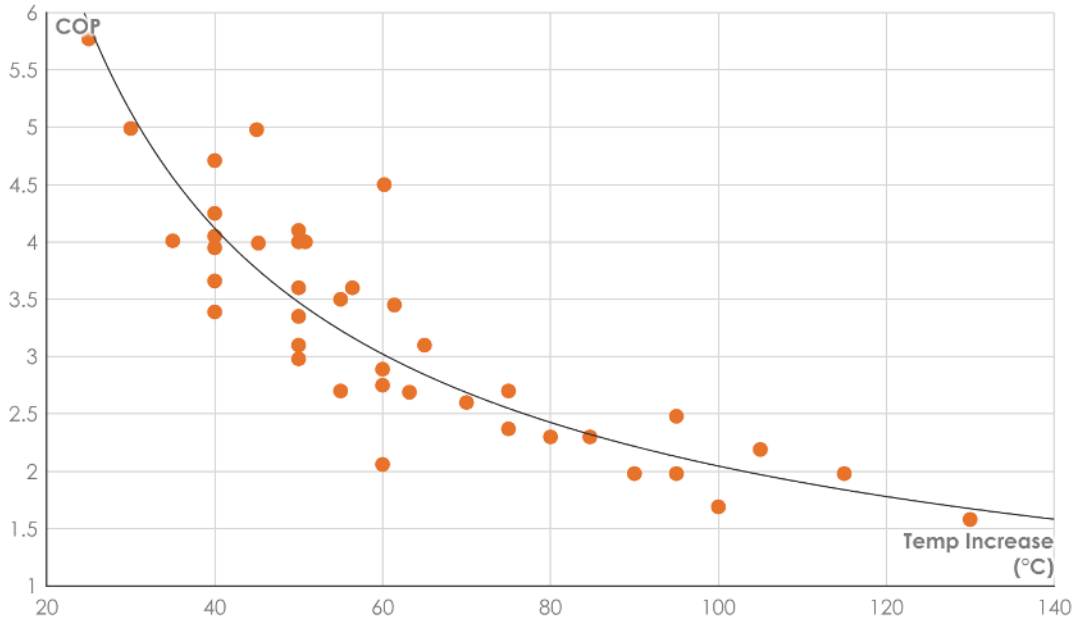
Heat pumps are highly efficient and are often the most cost-effective way to provide low-temperature heat (under 200°C) for many industrial processes. Heat pumps can be a straightforward substitute for combustion boilers in industries such as food processing, textiles, and pulp and paper that use hot water and low-pressure steam for processes like sterilization and cleaning, drying, and bleaching/dyeing.

Heat pumps are the only industrial heating technology that can output more heat than the energy they take in. Rather than convert electricity to heat, they use electricity to move heat from a source (e.g., ambient air) to a sink (e.g., water). A technology’s heat output per unit of input energy is also known as its coefficient of performance (COP), where an electric resistance heater that converts 99 percent of its input electricity to heat would have a COP of 0.99. Heat pumps, on the other hand, often have a COP of 3 to 5, meaning they can provide 3 to 5 units of heat per unit of electricity they consume. Heat pump efficiency declines when providing larger temperature increases, but even at the highest temperature lifts they can offer—corresponding to output temperatures of 165°C for commercial models and 200°C for pilot-stage models—the COP remains around 1.5, over 50 percent higher than that of an optimally efficient electric resistance heater or combustion boiler (Figure 5).

Figure 5

Industrial Heat Pump Efficiency vs. Delivered Temperature Increase

COP: Coefficient of Performance



Source: Baldwin et. al. (2025). *Overcoming all Barriers to Industrial Electrification*. Energy Innovation. <https://energyinnovation.org/report/overcoming-all-barriers-to-industrial-electrification/>

This incredible efficiency makes industrial heat pumps an attractive option for many of India’s industries by multiplying the cost-savings effect of cheap electricity. For example, if solar power with battery storage costs ₹3.58 per kilowatt-hour (kWh), energy costs for a heat pump with a COP of 4 would effectively be ₹0.90 per kWh. In India, coal costs slightly more than that (at ₹1.09/kWh of energy content in the fuel) and petroleum and gas cost around five times as much. Those fuels are even more expensive per unit of delivered heat due to energy losses during combustion.

High Temperature Heat Pump Pressure Considerations

To be suitable replacements for industrial boilers, heat pumps must output heat not only at certain temperatures but also at the requisite pressure for various industrial purposes. For many applications, pressure requirements are reasonably low: for textiles, ~0.4 bar for sizing and rarely exceeding 2 bars for high-pressure dyeing;⁶¹ for brewing, 7-10 bars that is frequently ramped down;⁶² and for milk pasteurization, around 6-7 bars.⁶³ Steam system capacities between 20 and 70 bars account for most boiler capacity in pulp and paper plants, about 60 percent of the chemical industry’s boiler capacity, and ~38 percent of petroleum refining boiler capacity.⁶⁴ For refining, the remaining 62 percent is below 20 bars.⁶⁴ However, the steam needed for industrial

processes is usually far below this pressure. In pulp and paper, pulping processes like bleaching, pulp drying, washing, and refining require steam pressure around 1.4 bars, capping out around 7-9 bars for some pulp digesting processes.⁶⁴ The diverse chemicals industry has a greater spread, depending on the specific process and chemical. While many processes require 1-8 bars, necessary steam pressure can reach as high as 12 bars in urea production, 45 bars in ammonia production, and 60 bars for melt compounding in polystyrene production.⁶⁴

Industrial high-temperature heat pump (HTHP) systems such as those developed by the company Heatlift can reach decently high pressures of 20 bars,⁶⁵ as can various heat pumps using CO₂ as a working fluid.⁶⁶ Steam compression mechanisms can boost the pump's output pressure much higher; for instance, Siemens piloted a coupled HTHP and steam compressor system for use in the paper industry. The heat pump could natively output temperatures ~150°C at pressure of 3.7 bars, and the compressor could boost the output steam to 55 bars.⁶⁷ Vapor compression heat pumps are considered a potentially competitive option for use in the chemical industry up to 200°C, with one study in Europe finding a favorable levelized cost of heat (LCOH) relative to natural gas boilers, heat transformers, and electric boilers.⁶⁸

The working fluids that have most often been used in HTHPs—natural refrigerants including water, NH₃, and CO₂^{69,70}—can suffer from safety and/or technical challenges.⁷⁰ For instance, heat pumps using water are likely to have high pressure ratios and higher discharge temperatures (as high as 180°C in a HTHP made by SINTEF in Norway⁷¹), in addition to significant pressure shifts when reacting to temperature fluctuations. These systems also need large vapor volume flow rates, used under a vacuum if the source heat is under 100°C.⁷⁰ This causes non-condensable gas leakage into the system, necessitating strong sealing and operational performance standards in the design of water vapor compressor-based systems.⁷⁰ A major issue for HTHP availability is the general lack of commercial compressors that can sustain high temperatures, have large capacity, and retain high efficiencies.⁷⁰ This is particularly true of centrifugal compressors, essentially the only option for megawatt-scale applications.⁷⁰

To meet high pressure and high temperature lift demands, advanced strategies need to be employed, such as multi-stage compression or, less frequently, cascade cycles.⁷² These approaches improve thermodynamic efficiency because increasing temperature or pressure in multiple, small steps is more energy efficient than achieving the same increase in one large step. Both strategies increase the system complexity and cost: a two-stage compression may require two compressors or complex (e.g., multiple-impeller or compound-cylinder) compression systems, while cascade configurations use thermally coupled dual-refrigerant stages, doubling the

number of many components.⁷² This can lead to increased floor space requirements, higher up-front capital costs, and more need for maintenance.

Commercial Availability of Heat Pumps

Heat pumps capable of reaching around 90°C are already commonly commercially available in India, offered by providers such as Thermax⁷³ and Promethean Energy.⁷⁴ A few firms have also introduced HTHPs, like systems by Rockshell Corp. and TrigenDC that deliver heat up to 130°C and 140°C, respectively.^{75,76} At these temperatures, heat pumps can cover a large share of industrial hot water and low-pressure steam demand. For instance, a dairy pasteurization plant could use a solar-powered heat pump system to supply its demand for ~80°C water alongside low-pressure steam during sunny hours, with low-temperature thermal storage solutions that are cheap and easy to implement (e.g., water tanks, phase-change materials) to get through the night. The economics are extremely competitive: even when accounting for capital costs, studies show heat pumps (below ~95°C) offer energy cost savings in the long run, becoming increasingly attractive as carbon costs rise.⁵ One major Indian dairy company, Amul Dairy, has already piloted an industrial heat pump at its chocolate plant in Mogar, Gujarat.⁷⁷ Heat pumps have also been piloted in other Indian industries, including at the DCM Shriram sugar plant in Hariawan and at a chemical manufacturing plant in Gujarat.^{78,79}

Globally, while most industrial heat pumps offered commercially cap out at 90–100°C, companies such as Kobelco Compressor Corporation of Japan and Viking Heating Engines of Norway previously offered models reaching 165°C. While these are no longer available, the firm Heaten, started by former Viking employees, claims that its HeatBooster industrial heat pump can provide temperatures up to 200°C. Industrial heat pumps in these higher temperature ranges would have a large addressable market and very few competitors. And while a 2022 study identified 47 manufacturers of heat pumps, industrial models made up under 2 percent of the global heat pump market, which ranged from US\$53 to 68 billion in 2021.⁸⁰

Worldwide, a number of case studies reveal industrial heat pumps' potential. In the United States, a Kraft foods plant in Iowa uses an ammonia heat pump system to provide hot water at 63°C,⁸¹ while a drop-in system from AtmosZero provides steam at 200°C for a New Belgium Brewing plant in Colorado.⁸² Chinese industrial firms have used heat pumps in the manufacture of diverse products like chemicals, crude oil, rubber, tobacco, and salt.⁸³ An International Energy Agency report chronicles case studies in Europe and Japan, where heat pumps are employed in the painting of automobiles, chromium plating, and food processing of chocolate and powdered milk.⁸⁴

Thermal Batteries

Thermal batteries are one promising option for industrial heat demand above the viable temperature range for heat pumps. Capable of converting electricity to heat that can then be stored for days in durable media such as brick, ceramic, graphite, and molten salts, thermal batteries can theoretically provide process heat at temperatures up to 1,700°C with minimal losses (as little as 1 percent per day).⁸⁵ However, today's commercial models deliver heat only up to around 500°C.

Thermal batteries can function in two flexible configurations: off-grid batteries paired with dedicated solar or wind, ensuring stable, low-cost energy and compliance with corporate clean energy targets, or grid-connected batteries that buy electricity at low-tariff hours and supply heat during peak hours, cutting costs while supporting grid stability by providing demand-response and grid-balancing services. For a deeper investigation of how grid-connected thermal batteries perform across the Indian states based on electricity price variance, see the “

Electricity Costs in India” section below.

Industrial thermal batteries have far lower capital costs per unit of capacity compared to electrical battery counterparts, such as lithium-ion. When manufactured at scale, cost estimates place thermal batteries at approximately US\$27 per kWh of capacity, compared to US\$150 per kWh for lithium-ion batteries.^{85,86} Lack of dependence on rare earth metals and overall simpler components contribute to this price advantage.

Like other electrified technologies, thermal batteries eliminate on-site emissions such as NO_x, SO₂, or particulates,⁵⁰ benefiting worker health and air quality regulatory compliance in high-heat industries.

If commercialized, high-temperature thermal batteries that deliver heat up to 1,700°C could serve the vast majority of India’s industrial process heating needs (Figure 7). However, some processes present challenges. Primary steel production—one of India’s largest manufacturing industries—requires not just high-temperature heat but also a system that chemically reduces iron ore to metallic iron, like hydrogen-fired direct reduced iron furnaces or electrolytic steelmaking technologies. Moreover, certain high-temperature processes require large, momentary bursts of heat in addition to continuous heat,⁸⁷ so thermal batteries must be sized to handle peak heat discharge rates rather than just total heat requirements. Finally, certain niche applications require specific heating dynamics, like radio waves’ ability to heat materials evenly inside and out, or precision work like laser welding.⁵⁰

Commercial Availability of Thermal Batteries

Given the challenges of scaling heat transfer methods at high temperatures, commercial thermal batteries top out at around 500°C. At low and medium temperatures, thermal batteries can transfer stored heat to industrial processes using a working fluid that travels via pipeline from the storage media to the industrial process, where a heat exchanger extracts the heat. These systems can easily be scaled by circulating the pipeline through multiple batteries. But it becomes difficult to use working fluids at very high temperatures, and alternative heat transfer methods, like heating materials through direct radiation from the storage media, are not as straightforward to scale.

Therefore, further research and demonstration is required to commercialize thermal batteries that can deliver heat up to 1,700°C.⁵⁰ Companies like Rondo Energy and Antora Energy have demonstrated systems delivering heat at above 1,000°C, with efficiencies above 98 percent, an estimated 40-plus year lifespan, and capability for daily cycling without degradation.⁸⁸ Moreover, market research firm Solrico identified 32 companies offering thermal storage technologies that could at least store energy at high temperatures, with 20 firms storing thermal energy above 565°C and 12 storing energy above 1,000°C.⁸⁹

Norwegian company ENERGYNEST has piloted its thermal battery technology in two very different environments: directly integrated into a fertilizer producer's steam grid, and in a 20-month peer-reviewed demonstration at the Masdar Institute Solar Platform in Abu Dhabi.⁹⁰ Both pilots showed no decline in the system's performance or deterioration of storage materials. In the Netherlands, Kraftblock, a German start-up, installed thermal storage capable of providing up to 1,300°C at PepsiCo's production plant. The system captures excess wind power when it is cheapest, storing it for up to two weeks before release. Paired with electrified thermal oil boilers, the system was reported to cut CO₂ emissions by 50 percent, with a target of increasing the abatement rate to 98 percent.⁹¹ This may provide India with a real-world example of high-temperature thermal storage use for industrial food processing.

Electric Resistance

Electric resistance heating runs an electric current through a resistor, traditionally a metal, metal oxide, or carbon-based material in which electrical resistance converts electricity into heat.⁶⁰ Commonly found in a range of heating equipment from electric boilers to thermal batteries, electric resistance technologies can meet high temperature needs depending on the resistor material. Nichrome is a common resistor that can provide heat up to 1,250°C, and tungsten can provide heat up to 2,500°C.⁹²

Some industrial materials, like molten glass and certain metals, have resistive properties and can be heated directly by running a current through them. Heating other materials with electric resistance requires indirect heating, or heat transfer, via air or steam. In heavy industries like aluminum, cement, and chemicals, resistors can heat materials through convection and radiation, avoiding the heat transfer challenges faced by high-temperature thermal batteries. Electric resistance boilers can transfer heat via steam for processes below 500°C, serving as drop-in substitutes for combustion boilers.⁴⁹

Electric resistance technologies are typically close to 100 percent efficient⁶⁰ and can be an important element of industrial decarbonization, but powering them with grid electricity can be expensive and exacerbate pollution where the grid is not clean. These challenges can be avoided by powering electric resistance with dedicated renewables, as with beverage company Diageo's distillery in Kentucky, where electric boilers backed by wind and solar avoid 117,000 metric tons of CO₂ emissions annually.⁹³

Combining Electric Technologies for Optimal Economics

A mix of electric technologies often offers the best path to industrial decarbonization. For instance, a plant might run on its own solar array and thermal battery, cutting fuel demand, but remain grid-tied to sell surplus power in the afternoon or draw electricity at night.

Hybrid heating strategies also boost efficiency. A heat pump can efficiently meet baseload needs up to its temperature limit, while electric resistance heaters cover short periods of high demand or boost heat pump output to higher temperatures. One effective mid-temperature setup combines solar photovoltaics (PV), a heat pump, and a thermal battery in sequence: the heat pump lifts low-grade heat to ~80°C, then an electric heater or thermal battery raises it further to 150°C–200°C. This approach cuts electricity use by improving the overall COP compared to resistive-only heating.

Another option is to combine solar with electrical storage and a heat pump. The optimal mix will vary by site, but today's toolkit makes it possible to design clean, reliable heat solutions for nearly any industrial process.

THE ELECTRIFICATION POTENTIAL OF INDIA'S INDUSTRIAL SUBSECTORS

Heavy industries that rely on high-temperature heat—iron and steel, chemicals, refining, and non-metallic minerals (mainly cement)—are some of the highest energy users in Indian industry, collectively accounting for more than 60 percent of the entire sector's energy use (Figure 3). Both the food, beverage, and tobacco industry and the pulp and paper industry, which rely mainly on lower-temperature heat, are also major energy users in India, respectively accounting for 11 percent and 5 percent of the industrial sector's energy use.

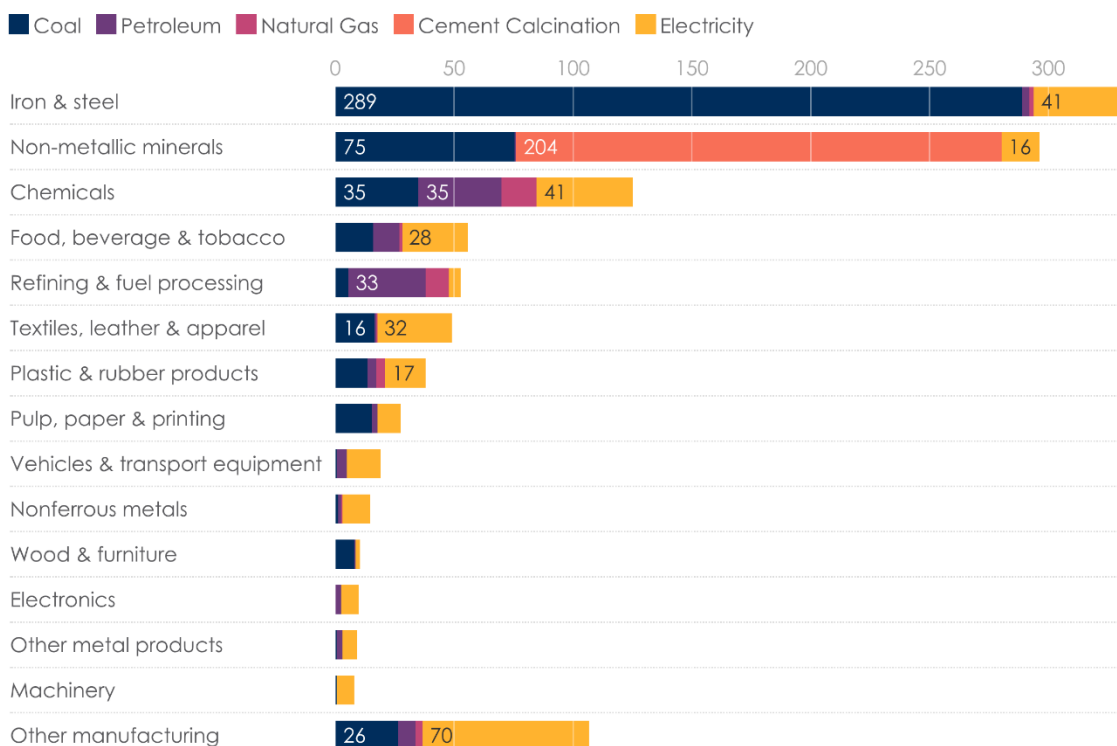
The current sources of energy differ widely by industry, with iron and steel and cement using mostly coal due to its high heat content and historically low price per unit energy. Coal also represents 31 percent of the energy used by “other manufacturing” industries not specified in Figure 3, typically light industries like miscellaneous consumer goods and fabricated goods. In addition to its CO₂ emissions impact, coal combustion comes with significant air pollution (SO₂, NO_x, PM).

Many smaller industries and those in regions without easy coal supply rely on oil products like furnace oil, diesel, or liquefied petroleum gas. These fuels are expensive and mostly imported, making operations vulnerable to global price swings.⁹⁴ Natural gas combustion creates fewer emissions, but its usage in industry has been limited by supply constraints—only about 6 percent of India's total energy comes from gas,⁹⁵ and pipeline coverage is incomplete. Where available (e.g., Gujarat, Maharashtra), some industries use piped natural gas for heat, but nationwide most thermal energy still comes from solid and liquid fuels.⁵ In Figure 3, we see chemicals and refining primarily using a mix of petroleum and natural gas, and food processing and paper relying heavily on biomass.

Indian industry's dependence on fossil fuels has major implications for the country's CO₂ emissions, with 334 MMT of CO₂ emissions from the iron and steel industry alone and 296 MMT from the cement industry when accounting for emissions from the calcination of limestone (Figure 6).

Figure 6

India's Industrial CO₂ Emissions from Fossil Fuels and Cement in 2022 (MMT CO₂)



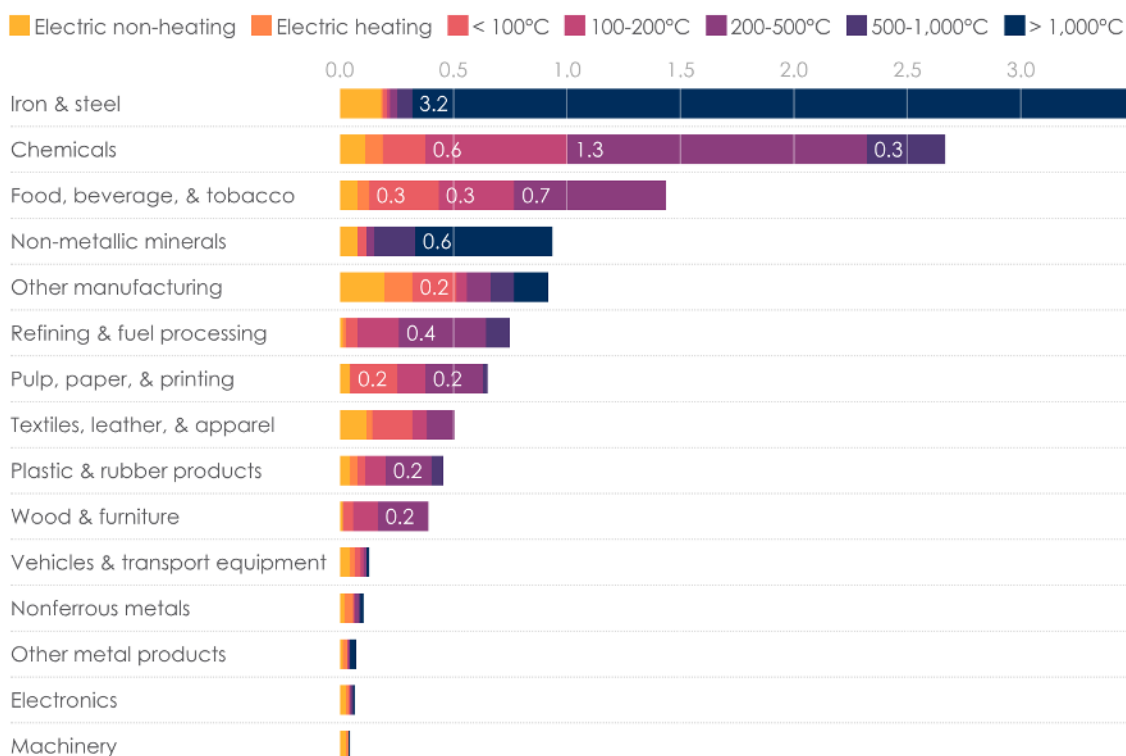
Data come from Rissman, et al. (2026). *The Industrial Transformation Technology And Investment Model, version 1.1.0.* Energy Innovation. <https://energyinnovation.org/report/the-industrial-transformation-technology-and-investment-model/>

Chemicals and refining are also heavy fossil fuel users with considerable emissions: 177 MMT CO₂, collectively. Of the remaining industries, nearly 60 percent of emissions come from purchased electricity, emphasizing the importance of decarbonizing India's power sector.

Identifying suitable electrified technologies to support these industries necessitates an understanding of their varying temperature requirements. Figure 7 demonstrates how non-feedstock energy demands are distributed by temperature in each industry. Figure 8 represents the energy demands across temperature ranges in each industry as a percentage of the industry's energy use, offering a clearer picture of which technologies may be most appropriate for a given industry.

Figure 7

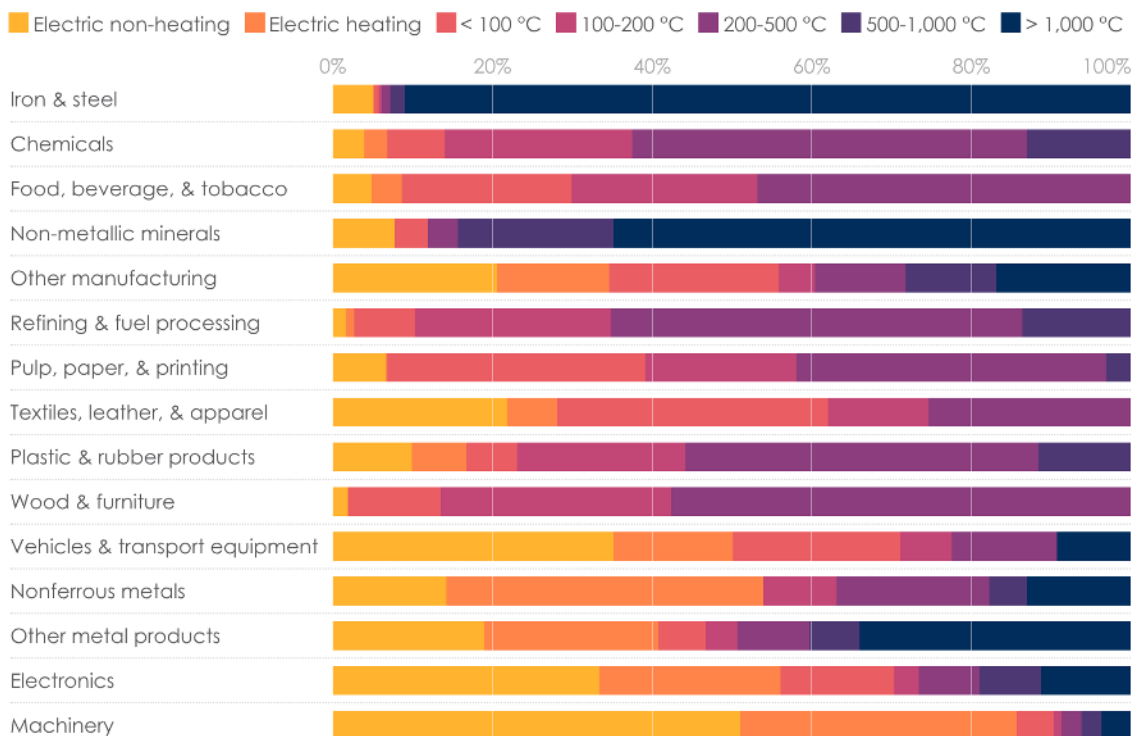
India's Industrial Non-Feedstock Energy Use by Temperature in 2022 (EJ)



Data come from Rissman, et. al. (2026). *The Industrial Transformation Technology And Investment Model, version 1.1.0*. Energy Innovation. <https://energyinnovation.org/report/the-industrial-transformation-technology-and-investment-model/>

Figure 8

India's Industrial Non-Feedstock Energy Use by Temperature as a Share of Each Industry in 2022



Notes: 1) Energy use data come from Rissman, et. al. (2026). *The Industrial Transformation Technology And Investment Model, version 1.1.0. Energy innovation.* <https://energyinnovation.org/report/the-industrial-transformation-technology-and-investment-model/> 2) Data on the share of useful energy by temperature by industrial subsector come from Madeddu et. al. (2020). *The CO2 reduction potential for the European industry via direct electrification of heat supply (power-to-heat).* *Environmental Research Letters.* <https://doi.org/10.1088/1748-9326/abbd02>

The need for high-temperature (>500°C) heat is greatest in the iron and steel industry, which accounts for a third of India's industrial non-feedstock energy use, followed by the non-metallic minerals (e.g., cement) industry. Across all industrial subsectors, nearly 40 percent of Indian industry's non-feedstock energy produces high-temperature heat. Medium-temperature heat (from 200°C to 500°C) accounts for about 27 percent of India's industrial non-feedstock energy use and is concentrated mainly in chemicals, refining, food and beverage, and pulp and paper. Low-temperature heat (below 200°C) and electricity used for non-heating purposes account for about a third of the sector's non-feedstock energy use and span a wide range of subsectors.

Promising Subsectors for Electrification in the Near Future

Some industrial subsectors in India are particularly well-suited for adopting solar energy, heat pumps, and thermal storage for their process heating needs. Targeting these subsectors can yield near-term wins in cost savings and emissions reductions:

- **Food and Beverage Processing:** This sector (which includes dairies, breweries, edible oils, and sugar) requires a high volume of low- to mid-temperature heat for pasteurization, boiling, and drying, primarily below 200°C. As the world's largest milk producer, India's dairy industry consumes vast amounts of low-pressure steam and hot water for processes like pasteurizing milk or making milk powder.⁹⁴ Solar heat through flat plate collectors or PV-driven heat pumps can supply these needs efficiently, and an accompanying thermal storage tank can hold hot water for night shifts. Heat pumps also provide cold, which can be useful for rapidly cooling pasteurized milk before it loses quality. Solar-powered heat pumps could also provide hot water and steam for brewing and other beverage industries, which often rely on expensive furnace oil boilers and require the precise temperature control that electric heating can provide. India is also one of the world's top sugar producers, with hundreds of sugar mills that rely mainly on bagasse-fired boilers for heating crushed sugarcane, evaporating the water, and crystallizing the sugar. While fossil fuels are less predominant in this industry, solar-powered heat pumps can still avoid localized pollution from bagasse combustion and offer cost advantages as competition drives up biomass prices.
- **Textiles (Textile Dyeing and Finishing):** Textile clusters like Tirupur in Tamil Nadu or Panipat in Haryana traditionally burn coal or biomass for steam (~100°C–130°C) in dyeing and finishing processes. Indeed, electricity made up only 5 percent of energy consumed in the five major textile clusters (Surat, Panipat, Jetpur, Tirupur, and Solapur).⁹⁶ This leaves extensive headroom for electrification, which would deliver large efficiency and air quality benefits, as boilers employed by India's textile industry have thermal efficiencies of only 35–50 percent and are a major source of local air pollution.⁹⁶ Recent policies have strengthened the case for a clean energy transition: for example, in Panipat (near Delhi), many dyeing units were forced to stop using coal. Fifteen percent of units shifted to electricity, 27 percent to natural gas, and others to biomass.²⁶ A better long-term solution is direct solar-electric systems. A combination of solar PV, electrode boilers, and potentially heat pumps for pre-heating could supply the required steam with zero emissions. Since textile manufacturers are often in pollution hotspots, clean heating provides both health and branding benefits, as many global apparel buyers favor cleaner production. Some pioneering mills have started installing rooftop solar and using electric boilers during peak sun hours to cut coal use. Scaling

up this transition could dramatically reduce coal consumption in India's textile sector.

- **Chemicals and Pharmaceuticals:** These industries need process heat across a wide temperature range, but a significant portion is in the low-mid range (e.g., distillation, reactors heating to ~200°C, and steam for pharmaceutical production). They also value reliability and cleanliness, needing to avoid soot or flame contamination. Electrification has several attractive opportunities here. For instance, a pharmaceutical plant can use high-temperature heat pumps to heat water for reaction baths or for HVAC reheating and use electric boilers for clean steam generation. Solar captive plants can supply the bulk of the necessary power. Moreover, chemical sites often have waste heat streams that a heat pump could upgrade, increasing overall efficiency. The chemical industry is also under global pressure to decarbonize supply chains, so demonstrating the viability of low-carbon process heat via solar and heat storage can provide Indian chemical exporters with a competitive edge.
- **Pulp and Paper:** Paper mills need large amounts of steam for pulp cooking and paper drying, typically in the 150°C–200°C range. Many Indian paper mills burn coal, bagasse, or gas. These mills could integrate utility-scale solar PV on-site—as they often have the requisite available land—and use that electricity in electric boilers or to charge thermal storage during the daytime. Even partial substitution of coal with solar heat can significantly cut fuel costs, as energy is a major portion of paper production costs. Given that many mills already handle biomass (e.g., bagasse in sugar integrated mills), adding electric heat would help diversify their energy, reduce particulate emissions, and reduce seasonality issues of biomass fuel.
- **Automotive and Electronics Manufacturing:** Industries like automotive component manufacturing, electronics, and machinery often require process heat in the form of oven curing, part washing (hot water), and paint shop heating (around 120°C–180°C). These needs are often met with small diesel or electric heaters. Replacing diesel-fired ovens with electric infrared heaters powered by solar could both reduce costs and improve workplace air (no more combustion fumes). Group captive solar is an attractive option for large auto manufacturing campuses—some have already installed massive solar plants for electricity. Extending that to process heat (with heat pumps for paint shop climate control, for example) is a logical next step to cut these factories' considerable energy bills.
- **Iron & Steel and Aluminum:** The steel industry's decarbonization should be prioritized due to its predominance in India's industrial energy use and its emissions from coal use. Promisingly, India is the largest direct reduced iron steel producer today,⁹⁷ and direct reduced iron furnaces may be able to shift to

clean fuels such as hydrogen with minor retrofits. In contrast, most countries rely on blast furnaces, which are harder to decarbonize.

While basic ironmaking is difficult to electrify without new processes, specific heat applications in steel plants could transition sooner. For example, reheating furnaces that heat steel billets for rolling could potentially use electric resistance or induction heating with sufficient power. Some forward-looking steel companies are exploring using thermal batteries to provide consistent high-grade heat for such furnaces, cutting coal use in those steps. Aluminum smelters already use electric current for the smelting process, but they use natural gas for calcining and heat treatments, and those could be switched to electric heating with renewables. Although heavy industries will likely adopt electrified heat more slowly than the subsectors discussed above due to scale and capital cost constraints, pilots in this space can target specific high-impact equipment.

Targeting support for electrification in industrial subsectors that are well suited for it can build success stories that pave the way for broader solar-powered process heating. The main consideration in selecting target industries is the temperature of heat required. Industries that rely on low- and medium-temperature heat can move immediately to adopt mature technologies like heat pumps and electric boilers, whereas some heavier industries must wait for high-temperature electric heating technologies to commercialize. Cost is another consideration, as industries that rely on expensive, imported fuels have the clearest incentive to electrify. The dairy, food, textiles, and pharmaceuticals industries are often cited as low-hanging fruit,⁹⁴ given their low-temperature processes and—at some facilities—high fuel costs. The benefits from targeting these subsectors can be considerable—the food industry, for example, contributes 44 percent of all particulate matter pollution from industrial steam generation.¹⁸

ELECTRICITY COSTS IN INDIA

ELECTRIFICATION IS A FIT FOR INDIA

India has unusually favorable economics for electrification, largely due to the low cost of its solar energy and relatively high costs of heavily imported oil and gas (Figure 9). The lion's share of heating technology costs is from energy use: for instance, in the U.S., fuel accounts for 96 percent of a typical industrial boiler's lifetime costs, while capital equipment expenditures make up 3 percent and operation and maintenance accounts for just 1 percent.⁶⁰

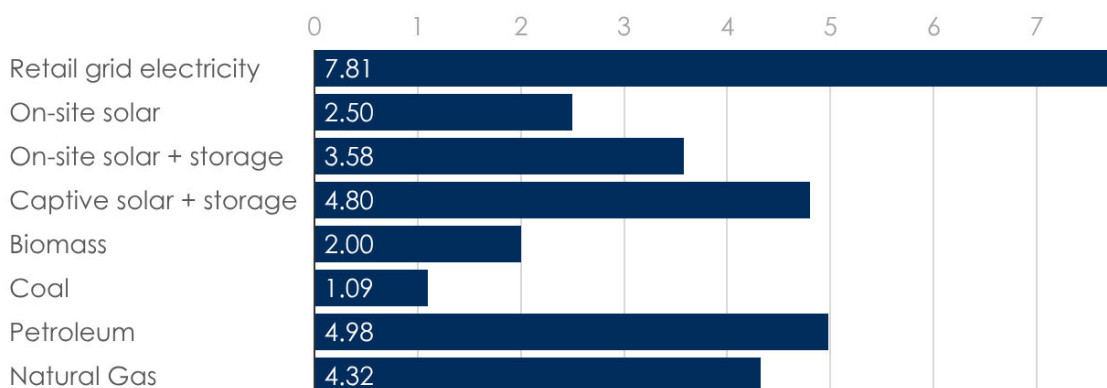
Globally, the average levelized cost of electricity from utility-scale PV has fallen about 90 percent since 2010, reaching as low as US\$0.044 per kWh in 2023.⁹⁸ India in particular has seen record-low solar tariffs—recent auctions have cleared at about ₹2.3–2.5 per kWh (approximately US\$0.03 per kWh), the lowest solar power prices among major economies.⁹⁹ The cost of petroleum products is nearly double that, at around ₹4.98 per kWh, and natural gas prices are also significantly higher, at around ₹4.32 per kWh.^{6,7} For firms that can access off-grid solar, the long-term savings of electrification are undeniable, especially when considering the superior efficiency of electrified equipment.

Although electrification via wind energy may cut industrial costs in India, it is not as promising an opportunity as solar-powered electrification. While India is a world leader in solar prices, not so with wind—in 2024, the weighted average levelized cost of energy (LCOE) from onshore wind was 60–66 percent higher in India than in countries like Brazil and China that lead on wind prices, and it was 26 percent higher than the cost of solar PV in India.¹⁰⁰ Moreover, wind energy may not provide sufficient, ongoing power to Indian industry. Wind production is highly seasonal in India, linked to the monsoon season that lasts only from June through September, and wind energy potential in India has been steadily declining since 1980 due to climate change.¹⁰¹

Solar energy production is also intermittent, but mostly on an inter-day rather than inter-seasonal basis, allowing it to provide round-the-clock power when paired with energy storage. Industrial firms can deploy solar and battery storage on-site, or they can leverage India's open access rules to obtain energy from offsite captive solar plants with battery storage, incurring grid wheeling charges. Firms can also pair on-site solar generation with thermal batteries, which keep costs down by serving as both energy storage equipment and industrial heating equipment.

Figure 9

Energy Price by Energy Source in India in 2025 (Rs/kWh)



1) "On-site solar" refers to a solar energy from a plant co-located with and owned by the consuming entity. 2) "Captive solar" refers to renewable energy from a plant that is owned by the consuming entity (equity stake of at least 26%) and provides over 51% of its energy to its owners, where the energy is wheeled through the grid and incurs transmission and distribution costs. 3) "Storage" refers to battery storage. 4) The price of retail grid electricity is based on the Centre for Social and Economic Progress' 2022 report, "A Granular Comparison of International Electricity Prices and Implications for India." 5) The price of onsite solar is based on a 2025 utility solar auction in India as reported by the International Energy Agency. 6) The price of a battery storage adder is based on a 2026 solar plus storage auction as reported by Energetica India. 7) The price of captive solar and storage reflects the cost of onsite solar + battery storage plus wheeling charges, which are based on wheeling charges published by the Maharashtra State Electricity Distribution Company in 2023. 8) The price of biomass is based on a 2024 biomass price benchmarking document from India's Ministry of Power. 9) The prices of coal and petroleum come from version 3 of NITI Aayog's India Energy Security Scenarios 2047 model. 10) The price of natural gas reflects the industrial gas tariff charged by the largest gas utility in Gujarat in 2023. 11) All data sources can be found in the open-source techno-economic analysis accompanying this report.

FACTORS LEADING TO LOW-COST SOLAR IN INDIA

In 2010, the weighted average LCOE of utility-scale solar in India was US\$375.9 per megawatt hour (MWh), over 50 percent higher than the global average. Smart policies and favorable market conditions joined forces to slash India's solar price to US\$37.4 per MWh, a 90 percent reduction by 2024,¹⁰² by which time India's solar market had become the most competitive in the world.¹⁰⁰

Policy Factors

Policy was the driving force for India's solar boom. GoI has supported renewables since the liberalization of India's electricity system in the 1990s, but initial incentives were only enough to accelerate the deployment of wind power.¹⁰³ By 2010, GoI recognized the need for dedicated policies to help the country realize its solar potential and launched a three-phase National Solar Mission (NSM) that combined government-facilitated solar procurement with financial support and other enabling policies.

Through the NSM, which is still active today, government entities serve as intermediaries between solar developers and distribution companies (DISCOMs)—buying solar from the former through a competitive bidding process and selling solar to the latter—to reduce the payment risk posed by many DISCOMs’ poor financial health. In the early years of the NSM, GoI encouraged solar bids by offering developers fixed feed-in tariffs (FITs) to reduce their financial risk and made solar more financially attractive to DISCOMs by bundling then-expensive solar with low-cost coal power. As solar grew more commercially viable and less expensive, the government replaced FITs with reverse auctions, where developers bid the lowest tariffs they could afford, initially supported by viability gap funding that promised capital cost support to winning bidders.

Despite solar’s declining prices, the costs and difficulty of securing land and infrastructure impeded its scale-up. In 2014, GoI set out to address these barriers with government-led “solar parks” that co-located multiple utility-scale solar projects in large, centralized areas. These parks offered developers pre-identified land parcels, pre-built transmission and distribution lines, and all the relevant permits, saving developers time and money by allowing them to simply bid for capacity within a park, build their project, and connect to plug-and-play infrastructure.¹⁰³ Additional support came in 2015 from the Green Energy Corridors program, which sought to build enough transmission infrastructure to integrate 500 GW of renewable energy capacity in the national grid by 2030, further de-risking solar projects.¹⁰⁴ Both programs also included financial support: grants for project planning and infrastructure development in solar parks,¹⁰⁵ and direct funding and financing for Green Energy Corridors.¹⁰⁴

In addition to the financial support already mentioned, GoI has offered solar developers concessions and exemptions on taxes related to capital equipment, critical minerals, and project imports¹⁰³ (though a new Goods and Services Tax revoked some of those benefits in 2018¹⁰⁶). In 2016, GoI began waiving interstate transmission charges and losses to facilitate interstate trading.¹⁰³ To help developers raise capital—typically debt-heavy project finance¹⁰⁷—public entities like IREDA offer concessional loans and credit-enhancing mechanisms, often in collaboration with international financing institutions.¹⁰⁶ Finally, GoI has offered tax exemptions and production-linked incentives (PLIs) for the domestic manufacturing of renewable energy components,¹⁰⁸ though most of India’s solar components are imported.²³

Standards also played a role, albeit a small one. Before the NSM got its start, GoI established Renewable Purchase Obligations—now called Renewable Consumption Obligations—requiring DISCOMs and large electricity consumers to purchase a minimum share of their power from renewables. Despite the option for firms to fulfill their requirement using Renewable Electricity Certificates, Renewable Purchase Obligations were poorly followed and enforced.¹⁰⁸ A different standard, one limiting non-GHG air pollutant emissions from urban coal plants, was likely a stronger driver of renewable energy adoption in India.

Market Factors

Comprehensive, predictable, and stable policies laid the groundwork for India's solar rise, but it was the convergence of timely market factors that pushed the industry into hypergrowth. For one, solar auctions became much more competitive as they transitioned from FITs to reverse auctions, especially as large, capital-rich power conglomerates began to participate. Developers began bidding aggressively low, many of them sacrificing profits for a greater share of a burgeoning market.^{109,107}

But developers that wanted to maintain their profits were also able to bid low. One key reason, besides financial support from the government, was the falling costs of PV hardware globally, the timing of which coincided with the greatest dip in solar costs in India.¹⁰⁹ According to the International Renewable Energy Agency, in India, hardware represents two-thirds of the cost of solar, and reductions in module pricing alone accounted for nearly half of solar's cost decline between 2010 and 2024.¹⁰⁰ These cost declines owe to technological improvements like improved efficiencies¹¹⁰ and a recent influx of low-cost imports from China.¹¹¹ In addition to low hardware costs, India's solar developers face some of the world's lowest soft costs, such as installation, operation, and maintenance costs.¹⁰⁰ Finally, competitive interest rates have recently unlocked low-cost debt for developers, even where concessional financing is not available.¹¹²

ACCESSING LOW-COST SOLAR VIA OPEN ACCESS RULES

Indian firms can directly access the low prices of utility-scale solar through third-party procurement (e.g., via power purchase agreements) or by investing in a captive or group-captive solar plant. India's Electricity Act introduced this "open access" entitlement to large electricity consumers in 2003, and the Ministry of Power introduced an updated set of Green Energy Open Access (GEOA) rules in 2022 to expand renewable energy access to a broader set of commercial and industrial (C&I) firms, including MSMEs.

C&I firms with a load of at least 100 kW can now obtain renewable energy from generators or the open market through a single-window digital portal (reducing administrative burden), and smaller firms can meet the eligibility threshold by aggregating their load with that of other firms. The new rules also allow firms to access the interstate transmission network (to tap resources in renewables-rich states) and offer greater regulatory clarity and certainty (lowering costs and unlocking investment).¹⁶

The GEOA rules cover both third-party procurement and grid-connected captive solar, where firms obtain energy from plants that they fully or partially own. In a group-captive solar arrangement, firms must co-own at least 26 percent of the plant (in partnership with other firms) and consume over half of the plant's electricity. Under the GEOA rules, third-party arrangements are subject to wheeling charges, cross-

subsidy surcharges, and an additional surcharge, whereas captive and group-captive arrangements are only subject to wheeling charges.¹¹³

REGIONAL AND CROSS-SECTORAL VARIANCE IN ELECTRICITY PRICING

Indian electricity prices vary widely by sector and locale (Figure 10). Industrial and commercial users pay higher rates to cross-subsidize residential and agricultural users.¹¹⁴ However, if these cross-subsidies were removed, leveling off pricing across sectors, industrial electricity prices could fall by an average of 20 percent (Figure 10). This may be a reasonable way to improve Indian industrial competitiveness and the attractiveness of direct electrification.

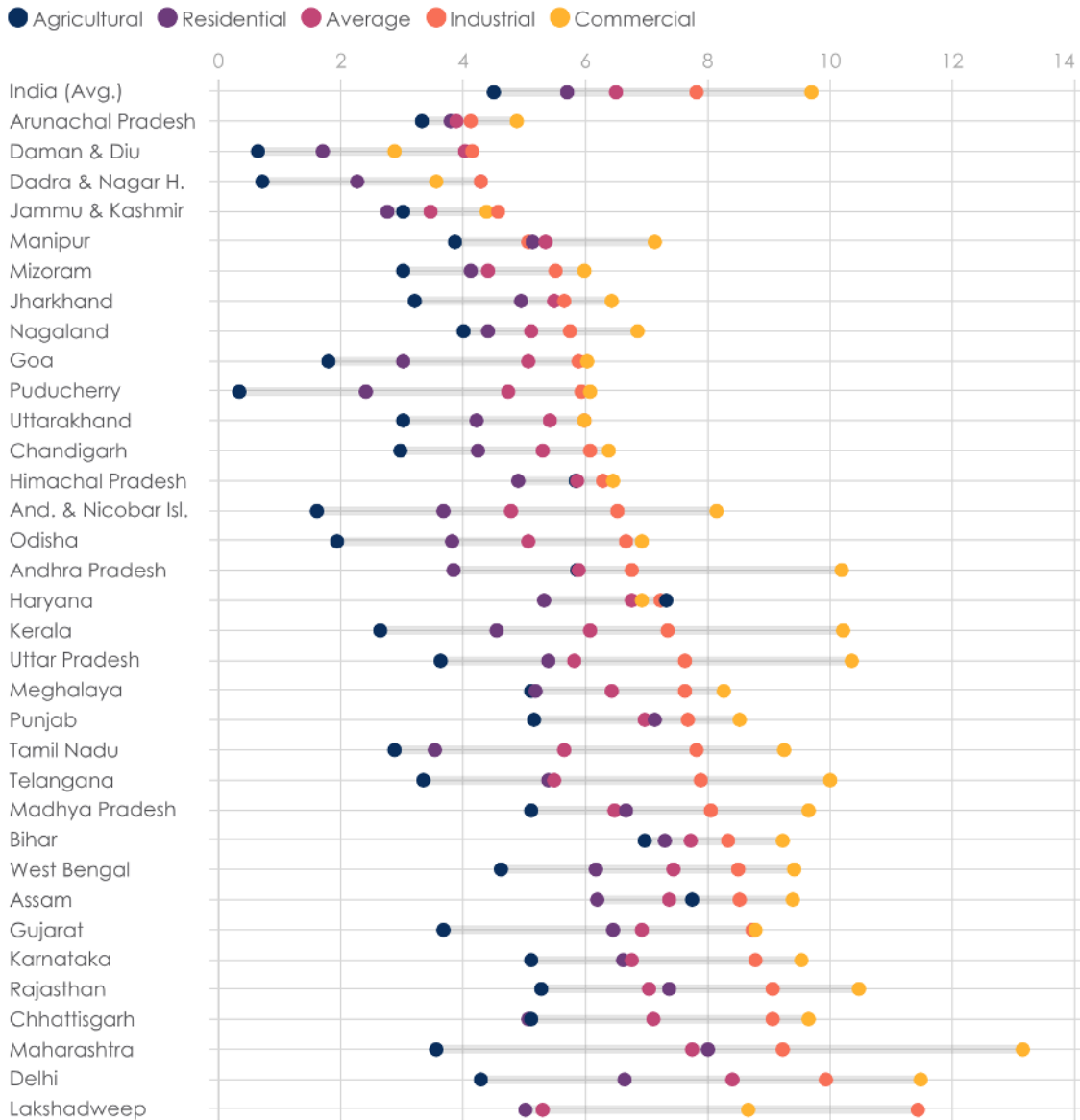
In fact, electricity is supplied to industrial users at higher voltages with lower losses and infrastructure costs, implying a lower cost to serve the sector.¹¹⁴ In some countries, such as the U.S., industrial firms are charged less per unit of electricity than residential or commercial customers, even after accounting for capacity-based demand charges. This reflects the lower cost to serve these customers, as well as regulators' desire to protect local industries, which are often major employers in their communities. Adopting the same sectoral price ratios as in the U.S. would reduce industrial electricity rates by an average of 46 percent (Figure 11). However, this would entail large increases in electricity rates for residential and agricultural electricity buyers, which may not be practical or desirable in India.

Captive renewables may be a better option for reducing industrial electricity prices. Based on data from Ember Energy,¹¹⁵ captive renewable energy prices are on average 58 percent lower than actual grid pricing for industrial buyers, 48 percent lower than grid pricing if cross-subsidies were ended, and 20 percent lower than grid prices for industrial buyers if India were to adopt U.S.-like sectoral price ratios (Figure 11). Adding battery storage increases the price, though captive solar with storage is still 39 percent cheaper than average grid electricity prices for industrial customers in India (Figure 9). Unlike changes to cross-subsidization policy, a firm's choice to use captive renewable energy would not directly affect the rates paid by non-industrial electricity buyers.

India's time-of-day tariffs include beneficial solar hours, 8 hours during midday when electricity is discounted at least 20 percent from normal tariff prices. The peak hours tariff, when demand is high and the grid is stressed—generally during the evenings—is at least 20 percent higher than normal.¹¹⁵ These price modifiers apply to the energy portion of the bill (not fixed charges), which makes up around 80 percent of industrial customer costs.¹¹⁶ Factoring in these variances in time-of-day pricing, one can expect a fluctuation of +/-16 percent which, while significant, is not particularly attractive to arbitrage across the day using thermal battery storage. The true variance in electricity generation costs throughout the day is much higher than this time-of-day tariff variation, so industrial firms could benefit from better exposure to true costs to best optimize grid load flexibility and energy storage deployment.

Figure 10

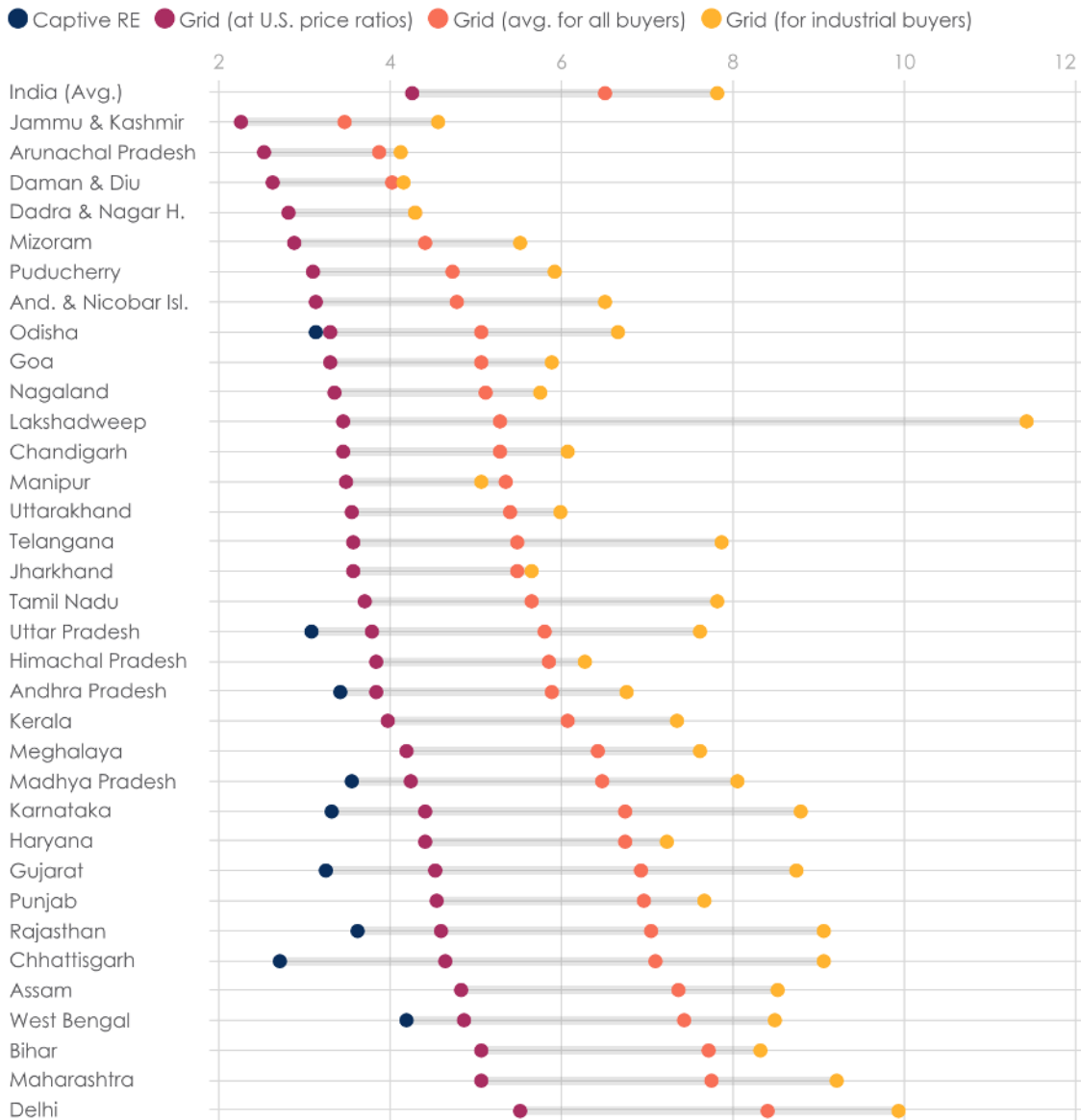
Average Electricity Prices in India in 2022 (Rs/kWh)



1) Data are not available for the Indian states of Sikkim and Tripura. All other states and territories are included. 2) Data come from: Kanak Gokarn, Nikhil Tyagi, and Rahul Tongia (2022). A Granular Comparison of International Electricity Prices and Implications for India. Centre for Social and Economic Progress. <https://csep.org/working-paper/a-granular-comparison-of-international-electricity-prices-and-implications-for-india/>

Figure 11

Industrial Electricity Prices in India under Four Pricing Regimes (Rs/kWh)



1) Data are not available for the Indian states of Sikkim and Tripura. All other states and territories are included. 2) All prices except for captive renewable energy are based on data from: Kanak Gokarn, Nikhil Tyagi, and Rahul Tongia (2022). *A Granular Comparison of International Electricity Prices and Implications for India*. Centre for Social and Economic Progress. <https://csep.org/working-paper/a-granular-comparison-of-international-electricity-prices-and-implications-for-india/> 3) Captive RE prices are from: Duttatreya Das and Neshwin Rodrigues (2025). *RE-Powering India's Heavy Industries: 20 GW Today, 24/7 Tomorrow*. Ember Energy. <https://ember-energy.org/latest-insights/re-powering-indias-heavy-industries-20-gw-today-24-7-tomorrow/chapter-1-mechanisms-for-re-procurement/>

TECHNO-ECONOMIC ANALYSIS

We conducted a techno-economic analysis to identify the cases where industrial electrification is already cost-competitive in India. We analyzed the LCOH of 15 industrial heating configurations, all leveraging various electric or combustion-based energy sources. We also estimated the emissions of CO₂ and non-GHG air pollutants from each configuration.

METHODOLOGY

We built a computer model in Excel to conduct the techno-economic analysis. The model calculates the LCOH of industrial heating configurations across five temperature bands, spanning the entire range of temperatures that industry uses for bulk heating today. (Precision heating applications, like laser cutting, are typically already electrified.)

The analysis considers the technology configurations and temperature scenarios listed in Table 1, which notes the temperature bands at which each configuration is applicable. Temperature-constrained technologies include heat pumps, which top out at 200°C (including models that use mechanical vapor compression), and thermal batteries, which are only cost-effective for providing heat over 100°C, where heat pumps are less efficient or unavailable.

Both heat pumps and electric resistance heating equipment are split into three configurations that leverage different electricity sources: grid electricity at retail rates (₹7.81/kWh), on-site renewable energy (RE) paired with battery storage (₹3.58/kWh), and captive RE paired with battery storage (₹4.80/kWh). In this analysis, “captive” RE refers to consumer-owned renewable power that is wheeled by the grid, incurring some transmission and distribution costs—a common arrangement in India made possible by GEOA rules. For both on-site and captive RE, battery storage is critical for enabling continuous heat output.

Thermal batteries are only configured to leverage on-site RE (₹2.50/kWh). Since they are energy storage technologies, they do not need battery storage to produce 24/7 heat. It does not make financial sense for thermal batteries to use retail electricity in India, as retail prices do not vary enough during the day to achieve meaningful cost savings by selectively purchasing grid electricity when it is cheapest. Nor do we assume they use captive RE, which entails high wheeling costs when the RE is not paired with battery storage.

Rates for on-site and wheeled captive RE assume load sizes on the order of tens of megawatts (or larger) that use higher-voltage, three-phase power, a level of electricity demand that would be met by most medium-to-large industrial facilities after electrification, especially those in heavy industries like steel, cement, or chemicals.

Small manufacturers located in urban areas and served by a local utility might need to rely on grid power.

Combustion technologies are configured with and without waste heat recovery (WHR), a technology that recovers some heat from exhaust gases or steam and reuses it in the industrial process, improving efficiency. For example, WHR can raise the efficiency of gas-fired equipment from 83 percent to 95 percent at low temperatures (100°C to 200°C) and from 23 percent to 53 percent at very high temperatures (1,000°C to 1,800°C),¹¹⁷ reducing the energy costs of combustion-based heating.

Table 1

Technology configurations and temperature bands

	< 100°C	100 – 200°C	200 – 500°C	500 – 1,000°C	1,000 – 1,800°C
Heat pumps – grid electricity	y	y			
Heat pumps – on-site RE + battery storage	y	y			
Heat pumps – captive RE + battery storage	y	y			
Thermal batteries – on-site RE		y	y	y	y
Electric resistance boiler or furnace – grid electricity	y	y	y	y	y
Electric resistance boiler or furnace – on-site RE + battery storage	y	y	y	y	y
Electric resistance boiler or furnace – captive RE + battery storage	y	y	y	y	y
Biomass-fired boiler or furnace	y	y	y	y	y
Biomass-fired boiler or furnace + WHR	y	y	y	y	y
Coal-fired boiler or furnace	y	y	y	y	y
Coal-fired boiler or furnace + WHR	y	y	y	y	y
Petroleum-fired boiler or furnace	y	y	y	y	y
Petroleum-fired boiler or furnace + WHR	y	y	y	y	y
Natural gas-fired boiler or furnace	y	y	y	y	y
Natural gas-fired boiler or furnace + WHR	y	y	y	y	y

The model calculates the LCOH of each configuration by adding up energy costs (based on the price of the input energy), annualized capital costs of heating equipment (assuming a 26-year lifetime and 11 percent discount rate), and carbon emissions costs (based on fuel emissions factors, India’s carbon price, or the social cost of carbon), all of which are adjusted for equipment efficiency to reflect the cost of delivered heat.

Other expenses, like the costs of land and buildings, equipment installation, and operation and maintenance, are assumed to be similar across all configurations and thus are excluded from the analysis. The model also uses fuel emissions intensities and equipment efficiencies to calculate the emissions of CO₂, PM_{2.5}, SO₂, and NO_x from the grid-connected and fossil-fuel-fired configurations (the on-site and captive RE configurations are assumed to be emissions free).

Data Sources

All data in the techno-economic analysis derive from published reports and analyses and are cited in our open-source Excel model released alongside this report.

Energy price data are shown in Figure 9 and come from multiple sources. Grid electricity prices are based on the average per-kilowatt-hour electricity price paid by industrial customers across nearly all Indian states. The prices of on-site renewables and battery storage are based on recent auctions in India and form the basis of the price of captive RE and battery storage, which also includes a wheeling charge adder based on published open-access charges from Maharashtra's largest DISCOM. The price of biomass comes from a price benchmark advisory from India's Ministry of Power. (This reflects the cost of purchased biomass pellets; certain subindustries that use biogenic inputs, such as pulp and paper and some food processing operations, can access biomass more cheaply. But for comparability with other energy sources in this analysis, which are purchased, we use market prices for purchased biomass.) Coal and petroleum prices are taken from NITI Aayog's India Energy and Security Scenarios tool, while natural gas prices reflect the industrial tariff charged by the largest gas utility in Gujarat.

Data on the capital costs of different industrial heating equipment mainly come from version 4.1.0 of Energy Innovation's Energy Policy Simulator, an open-source tool for evaluating the emissions, GDP, and other impacts of decarbonization policies in many regions of the world, including India. Within that tool, the underlying capital cost data derive mainly from U.S. sources, save for data on heat pumps, which come from a recent International Energy Agency report on global industrial heat pump deployments. The capital costs of WHR equipment are derived separately, from a journal article that disaggregates the cost of a heat exchanger within a waste-heat-to-power system.¹¹⁸

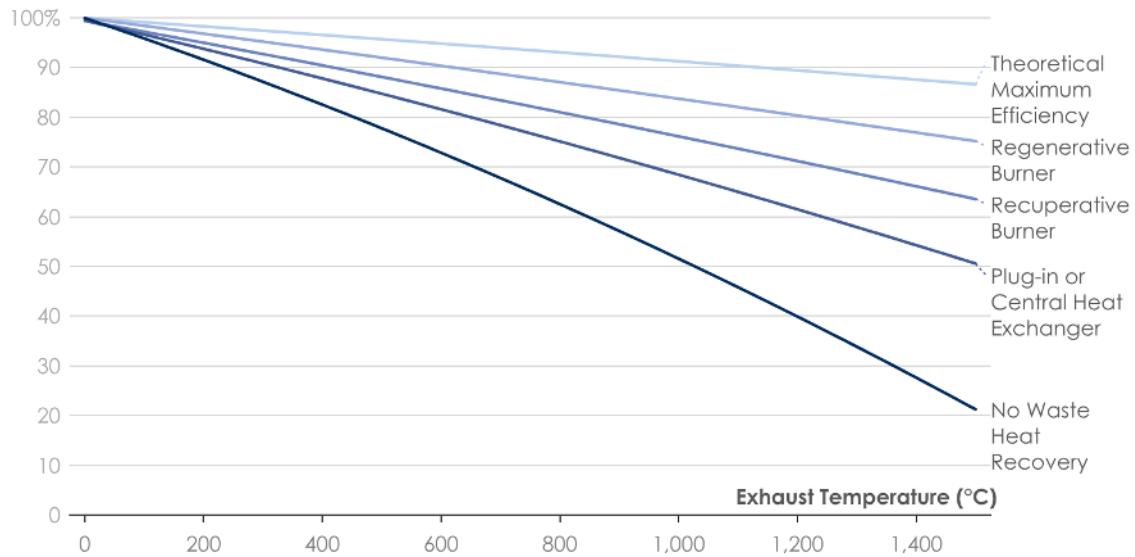
Our model uses a carbon price of US\$10/tCO₂e, the government's initial target price for carbon credits under the CCTS program.³⁰ Note that the CCTS is an emissions intensity-based standard (discussed above), and only facilities emitting above the standard have to buy credits, so some facilities would not be subject to this fee. We include the fee in our analysis to reflect the costs faced by those firms that exceed the standard (and therefore have the most financial incentive to decarbonize), as well as in expectation that India may tighten the standard in future years to cover more

facilities and drive continued improvement. For reference, the model also calculates the additional carbon emissions cost that each configuration would face if the carbon price reflected India’s US\$86/tCO₂e social cost of carbon. The CO₂ and non-GHG pollutant intensities of India’s grid are based on Indian government data, while the emissions intensities of fossil fuels are based on U.S. government data (cited in the attached model).

Data on the energy efficiency of electric heating equipment come directly from published resources. Efficiency data for heat pumps and electric resistance equipment come from Agora Industry’s Power-2-Heat Transformation Cost Calculator,¹¹⁹ while thermal battery efficiency data come from a 2023 Energy Innovation report.⁸⁵ Gas combustion efficiency data are based on a U.S. Department of Energy fact sheet that includes a graph of the efficiency of industrial gas combustion using different levels of excess air.¹²⁰ We selected efficiency values along the curve anchored to an excess air ratio of 10 percent (common for high-temperature direct-fired furnaces to ensure complete combustion of the fuel), using reference temperatures that corresponded to each temperature band in our analysis. Data on gas combustion with WHR are based on a published article in *Thermal Processing* with a graph showing gas combustion efficiency using industrial equipment with and without various WHR improvements (Figure 12).¹¹⁷

Figure 12

Efficiency of Natural Gas Combustion vs. Temperature in Industrial Equipment



Notes: 1) Efficiencies depicted in this figure reflect energy losses in exhaust gases (both sensible heat and water vapor’s latent heat). Conductive and radiant losses through machinery surfaces and openings are excluded. 2) Figure adapted from Steven R. Mickey (2017). *Efficient Gas Heating of Industrial Furnaces*. *Thermal Processing*. <https://thermalprocessing.com/efficient-gas-heating-of-industrial-furnaces/>

Using the same reference temperatures selected earlier, we identified efficiency values based on the curve depicting a gas-fired furnace equipped with a “plug-in or central heat exchanger,” one of the simpler WHR technologies. For coal and petroleum combustion, we adjusted our gas combustion efficiency values based on the relative efficiency differences between gas, coal, and oil boilers (using published data on boiler efficiencies). Finally, we assumed biomass combustion efficiency to be equivalent to coal combustion efficiency.

Energy Efficiency’s Impact on LCOH

Cost differences across temperature bands are driven by changes in equipment energy efficiency across temperature bands. As Figure 12 demonstrates for gas-burning industrial furnaces, combustion efficiency declines as output temperatures climb. The dark blue line depicts the efficiency of gas equipment without WHR, which is close to 100 percent at very low temperatures but drops dramatically, reaching around 52 percent at 1,000°C and 21 percent at 1,500°C. These efficiency drops improve when furnaces are equipped with WHR, as shown by the lighter blue efficiency curves above the no-WHR curve. Our analysis uses the “plug-in or central heat exchanger” curve, where efficiency drops only to 68 percent by 1,000°C and 51 percent by 1,500°C.

Our combustion efficiency data include energy losses in exhaust gases (both sensible heat and water vapor’s latent heat) but not conductive or radiant losses through machinery surfaces and openings. Losses through machinery surfaces and openings are similar across combustion and electric versions of the same type of equipment (such as a boiler or a furnace) and are much smaller than losses related to exhaust gases in well-insulated equipment, so the exclusion of these loss modes from the analysis is unlikely to affect the cost comparison between combustion and electrified heating equipment.

Both electric resistance equipment and thermal batteries convert electricity to heat using electric resistance, whose efficiency is stable at all temperatures where it is viable. Therefore, we assume both technologies have stable efficiencies across temperature bands—99 percent for electric resistance equipment and 95 percent for thermal batteries, which lose some energy in the transfer of heat to materials—meaning they have the same LCOH across temperature bands. Heat pumps, on the other hand, lose efficiency at higher temperatures (Figure 5), though they are still the only technology that outputs more heat than the electricity they take in. We assume that heat pumps have a COP of 3.7 in the <100°C band and a COP of 2.2 in the 100°C–200°C band, making them more cost effective at lower temperatures.

RESULTS

Levelized Cost of Heat

Our analysis demonstrates that electrification is economically viable at all temperatures industry uses today (Table 2). Nearly all RE-powered technologies are competitive with petroleum and gas combustion, whether those electric technologies use on-site solar and storage or captive solar and storage wheeled by the grid. Electrified technologies are most competitive at higher temperatures, where the efficiency of combustion drops significantly, and at low temperatures that can be delivered by heat pumps, whose efficiency is unparalleled by any other electric or combustion technology.

Moreover, at the lowest and highest temperatures, at least one electric configuration can compete with coal: all heat pumps at temperatures under 100°C, RE-powered heat pumps at temperatures under 200°C, and all RE-powered technologies at temperatures above 1,000°C. Today's commercial thermal batteries can be used in 200°C-500°C processes, where they cost only 34 percent more than coal-fired boilers by leveraging ultra-low-cost on-site solar without the need for battery storage. Pilot models can serve processes in the 500°C-1,000°C range, where they cost only one percent more than coal-fired furnaces.

Although WHR can increase the efficiency of combustion equipment, those efficiency gains are not enough to offset WHR's capital costs at low and medium temperatures, nor do they come close to the exceptional efficiency of electric equipment at high temperatures. Finally, a low carbon price of only US\$10/tCO₂e is insufficient to tip the scales in favor of industrial electrification at any temperature, indicating that India's carbon price will not encourage meaningful industrial decarbonization unless it steadily rises beyond US\$10/tCO₂e. Below, we explore LCOH results for each temperature band, breaking out the constituent energy, capital, and carbon costs.

Table 2

Levelized Cost of Heat by Technology Type Across Temperature Ranges (Rs/kWh_{th})

	<100°C	100-200°C	200-500°C	500-1,000°C	1,000-1,800°C
Heat pump (grid, retail)	2.58	4.34			
Heat pump - on-site RE	1.27	2.13			
Heat pump (captive RE)	1.60	2.68			
Thermal battery - on-site RE		3.94	3.94	3.94	3.94
Elec. resistance (grid, retail)	9.79	9.79	9.79	9.79	9.79
Elec. resistance (onsite RE)	4.87	4.87	4.87	4.87	4.87
Elec. resistance (captive RE)	6.10	6.10	6.10	6.10	6.10
Biomass-fired equip.	3.43	3.51	3.89	5.11	12.67
Biomass-fired equip. + WHR	5.24	5.33	5.62	6.64	9.55
Coal-fired equip.	2.59	2.65	2.94	3.86	9.57
Coal-fired equip. + WHR	4.50	4.58	4.83	5.71	8.21
Petroleum-fired equip.	6.81	6.98	7.72	10.16	25.17
Petroleum-fired equip. + WHR	8.00	8.14	8.58	10.14	14.58
Natural gas-fired equip.	5.95	6.09	6.74	8.87	21.97
Natural gas-fired equip. + WHR	7.15	7.28	7.67	9.07	13.04

Notes: 1) The levelized cost of heat values in this table reflect efficiency-adjusted energy costs, capital costs, and carbon costs (based on a \$10/tCO₂ carbon price), but not the un-priced social cost of carbon. 2) In the case of heat pumps and electric resistance equipment, "on-site RE" refers to on-site solar plus battery storage to enable continuous use of heat. 3) In the case of thermal batteries, which are themselves energy storage technologies, "on-site RE" refers to on-site solar without battery storage. 4) "Captive RE" refers to RE plus battery storage from a plant that is owned by the consuming entity (equity stake of at least 26%) and provides over 51% of its energy to its owners, where the energy is wheeled through the grid and incurs transmission and distribution costs.

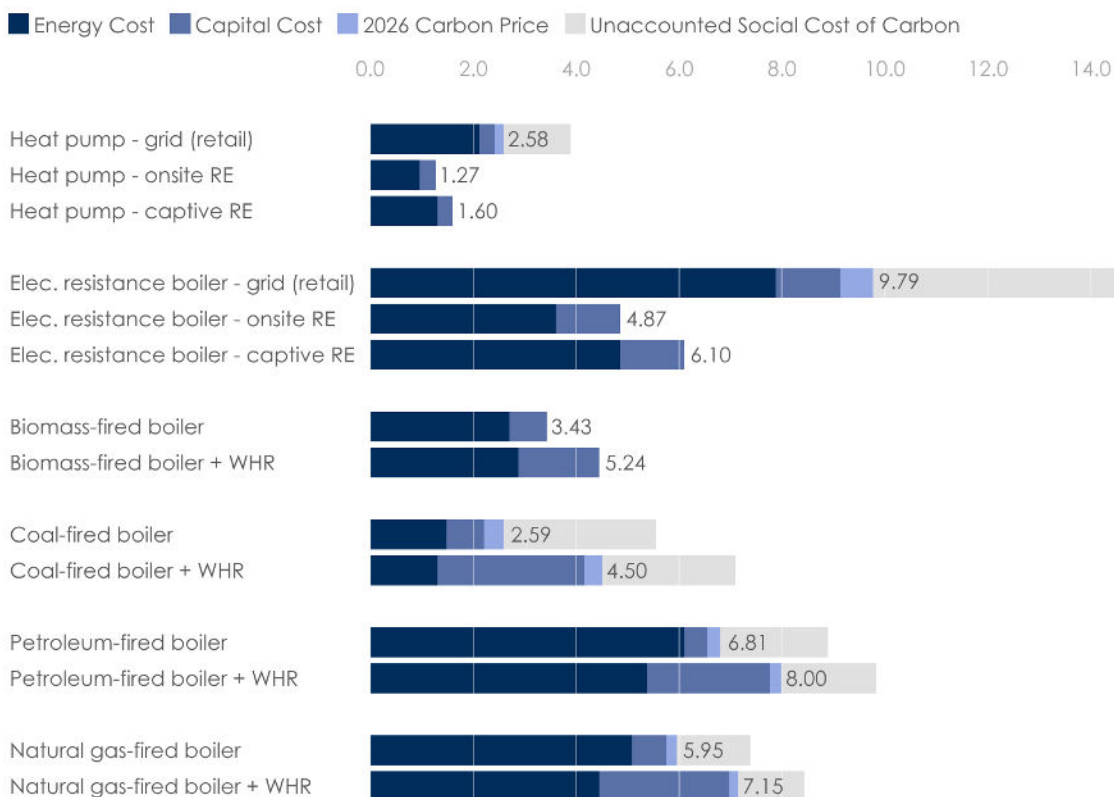
At temperatures under 100°C, all heat pump configurations, as well as electric resistance boilers powered by onsite solar and battery storage, are cost-competitive with petroleum- and natural gas-fired boilers (Figure 13). Heat pumps are particularly cost effective because they are extremely efficient, outputting 2.5 to five times more energy than they take in at these low temperatures. Heat pumps' energy costs are 84 percent less than those of petroleum boilers when using on-site RE, 79 percent less when using captive RE, and 66 percent less when using retail electricity from the grid. Electric resistance boilers, which are not as efficient as heat pumps (though still more efficient than combustion equipment), require inexpensive on-site RE or captive RE to compete with petroleum-fired boilers, or on-site RE to compete with gas-fired boilers. Heat pumps also outcompete biomass combustion in this temperature range, no matter the electricity source, as do electric resistance boilers powered by on-site RE.

Given their exceptional efficiency at these low temperatures, heat pumps are competitive with coal-fired boilers under 100°C—even when powered by grid electricity. Heat pumps have a much lower LCOH than coal-fired boilers when powered by RE and battery storage, at ₹1.27 per kWh of thermal output (kWh_{th}) when powered by on-site RE and ₹1.60/ kWh_{th} when powered by captive RE, compared to ₹2.59/ kWh_{th} for coal-fired boilers (₹4.50/ kWh_{th} with WHR). Heat pumps powered by grid electricity (at ₹2.58/ kWh_{th}) are only slightly cheaper than coal-fired boilers at these temperatures. If India's carbon price were to include the entire social cost of carbon (represented by the light gray bar on the graph), even the RE-powered electric boilers would outcompete coal boilers. However, electric boilers powered by grid electricity would still be uncompetitive in that scenario due to the significant role of coal in India's grid mix.

WHR significantly increases the costs of combustion at these low temperatures, where its capital costs outweigh marginal efficiency gains. In fact, WHR only delivers financial benefits at temperatures above 500°C for petroleum-fired technologies and above 1,000°C for biomass-, coal-, and natural gas-fired technologies.

Figure 13

Levelized Cost of Heat by Technology Type, <100 °C (Rs/kWh_{th})



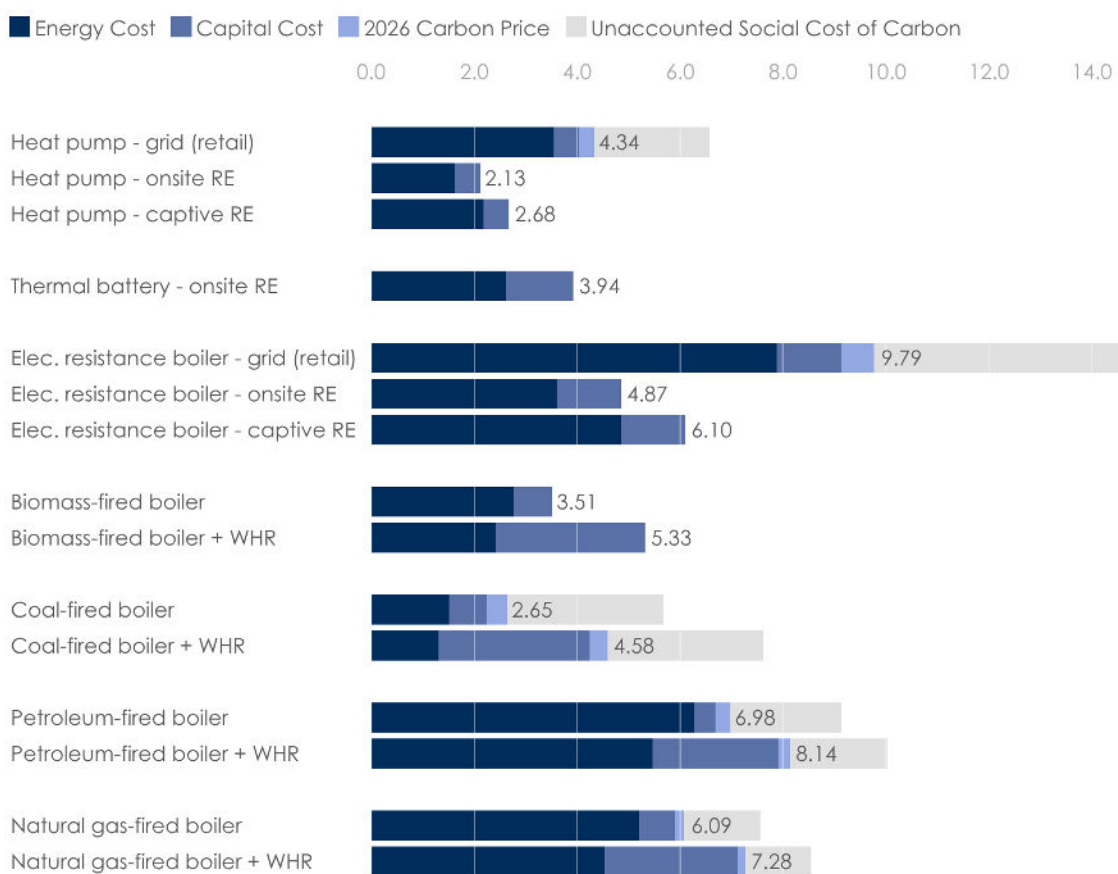
Notes: 1) "Onsite RE" refers to onsite solar plus battery storage to enable continuous use of heat. 2) "Captive RE" refers to consumer-owned and grid-delivered captive solar plus battery storage, where the consuming entity holds an equity stake of at least 26% in the plant, the plant provides over 51% of its energy to its owners, and the consuming entity pays transmission and distribution costs. 3) WHR stands for waste heat recovery. 4) All costs are adjusted for equipment efficiency to reflect the cost of delivered heat. 5) Capital costs are annualized over a 26-year equipment lifetime using an 11 percent discount rate. 6) The light blue bar represents the cost of complying with India's carbon intensity threshold, assuming firms exceed that threshold and a compliance credit costs \$10/tCO₂e. 7) The light gray bar represents the additional incremental carbon cost if it reflected India's social cost of carbon of \$86/tCO₂e. 8) The total LCOH of each configuration, including energy, capital, and carbon costs but not the unaccounted social cost of carbon, is listed to the right of the relevant blue bars.

Heat pumps powered by solar and storage are also competitive with all fossil fuels at temperatures between 100°C and 200°C (Figure 14). Although heat pumps are less efficient at higher output temperatures, they are still 1.5 to 2.5 times more efficient than the next most efficient option, electric resistance boilers. In this temperature range, heat pumps powered by on-site RE are the least expensive configuration, 20 percent cheaper than coal-fired boilers and 39-69 percent cheaper than biomass-, petroleum-, and gas-fired boilers. Captive RE-powered heat pumps are not far from cost parity with coal, with an LCOH of ₹2.68/kWh_{th} compared to ₹2.65/kWh_{th} for coal-fired boilers, and are 24-62 percent cheaper than biomass-, petroleum-, and gas-fired boilers.

Grid-powered heat pumps, solar-powered thermal batteries, and solar-and-storage-powered electric resistance boilers are competitive with petroleum- and gas-fired boilers at these temperatures, but not biomass- or coal-fired boilers. However, if India's carbon price were to reflect the social cost of carbon, emissions-free RE-powered technologies would outcompete all combustion boilers, including coal boilers. Grid-powered electric resistance boilers would be uncompetitive in either scenario.

Figure 14

Levelized Cost of Heat by Technology Type, 100-200 °C (Rs/kWh_{th})



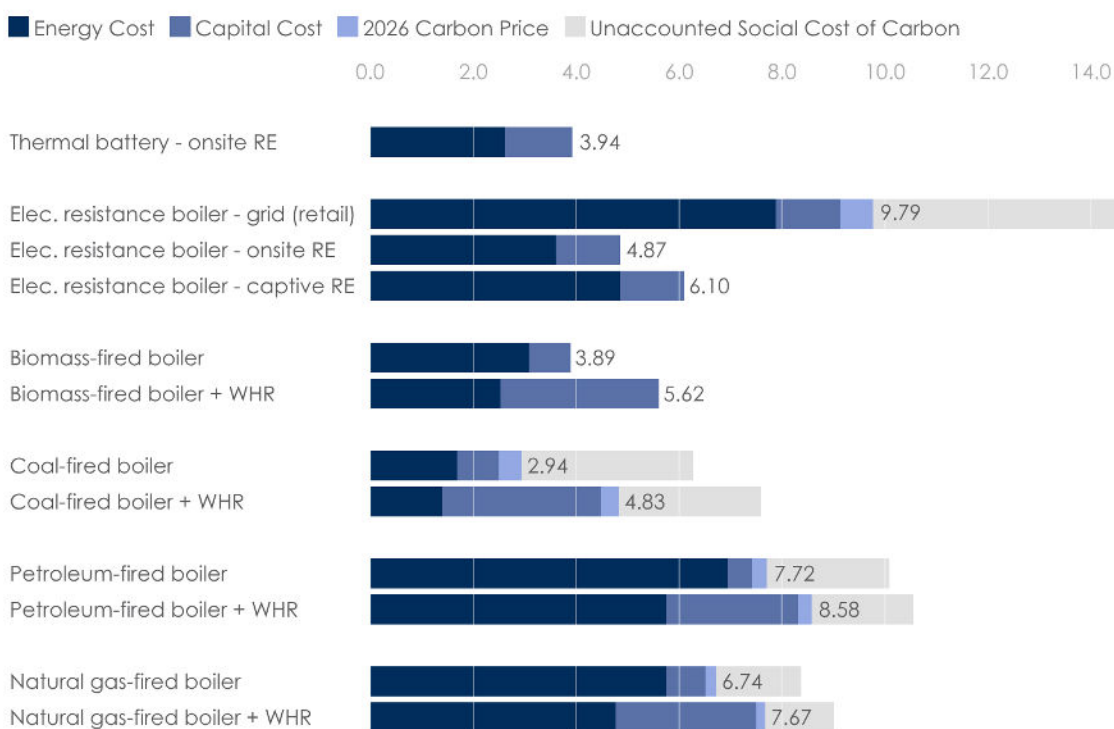
Notes: 1) In the case of heat pumps and electric resistance boilers, "onsite RE" refers to onsite solar plus battery storage to enable continuous use of heat. 2) In the case of thermal batteries, which are themselves energy storage technologies, "onsite RE" refers to onsite solar without battery storage. 3) "Captive RE" refers to consumer-owned and grid-delivered captive solar plus battery storage, where the consuming entity holds an equity stake of at least 26% in the plant, the plant provides over 51% of its energy to its owners, and the consuming entity pays transmission and distribution costs. 4) WHR stands for waste heat recovery. 5) All costs are adjusted for equipment efficiency to reflect the cost of delivered heat. 6) Capital costs are annualized over a 26-year equipment lifetime using an 11 percent discount rate. 7) The light blue bar represents the cost of complying with India's carbon intensity threshold, assuming firms exceed that threshold and a compliance credit costs \$10/tCO₂e. 8) The light gray bar represents the additional incremental carbon cost if it reflected India's social cost of carbon of \$86/tCO₂e. 9) The total LCOH of each configuration, including energy, capital, and carbon costs but not the unaccounted social cost of carbon, is listed to the right of the relevant blue bars.

The 200°C–500°C temperature band includes thermal batteries and electric resistance boilers but not heat pumps, which currently top out at around 200°C. Our model assumes that these electric technologies have stable efficiencies—and therefore costs—across all temperature ranges (Figure 15). Combustion technologies are five to seven percent less efficient in this temperature band than in the two lowest-temperature bands (Figure 12), but they are still efficient enough that WHR raises the LCOH of combustion-based heating at these temperatures.

Between 200°C and 500°C, RE-powered thermal batteries and electric resistance boilers are competitive with petroleum- and gas-fired boilers. However, this is the only temperature range where no electric technologies outcompete coal or biomass combustion. Still, on-site solar-powered thermal batteries, which do not require battery storage or owe grid wheeling charges, cost only one percent more than biomass-fired boilers and 34 percent more than coal-fired boilers.

Figure 15

Levelized Cost of Heat by Technology Type, 200-500 °C (Rs/kWh_{th})



Notes: 1) In the case of electric resistance boilers, "onsite RE" refers to onsite solar plus battery storage to enable continuous use of heat. 2) In the case of thermal batteries, which are themselves energy storage technologies, "onsite RE" refers to onsite solar without battery storage. 3) "Captive RE" refers to consumer-owned and grid-delivered captive solar plus battery storage, where the consuming entity holds an equity stake of at least 26% in the plant, the plant provides over 51% of its energy to its owners, and the consuming entity pays transmission and distribution costs. 4) WHR stands for waste heat recovery. 5) All costs are adjusted for equipment efficiency to reflect the cost of delivered heat. 6) Capital costs are annualized over a 26-year equipment lifetime using an 11 percent discount rate. 7) The light blue bar represents the cost of complying with India's carbon intensity threshold, assuming firms exceed that threshold and a compliance credit costs \$10/tCO₂e. 8) The light gray bar represents the additional incremental carbon cost if it reflected India's social cost of carbon of \$86/tCO₂e. 9) The total LCOH of each configuration, including energy, capital, and carbon costs but not the unaccounted social cost of carbon, is listed to the right of the relevant blue bars.

At temperatures above 500°C, where boilers top out, the efficiency of fossil fuel-fired equipment drops dramatically, whereas the efficiency of electric configurations remains high. WHR just barely pencils out for petroleum-burning furnaces in this temperature range, yet that configuration is still 2.6 times more expensive than thermal batteries and 1.7–2.1 times more expensive than RE-powered electric resistance furnaces (Figure 16). The LCOH of gas furnaces is 1.5–2.3 times higher than that of RE-powered heating.

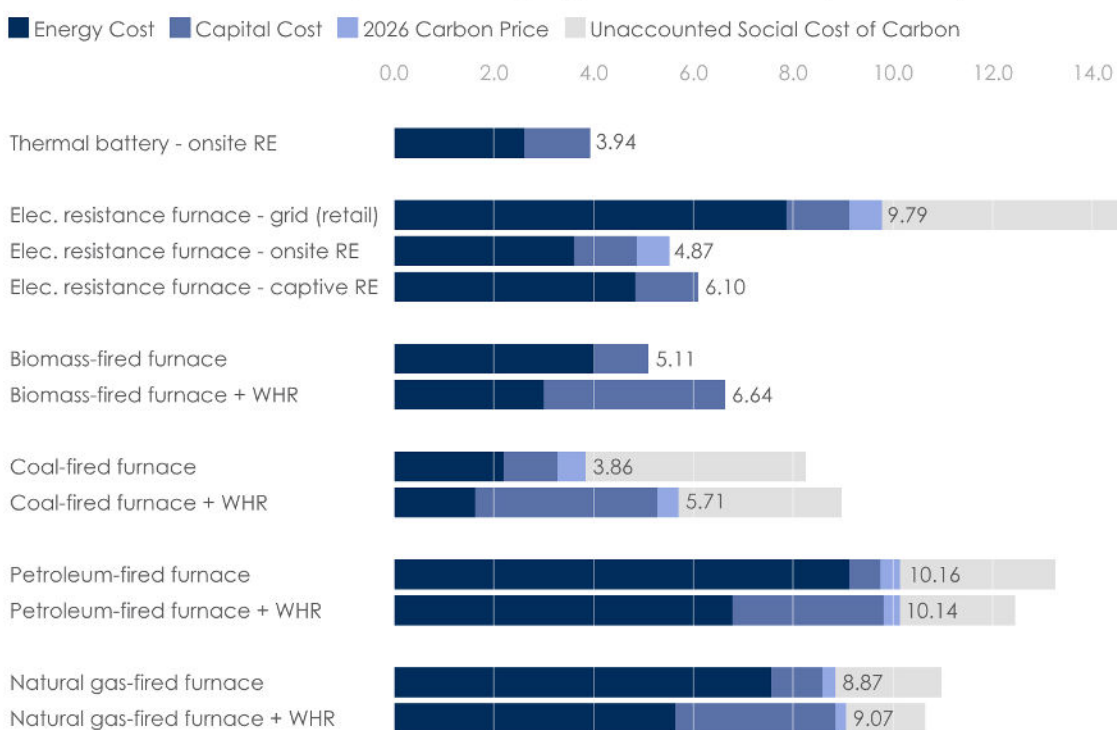
Although electrification does not out-compete coal at this temperature range, thermal batteries powered by cheap on-site solar get close, at ₹3.94/kWh_{th} compared to ₹3.86/kWh_{th} for coal furnaces, and they cost 23 percent less than biomass combustion. However, thermal batteries that deliver heat above 500°C are still in development today and may not be compatible with certain industrial processes (e.g., primary steel production, which requires a chemical agent or electrolysis to reduce iron ore).

Electric resistance furnaces are well-suited for a wide range of high-temperature processes but have a higher LCOH than thermal batteries, either because they must pair on-site solar with battery storage for continuous heat or because they incur wheeling charges for grid-delivered captive RE. Electric resistance furnaces only outcompete biomass combustion when powered by on-site RE, and they do not outcompete coal combustion no matter the electricity source.

If the carbon price were to reflect the social cost of carbon, emissions-free solar-powered heating would outcompete all fossil fuels, especially petroleum and natural gas. But in that scenario, electric resistance furnaces powered by India's coal-heavy grid would be the most expensive option, at ₹14.75/kWh_{th}.

Figure 16

Levelized Cost of Heat by Technology Type, 500-1,000 °C (Rs/kWh_{th})



Notes: 1) In the case of electric resistance furnaces, "onsite RE" refers to onsite solar plus battery storage to enable continuous use of heat. 2) In the case of thermal batteries, which are themselves energy storage technologies, "onsite RE" refers to onsite solar without battery storage. 3) "Captive RE" refers to consumer-owned and grid-delivered captive solar plus battery storage, where the consuming entity holds an equity stake of at least 26% in the plant, the plant provides over 51% of its energy to its owners, and the consuming entity pays transmission and distribution costs. 4) WHR stands for waste heat recovery. 5) All costs are adjusted for equipment efficiency to reflect the cost of delivered heat. 6) Capital costs are annualized over a 26-year equipment lifetime using an 11 percent discount rate. 7) The light blue bar represents the cost of complying with India's carbon intensity threshold, assuming firms exceed that threshold and a compliance credit costs \$10/tCO₂e. 8) The light gray bar represents the additional incremental carbon cost if it reflected India's social cost of carbon of \$86/tCO₂e. 9) The total LCOH of each configuration, including energy, capital, and carbon costs but not the unaccounted social cost of carbon, is listed to the right of the relevant blue bars.

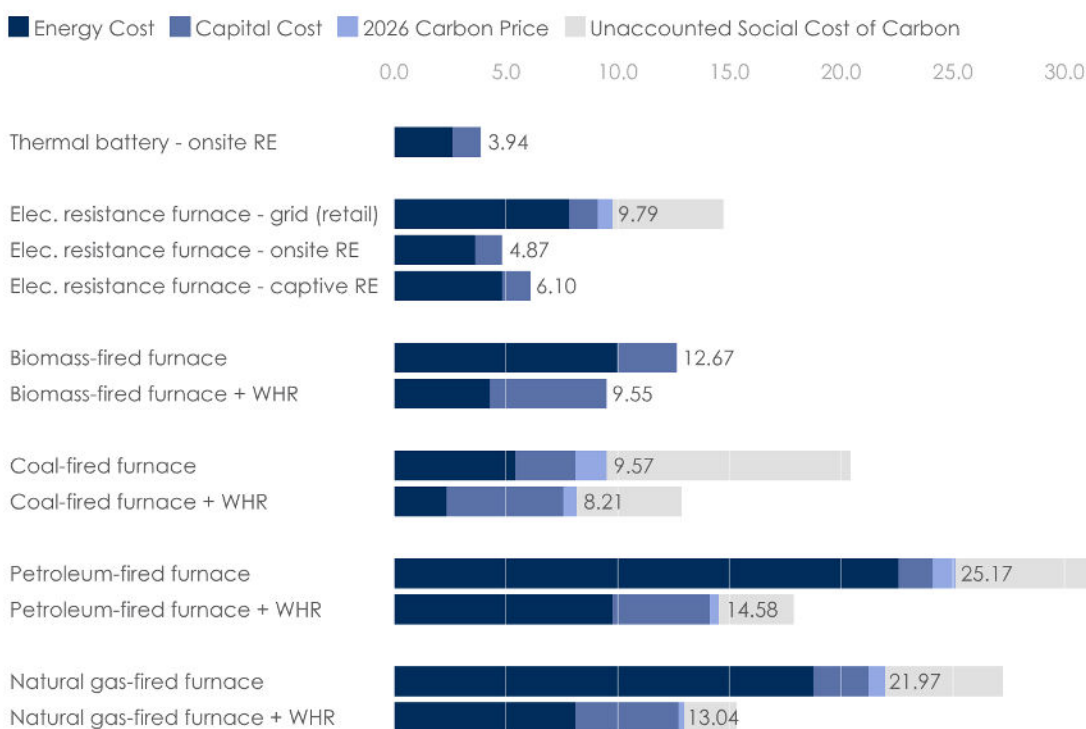
Combustion furnace efficiencies plummet even more at the highest temperatures that industry uses for bulk heating today, tipping the scales even further in favor of

electrification. While WHR pencils out for all combustion technologies from 1,000°C to 1,800°C, it does not deliver enough savings for any combustion technology to outcompete solar-powered heat (Figure 17). RE-powered thermal batteries and electric resistance furnaces cost 26-52 percent less than coal combustion with WHR and 36-59 percent less than biomass combustion with WHR. When compared to petroleum- and gas-fired furnaces with WHR, all electric technologies—even grid-powered electric resistance furnaces—are competitive.

At these high temperatures, India's carbon price need not account for the social cost of carbon for RE-powered electric technologies to compete. For example, even without that extra carbon cost, electric resistance furnaces powered by on-site solar and battery storage are 41 percent cheaper than coal combustion with WHR. But accounting for the full social cost of carbon would further promote electrification, boosting that cost advantage to 62 percent below the cost of WHR-equipped coal combustion.

Figure 17

Levelized Cost of Heat by Technology Type, 1,000-1,800 °C (Rs/kWh_{th})



Notes: 1) In the case of electric resistance furnaces, "onsite RE" refers to onsite solar plus battery storage to enable continuous use of heat. 2) In the case of thermal batteries, which are themselves energy storage technologies, "onsite RE" refers to onsite solar without battery storage. 3) "Captive RE" refers to consumer-owned and grid-delivered captive solar plus battery storage, where the consuming entity holds an equity stake of at least 26% in the plant, the plant provides over 51% of its energy to its owners, and the consuming entity pays transmission and distribution costs. 4) WHR stands for waste heat recovery. 5) All costs are adjusted for equipment efficiency to reflect the cost of delivered heat. 6) Capital costs are annualized over a 26-year equipment lifetime using an 11 percent discount rate. 7) The light blue bar represents the cost of complying with India's carbon intensity threshold, assuming firms exceed that threshold and a compliance credit costs \$10/tCO₂e. 8) The light gray bar represents the additional incremental carbon cost if it reflected India's social cost of carbon of \$86/tCO₂e. 9) The total LCOH of each configuration, including energy, capital, and carbon costs but not the unaccounted social cost of carbon, is listed to the right of the relevant blue bars.

CO₂ and Non-GHG Pollutant Emissions

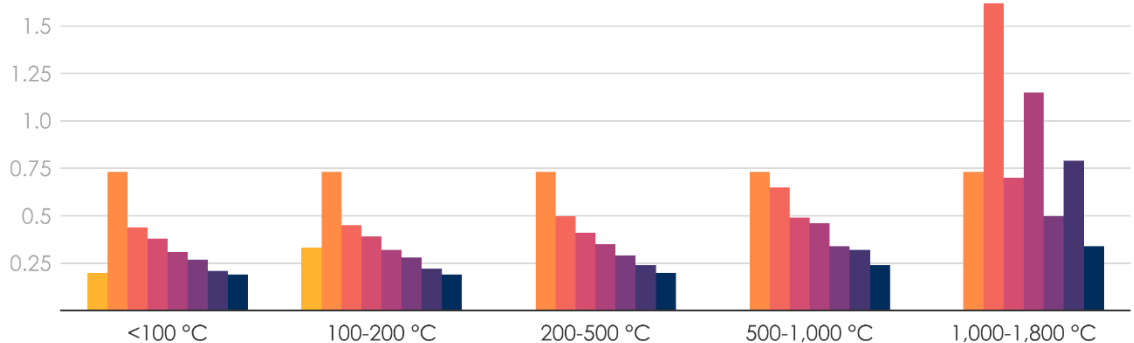
Our model also compares CO₂ emissions per unit of delivered heat across grid-powered and fossil fuel-fired technologies, finding that grid-powered electric resistance technologies are consistently the highest-emitting configurations at all temperature ranges up to 1,000°C, given India's coal-heavy grid (Figure 18). (They also have the same efficiency at all temperatures and thus a consistent emissions intensity of 0.73 kg CO₂/kWh_{th}.) Grid-powered heat pumps avoid this problem by being highly efficient, making them the lowest-emitting configuration under 100°C. Although their efficiency decreases at higher output temperatures, it is high enough that they only produce around 0.33 kilograms (kg) of CO₂ per kWh_{th} between 100°C and 200°C, less than the 0.45 kg CO₂/kWh_{th} produced by coal-fired boilers and the 0.73 kg CO₂/kWh_{th}

produced by grid-powered electric boilers at those temperatures. These numbers are a snapshot given India's present-day electric grid composition. As India's grid becomes more decarbonized in the future, the emissions intensities of grid-powered heat pumps and electric resistance boilers and furnaces will decline.

Figure 18

CO₂ Emissions Per Unit of Delivered Heat by Technology Type (kg CO₂/kWh_{th})

Heat pumps - grid Electric resistance equipment - grid Coal-fired equipment Coal-fired equipment + WHR Petroleum-fired equipment Petroleum-fired equipment + WHR Natural gas-fired equipment Natural gas-fired equipment + WHR



Notes: 1) RE-powered technologies are assumed to be emissions-free and are thus excluded from this figure. 2) Biomass is often omitted from CO₂ emissions inventories, and an assessment of its impacts requires a life cycle analysis that accounts for land use impacts, so biomass is also excluded from the figure. 3) WHR stands for waste heat recovery.

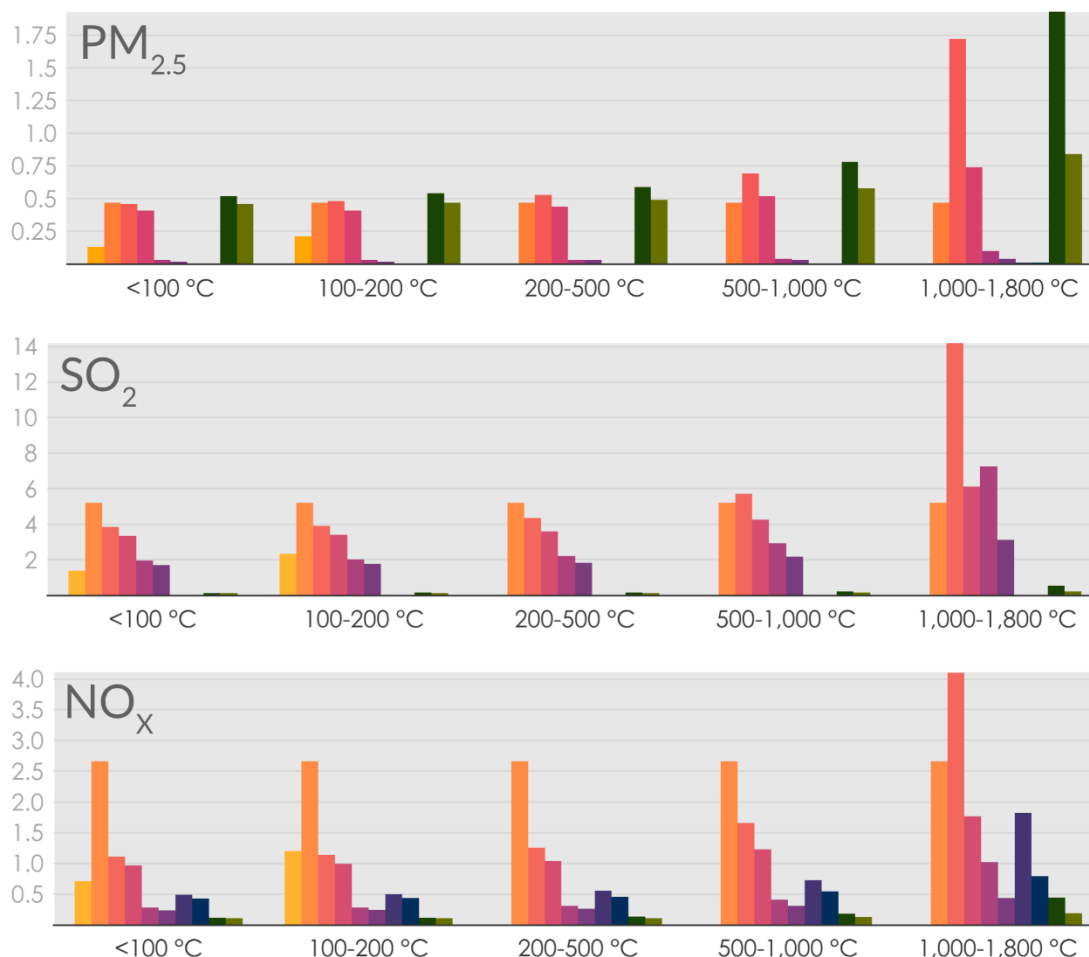
Emissions intensities for fossil fuel-fired equipment are only slightly higher at temperatures between 200°C and 500°C, since their efficiencies decrease only slightly. But their emissions intensities increase much more at higher temperatures, with emissions from coal-fired furnaces (0.65 kg CO₂/kWh_{th}) approaching that of grid-powered electric furnaces in the 500°C–1,000°C band. Meanwhile, emissions from petroleum- and gas-fired furnaces rise 31 percent higher (to 0.46 kg CO₂/kWh_{th} and 0.32 kg CO₂/kWh_{th}, respectively) in that temperature band compared to the previous one. At the 1,000°C–1,800°C range, the low efficiencies of fossil fuel equipment increase the emissions intensity of coal- and petroleum-fired equipment far beyond that of electric furnaces (1.62 kg CO₂/kWh_{th} and 1.15 kg CO₂/kWh_{th}, respectively), while the emissions intensity of gas-fired equipment (0.79 kg CO₂/kWh_{th}) exceeds that of grid-powered electric furnaces.

The same equipment efficiency trends also impact the emissions of non-GHG pollutants per unit of delivered heat across grid-powered and fossil fuel-fired configurations (Figure 19). However, the emissions intensity of each energy source is different for each non-GHG pollutant than it is for CO₂.

Figure 19

Conventional Pollutant Emissions Per Unit of Delivered Heat by Technology Type (g/kWh_{th})

■ Heat pump - grid ■ Elec. res. boiler or furnace - grid ■ Coal-fired boiler or furnace ■ Coal-fired boiler or furnace + WHR ■ Petroleum-fired boiler or furnace ■ Petroleum-fired boiler or furnace + WHR ■ Natural gas-fired boiler or furnace ■ Natural gas-fired boiler or furnace + WHR ■ Biomass-fired boiler or furnace ■ Biomass-fired boiler or furnace + WHR



Notes: 1) RE-powered technologies are assumed to be emissions-free and are thus excluded from this figure. 2) WHR stands for waste heat recovery.

Grid-powered electric resistance equipment emits 0.47 g PM_{2.5}/kWh_{th} at every temperature range, making it the highest emitting option for heat under 100°C. Grid-powered heat pumps emit 27 percent of those PM_{2.5} levels at low temperatures and 45 percent of them at temperatures between 100°C and 200°C. Coal-fired equipment produces the most PM_{2.5} at every temperature above 100°C, ranging from 0.48 g

PM_{2.5}/kWh_{th} to 1.72 g PM_{2.5}/kWh_{th}. Petroleum- and gas-fired boilers emit a comparatively small or even negligible amount.

Grid-powered electric resistance equipment emits 5.22 g SO₂/kWh_{th} at every temperature range, making it the highest emitting option for heat under 500°C. Grid-powered heat pumps emit comparatively less (by the same percentages as for PM_{2.5}). However, coal inches ahead at higher temperatures, reaching 5.72 g SO₂/kWh_{th} at the 500°C–1,000°C range and reaching 14.18 g SO₂/kWh_{th} at the 1,000°C–1,800°C range. Petroleum-fired equipment is also responsible for some SO₂ emissions, ranging from 1.97 g SO₂/kWh_{th} at the lowest temperatures to 7.27 g SO₂/kWh_{th} (higher than those from grid-powered electric) equipment at the highest temperatures. As with particulates, SO₂ emissions from natural gas-fired equipment are negligible at all temperatures.

Grid-powered electric equipment emits 2.66 g NO_x/kWh_{th} at every temperature range, making it the highest emitting option for heat at most temperatures, only exceeded by coal at the highest temperatures. Heat pumps using grid electricity produce significantly more NO_x per unit of delivered heat than petroleum- or gas-fired equipment, but they still produce less NO_x than coal-fired equipment under 100°C and only slightly more between 100°C and 200°C. Among fossil fuel-fired equipment, coal-fired equipment is the biggest NO_x emitter (ranging from 1.11 g NO_x/kWh_{th} to 4.10 g NO_x/kWh_{th}), followed by gas-fired equipment (ranging from 0.49 g NO_x/kWh_{th} to 1.82 g NO_x/kWh_{th}) and petroleum-fired equipment (ranging from 0.28 g NO_x/kWh_{th} to 1.02 g NO_x/kWh_{th}).

These results show that grid-powered electric technologies can typically only reduce CO₂ and non-GHG pollutant emissions if they are much more efficient (e.g., low-temperature heat pumps and very high-temperature electric resistance equipment) than their counterparts. In other cases, grid-connected electric heating technologies could actually worsen emissions, especially if power sector decarbonization lags. Until India phases out significantly more coal power plants in favor of renewable energy, electrification using on-site or wheeled captive renewable energy is a much more reliable way to reach climate targets and protect public health.

IMPACTS OF ELECTRIFICATION ON ENERGY USE AND CO₂ EMISSIONS

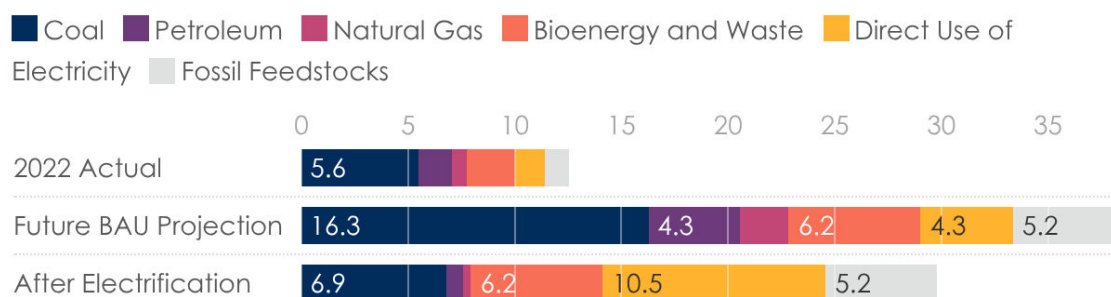
The impacts of electrification of India's industrial sector were modeled using the Industrial Transformation Technology and Investment Model (ITTIM) v1.1.0,⁴ an open-source tool for estimating the impacts of industrial energy transition pathways on outputs including energy use, CO₂ and non-GHG pollutant emissions, energy expenditures, capital investment needs, and more. The ITTIM was recently used in a

flagship report by the World Bank¹²¹ to model industrial decarbonization pathways and impacts across the East Asia-Pacific region. In modeling for this report, the ITTIM measured the collective impact of electrification approaches on energy use, emissions, and public health impacts across India’s entire industrial sector. For the purposes of this report, we did not model additional ITTIM-supported decarbonization strategies such as material efficiency measures, clean hydrogen usage, or CCS.

The ITTIM uses data for India from 2022, when industrial energy use was 12.6 exajoules (EJ) (Figure 20). In a business-as-usual (BAU) scenario, the model projects that annual energy use will more than triple to 38.6 EJ by 2070—of which 16.3 EJ are fueled by coal—to serve growing demand for goods as India continues to industrialize. Industrial electrification measures would reduce this future usage by 22.6 percent to 29.9 EJ annually.

Figure 20

Annual Industrial Energy Use by Energy Type in India (EJ)

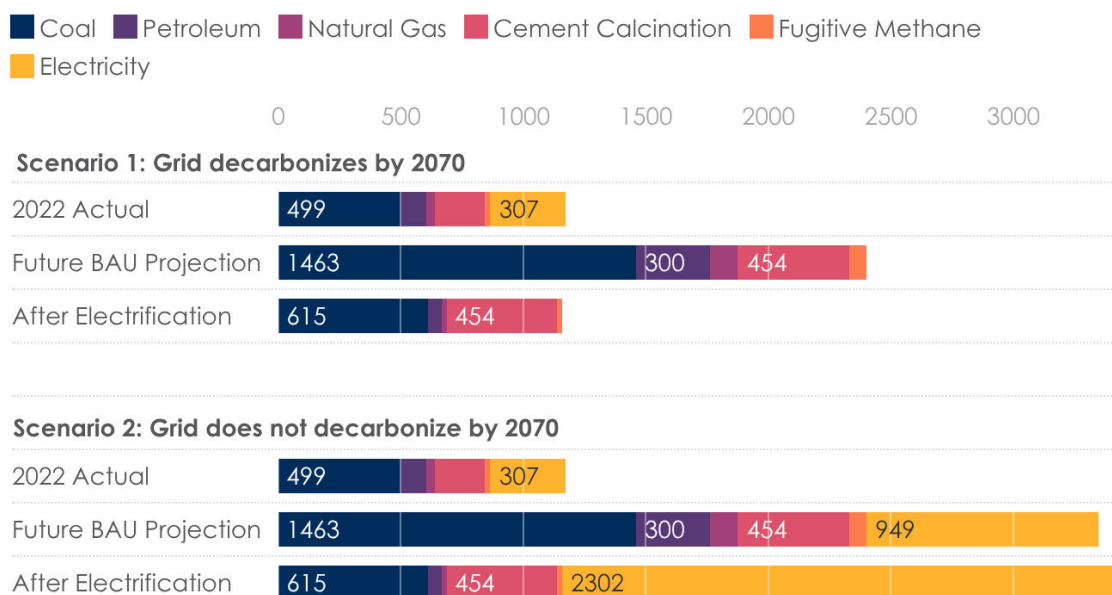


Notes: 1) Data come from Rissman, et al. (2026). *The Industrial Transformation Technology and Investment Model, version 1.1.0. Energy Innovation.* <https://energyinnovation.org/report/the-industrial-transformation-technology-and-investment-model/> 2) The first two bars show industrial energy use in 2022 followed by a projection of industrial energy use in 2070 if industry continues on its current path. 3) The last bar demonstrates how future industrial energy use would change if electrification were applied wherever possible, including electrification of low- to high-temperature heat, electrification of non-thermal processes, and shifting primary steelmaking to secondary steelmaking.

Electrification’s energy use reduction is accompanied by a similar reduction in industrial CO₂ emissions (Figure 21). Historical industrial non-feedstock emissions were 1,175 MMT of CO₂ in 2022 and were projected in future BAU and electrification scenarios to be 2,404 MMT and 1,161 MMT, respectively, yielding a 51 percent emissions reduction from industrial electrification. Note that these numbers are predicated on electrification supported by clean energy sources; in the event that industrial electrification is grid-powered and the grid mix remains unchanged from today, then emissions from the future BAU and electrification scenarios would be 3,353 MMT and 3,479 MMT, respectively, as seen in Figure 21’s scenario 2.

Figure 21

Annual Industrial CO₂ Emissions by Energy Type in India (MMT CO₂)



Notes: 1) Data come from Rissman, et al. (2026). The Industrial Transformation Technology and Investment Model, version 1.1.0. Energy Innovation. <https://energyinnovation.org/report/the-industrial-transformation-technology-and-investment-model/> 2) The first two bars in each scenario show industrial energy use in 2022 followed by a projection of industrial CO₂ emissions in 2070 if industry continues on its current path. 3) The last bar in each scenario demonstrates how future industrial CO₂ emissions would change if electrification were applied wherever possible, including electrification of low- to high-temperature heat, electrification of non-thermal processes, and shifting primary steelmaking to secondary steelmaking. 4) Both scenarios assume electricity comes from the grid. In scenario 1, the grid decarbonizes by 2070. In scenario 2, the grid stays on its current path. Electricity emissions would be lower in scenario 2 if some electrification were powered by on-site or captive renewables.

PUBLIC HEALTH IMPACTS OF INDUSTRIAL ELECTRIFICATION

The ITTIM⁴ also supports the modeling of non-GHG pollutant emissions and public health impacts. Industrial electrification is shown to reduce PM_{2.5} emissions by 38.4 percent, SO₂ emissions by 60.9 percent, and NO_x emissions by 53.7 percent (Table 3).

Table 3**Conventional Pollutant Emissions by Energy Type for Historical, Future BAU, and Industrial Electrification Scenarios (thousand tonnes)**

Energy Type	Coal & Coke	Petroleum	Natural Gas	Bioenergy & Waste	Total
PM2.5 Emissions					
2022 Actual	530	10	1	295	835
Future BAU	1,554	27	2	823	2,406
After Electrification	653	5	0	823	1,482
Reduction from Electrification					38%
SO2 Emissions					
2022 Actual	4,379	680	0	24	5,082
Future BAU	12,838	1,905	1	66	14,810
After Electrification	5,395	331	0	66	5,792
Reduction from Electrification					61%
NOx Emissions					
2022 Actual	1,268	96	83	209	1,656
Future BAU	3,716	268	268	584	4,837
After Electrification	1,562	47	47	584	2,239
Reduction from Electrification					54%

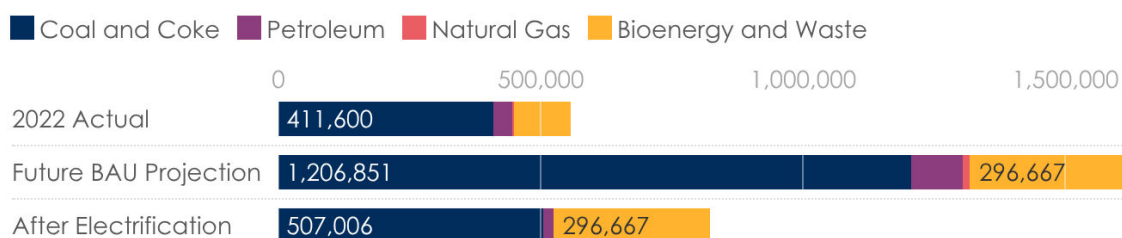
Notes: 1) Emissions represent direct emissions from fuel combustion at industrial facilities and do not include indirect emissions from purchased electricity. 2) Data come from Rissman, et al. (2026) *The Industrial Transformation Technology and Investment Model*, version 1.1.0. Energy Innovation. <https://energyinnovation.org/report/the-industrial-transformation-technology-and-investment-model/>

These emissions reductions have enormous ramifications for public health. Industrial electrification is estimated to save around 794,000 lives per year when compared to the future BAU scenario, reducing annual mortality from industrial air pollution by almost half (Figure 22). While estimates of the value of a statistical life in India vary widely, a frequently used¹²²⁻¹²⁴ value of US\$0.64 million, originally derived using the hedonic wage method,¹²² provides a middle ground estimate. Using this value, the

annual cost of mortality from air pollution averted by industrial electrification is over US\$508 billion, or over ₹47 trillion.

Figure 22

Deaths Caused Annually by Industrial Air Pollution by Energy Type in India (Deaths per year)



Notes: 1) Data come from Rissman, et al. (2026). *The Industrial Transformation Technology and Investment Model, version 1.1.0. Energy Innovation*. <https://energyinnovation.org/report/the-industrial-transformation-technology-and-investment-model/> 2) The first bar shows deaths caused annually by industrial energy use in 2022 followed by a second bar showing deaths caused annually by projected industrial energy use in 2070 if industry continues on its current path. 3) The last bar demonstrates how those future annual deaths would change if electrification were applied wherever possible, including electrification of low- to high-temperature heat, electrification of non-thermal processes, and shifting some primary steelmaking to secondary steelmaking.

Industrial air pollution has severe morbidity impacts as well. Compared to the future BAU scenario, the ITTIM projected that industrial electrification reduced incidence of a range of adverse air pollution health outcomes by 48 to 50 percent, averting 321,000 nonfatal heart attacks, more than 1.73 million new asthma cases, nearly 32,000 new lung cancer cases, and over 27,000 strokes annually.⁴

POLICY RECOMMENDATIONS

Industrial electrification could be a triple-win for India, helping the government to achieve its climate targets, improving industry’s long-term economic resilience, and protecting India’s population from the dangers of toxic air pollution and climate change. However, despite the record-low costs of solar energy that India is experiencing today, industrial firms face a range of barriers to adopting electric heating technologies, leaving the immense benefits of industrial electrification on the table. Fortunately, a range of policy options can work together to overcome these barriers, unlocking the rapid scale-up of electrified technologies across Indian industry.

POLICIES TO INCREASE INDUSTRIES’ ACCESS TO LOW-COST SOLAR

As our analysis shows, much of India’s industrial process heat can be electrified at reasonable costs. However, not all firms are aware of this opportunity, and not all firms

can access the record-low solar tariffs India has seen in recent years. A few straightforward policies can address these challenges and supercharge electrification of Indian industry at little cost to India's government.

Streamline Open Access Rules

One key way industrial firms can access low-cost solar is direct procurement via power purchase agreements or captive solar, made easier by India's recently updated GEOA rules.¹⁶ Industry has expressed growing interest in captive solar,¹²⁵ and further simplification, standardization, and diligent implementation of the GEOA rules could expand firms' access to it.

For example, to support electrification of industries outside of solar-rich regions, India's existing waiver on interstate transmission charges could be extended beyond 2025 (e.g., to 2030) and the eligibility criteria for mid-sized customers (100 kilowatt to 1 megawatt) could be adjusted to allow firms outside of a power plant's regulated service area to source energy from that plant. Additionally, the central government could improve coordination with state governments to ensure state compliance with national rules, reduce discrepancies in state-level charges and settlement periods, and ensure the Green Open Access Registry portal includes adequate data from DISCOMs and state-level agencies. Finally, banking provisions—which require DISCOMs to credit surplus renewable energy for later offset within the banking period—can be standardized (e.g., banking periods and charges) and expanded to enable 24/7 renewable energy use.¹⁶

Integrate Industrial Electrification with Energy System Planning

Improved open access rules will only help industrial firms if they can physically connect to solar generation facilities (in the absence of widespread long-distance transmission). Government entities can facilitate industry's proximity to solar plants by considering industrial electrification opportunities in broad energy system planning. For example, the central government can site new solar parks or grid upgrades in areas where those opportunities are clustered, and state renewable energy nodal agencies can support the establishment of industrial parks that co-locate solar generation and electrified industry. In addition to providing land, common infrastructure, permits, and coordination support for industrial parks, state agencies could consider implementing shared heating systems like renewables-powered community boilers.

Accelerate Renewables Deployment

Not every firm can directly obtain solar energy from solar power plants. For example, some firms may lack the capital necessary to invest in captive solar, and others may be located far away from existing solar plants. These firms cannot easily electrify with

grid electricity, which not only is more expensive than off-grid electricity but also does not experience much intra-day price variation, meaning that firms cannot lower their electricity costs by price arbitraging with thermal batteries. Therefore, the best way to encourage these firms to electrify is to reduce the average costs of grid electricity, which can be achieved by increasing the deployment of renewable resources that produce very inexpensive energy at certain times of the day.

India has made impressive strides in scaling up solar and wind in the last couple of decades. Today, renewables account for half of the country's electricity generation capacity (though this represents only a quarter of the country's generation, since renewables have lower capacity factors than fossil plants).¹²⁶ More progress is needed. Project implementation barriers like difficulties acquiring land, misaligned transmission build-out, and the limited supply of affordable wind turbine and solar PV components are one key hurdle to scaling up renewables, but dedicated policies can help to overcome them.²³ To increase the availability of land for renewable energy projects, the central government can streamline the classification of wasteland on which projects could be sited and create more solar parks, while state governments can take more proactive roles in land aggregation and acquisition. To address current transmission needs while new transmission is being built, GoI can optimize existing transmission infrastructure by deploying grid-enhancing technologies (e.g., advanced conductors), swapping coal plants for solar to reuse the coal plant's interconnection and transmission infrastructure, and deploying batteries where transmission congestion is greatest. Finally, GoI can introduce more policies to support domestic manufacturing of renewable energy components (e.g., offering long-term policy certainty around existing incentives, supporting research and development of component technologies, and promoting international knowledge-transfer) to improve components' availability and affordability.

Beyond facilitating project implementation, policy interventions can also ensure sufficient "ecosystem enablers" exist for renewable energy scale-up, like adequate resource planning and procurement processes and the deployment of utility-scale energy storage.²³ To improve resource planning and procurement processes, the central government could make Renewable Purchase Obligations technology neutral, and states could create their own resource adequacy frameworks and align renewable energy implementation efforts with state-level procurement tenders and resource adequacy plans. In addition, GoI could support the deployment of grid-scale batteries by mandating that planned renewables projects include storage or by offering viability gap funding for batteries co-located with solar plants.

Reduce Electricity Cross-Subsidies

Even if greater renewables deployment reduces average grid electricity costs, electrification may still be out of reach for grid-connected firms due to Indian states' cross-subsidy policies, which require commercial and industrial electricity customers

to partially cover residential and agricultural electricity rates. Eliminating cross-subsidies for industrial customers that electrify their process heat would bring grid electricity prices more in line with off-grid electricity prices for industry and could therefore be a powerful tool for encouraging industrial electrification.

Fortunately, a process for phasing out cross-subsidies in India is already underway. The Electricity Act of 2003 mandated that State Electricity Regulatory Commissions progressively reduce cross-subsidies as they transition to electricity tariffs that reflect the cost of supply, and in 2016, the National Tariff Policy stated that cross-subsidies must be kept within 20 percent of the average cost of electricity supply.¹²⁷ However, cross-subsidies are proving challenging to eliminate in a context in which DISCOMs are facing increasing costs of service and declining revenues (due in part to commercial and industrial firms switching to off-grid resources).

One policy solution is to change how electricity rates are subsidized, something India has already begun pursuing with its Direct Benefit Transfers for Power (DBT-P) policy.¹²⁷ Under this policy, DISCOMs can set electricity tariffs at the cost of service and use funding from the state government to offer rebates to customers that need it. But certain challenges have prevented DBT-Ps from scaling, including limited space in state budgets to cover these subsidies, political resistance, the poor cash flow of DISCOMs, a lack of transparent and accurate energy metering data, and the overuse of electricity among cross-subsidized customers.¹²⁸ The central government could help to overcome these challenges by legally requiring states to offer DBT-P funding and strictly enforcing the requirement that states pay the subsidy before DISCOMs begin supplying power. Meanwhile, states can limit the overall subsidy amount by targeting subsidies to customers that need it the most (e.g., by mapping customers according to socioeconomic and electricity consumption data), improving energy consumption measurements (e.g., deploying smart meters), and improving estimates for unmetered customers.¹²⁷

Other policies can help cover the gap between DISCOMs' cost of service and revenues, reducing the need for subsidies to cover the gap. Measures to lower electricity supply costs include policies to accelerate renewables deployment (explored earlier), policies to allow renegotiation of expensive coal power contracts that many DISCOMs are locked into, funding to support the deployment of smart metering and grid-enhancing technologies to reduce system losses, and incentives for households and farms to use off-grid resources (thus curbing demand-side load growth). To bolster DISCOM revenues, policymakers can support the deployment of feeder metering (adding meters to high-voltage lines leaving substations, which can help reduce electricity losses by enabling DISCOMs to quickly identify technical faults or electricity theft) and end-user smart meters that improve electricity billing.¹²⁷

Launch Awareness-Raising Campaigns

Industrial electrification opportunities are not well-known or understood among Indian firms, not only because industry has received less attention than the power and transportation sectors in climate efforts thus far, but also because no other regions of the world have demonstrated industrial electrification at meaningful scale (due in part to the limited availability of low-cost clean electricity in other regions).

Government agencies, in partnership with industry associations and industry sector experts, can launch campaigns to educate Indian firms about the commercial availability of electrified equipment, the economic viability of industrial electrification, and existing policy measures to further boost the solution's economic and practical viability. These campaigns can include workshops, one-on-one consultations with firms, and the provision of informational materials (e.g., toolkits and case studies highlighting successful industrial electrification projects).

POLICIES TO DRIVE ADOPTION OF CLEAN INDUSTRIAL TECHNOLOGIES

Our analysis shows that electrification cannot outcompete coal combustion when powered by retail electricity from the grid, or at temperatures between 200-500°C even when powered by low-cost solar. And electrification may sometimes be more expensive than our analysis suggests, since real-world energy prices, equipment costs, equipment characteristics, and discount rates could in some cases differ from our assumptions. Moreover, even when electrification is cost-competitive with fossil fuel combustion per unit of delivered heat, obstacles like high upfront costs and organizational inertia can still stand in the way of electrification.

Policies that fairly price fossil fuel use, subsidize clean manufacturing, mandate reductions in industrial energy consumption or emissions, and offset the up-front costs of clean industrial equipment can rebalance the scales, ensuring industry's widespread adoption of renewables-powered electric heating equipment. GoI could launch a Clean Heat Mission—similar to the National Solar Mission—to coordinate (e.g., phase) these policies and thus increase their effectiveness. Policy support could be targeted at industrial clusters or parks, where shared infrastructure lowers costs and financial risk, to increase its likelihood of success.

Policies to Fairly Price Fossil Fuels

While low-cost solar can make electrification cost-effective for many industrial firms, electrification would present an even more compelling opportunity for a greater number of firms if the price of fossil fuels reflected their social costs. Combusting coal, natural gas, and petroleum does not just emit GHGs that undermine climate targets and risk environmental disasters—it also releases non-GHG pollutants that cause millions of premature deaths every year in India. India's forthcoming carbon market

should ensure that firms pay for the social costs of GHG emissions, which will make solar-powered electrification (which emits zero GHGs or non-GHG pollutants) even more cost-competitive with fossil fuel combustion.

India's government has taken impressive steps to retract fossil fuel subsidies, reducing oil and gas subsidies by 85 percent between 2013 and 2023.¹²⁹ Removing the remaining subsidies, worth US\$3.5 billion in 2023, will be another important step toward social-cost-reflective fossil fuel prices.

Production-Linked Incentives for Clean Commodities

Where there is still a cost premium for electric heat, policymakers can encourage industry to adopt electric technologies by subsidizing the clean production of commodities like steel, cement, and ammonia. Commodities, or fungible goods, represent the lion's share of India's industrial energy use and emissions. They are also homogenous and standardized across manufacturers, allowing for consistent and fair comparison of emissions reductions across producers.

A production-linked incentive (PLI) for clean commodities can reward reductions in "embodied emissions," or emissions generated in the production of commodities. The PLI could compare the embodied emissions of a given firm's product, measured in tonnes of GHG per tonne of product, to a predetermined baseline. To avoid the complexity and resource intensity of conducting life-cycle analyses, policymakers can estimate the embodied emissions of a given firm's product based on the energy type used in the manufacturing process (as reported by the firm) and that energy source's emissions profile.

In establishing emissions profiles for different energy sources, policymakers should include Scope 1 emissions from on-site fuel combustion but exclude Scope 2 emissions from upstream electricity production, which will encourage electrification and simplify emissions accounting. Moreover, industry is most likely to electrify using clean energy, since on-site or wheeled captive solar costs are 39 to 68 percent less than grid electricity per kilowatt-hour in India (Figure 9). Finally, emissions from grid-based electrification are likely to decrease over time as India's grid decarbonizes, so delaying electrification to avoid some emissions in the near term risks firms deploying new fossil-fueled equipment that will run for decades, worsening the long-term prospects for emissions reductions in manufacturing.

A commodity's baseline should reflect the average embodied emissions of that commodity in a given air regulatory jurisdiction within India. In jurisdictions with strict air pollution regulations, manufacturers are more likely to burn natural gas or petroleum than coal, reducing those regions' baseline emissions relative to regions without such regulations. If the baseline does not vary by region, the policy risks rewarding firms for using natural gas or petroleum when regulations would have pressured them to do so anyway.

Standards on Industrial Energy Consumption and Emissions

Even when industrial electrification is economically viable and firms are aware of its benefits, they may choose not to electrify their processes for organizational and behavioral reasons, like competing priorities at the firm level, workers' familiarity with conventional processes, and split incentives (i.e., a firm leases rather than owns its facilities). Standards are the best policy mechanism to overcome these barriers, mandating a shift to cleaner equipment or processes.

Energy efficiency standards are one option, but they must be very stringent to drive electrification, since modern fossil-fueled process heating equipment can be highly efficient. Equipment-level energy efficiency standards are common globally, and India's Standards & Labeling program could be expanded to include all industrial heating equipment, beyond packaged boilers. Facility-level standards could drive important energy efficiency changes beyond electrification, like rightsizing pipes and equipment to streamline material flows. However, India is currently transitioning away from facility-level energy efficiency standards that were established under the PAT policy towards facility-level emissions intensity standards within the CCTS. Emissions standards can be more impactful than energy efficiency standards by directly limiting the GHGs that firms can emit per unit of output produced, and they can also cover non-GHG pollutants like SO₂, NO_x, and PM. Under the CCTS, India is setting facility-level CO₂ and perfluorocarbon limits per tonne of output for nine industries already regulated under PAT, including steel, cement, fertilizers, and textiles. GoI should consider expanding the CCTS to other manufacturing industries, like food and beverage, as well as non-metallic minerals other than cement (e.g., brick, glass, ceramics).

GoI could also consider implementing a clean heat obligation, mandating that a minimum share of an industrial firm's process heat come from low-carbon sources like clean electricity, similar to Renewable Consumption Obligations in the power sector. This policy would not require new legislation, since the Energy Conservation (Amendment) Act of 2022 already authorizes GoI to mandate that the industry, buildings, and transportation sectors consume a minimum share of their energy from non-fossil sources.⁴⁵

The CCTS' emissions intensity limits and any other standards to promote clean industry should become more stringent over time, ideally based on a predetermined schedule aligned with the typical lifespan of industrial equipment. This policy element will de-risk firms' investments and ensure that they have sufficient time to plan facility retrofits and upgrades. Technology-neutral standards that allow firms to choose any equipment that meets the policy's energy efficiency or emissions requirements are economically efficient, giving firms the flexibility to choose the option that best meets their technical and financial needs. Still, policymakers may wish to implement a standard that implicitly encourages firms to electrify rather than use carbon capture

or low-carbon fuels (e.g., a 95 percent energy-efficiency requirement for industrial heating equipment).

Capital Cost Support

Capital costs represent a small portion of the lifetime costs of industrial equipment (e.g., 3 percent in the case of natural gas boilers in the U.S.).¹³⁰ Still, firms may lack sufficient capital to pay those costs up front, making direct funding and financing support important levers for encouraging the adoption of electric heating equipment. Both forms of support could be provided directly to firms or to energy service companies that design, implement, and help finance equipment upgrades at industrial facilities.

Direct funding support could include grants or tax credits that offset a portion of the installation costs of electric heating equipment. Such policies could build on existing capital cost subsidies for “modernized” industrial equipment, such as the Credit Linked Capital Subsidy Scheme for Technology Upgradation in MSMEs³⁶ and the Textile Upgradation Fund Scheme,³⁷ amending those policies to explicitly target electric heating technologies and expanding them beyond MSMEs and the textile industry. Alternatively, GoI could create a new subsidy scheme modeled on these existing ones, targeting electrification of all industrial subsectors. Additional tax incentives, such as Goods and Services Tax (GST) exemptions and accelerated depreciation for electric heating equipment, could further offset the capital costs of electrification.

To finance the remaining capital costs, firms without sufficient internal capital must seek external financing. However, investors may perceive electric heating technologies as risky or unproven and therefore be reluctant to invest. Government entities like IREDA (or quasi-public institutions like green banks) can either invest directly in industrial electrification projects (e.g., offer traditional or concessional loans, or take an equity stake), co-lend with private investors, or subsidize the interest rates of private loans, potentially drawing on credit lines from international financing institutions. They can also de-risk private investments in industrial electrification by bundling multiple small loans to spread their risk among investors, or offering credit guarantees, loan loss reserves, or first loss protection.

Capital cost support may be even more successful when used to promote the use of innovative business models. “Heat as a service” (HaaS) models, for example, place the burden of financing, installing, and maintaining heating equipment on technology providers or energy service companies, which earn compensation from technology users for the heat that the equipment provides. This model encourages industrial firms to adopt clean heating equipment by eliminating upfront costs that firms would otherwise face, lowering workforce upskilling requirements, and reducing financial risk, and it benefits technology providers by expanding the market for their products.

ENABLING POLICIES

Policies to Commercialize Clean Industrial Technologies

Although industrial heat pumps are already commercially available in India¹³¹ and other electric heating technologies like e-boilers and thermal batteries are available in global markets, further development of these technologies will improve their costs and performance (e.g., increase the temperatures they can reach).

Governments can support research, development, and demonstration of industrial electrification technologies in a variety of ways. For early-stage technologies, GoI could conduct its own research at public institutes like the Department of Science and Technology, launch public-private research partnerships with industrial firms and academia (akin to the Steel Research and Technology Mission of India), and fund applied research at private, academic, and nonprofit research institutions. For proven technologies that need real-world testing and validation to become commercially viable (e.g., to reduce performance risks), GoI can offer cost-sharing grants or technical assistance to support pilot and demonstration projects at industrial facilities. GoI can also partner with universities and industries to create dedicated test beds for clean industrial technologies, in the vein of India's Industry 4.0 centers.¹³²

Domestic Manufacturing Incentives

Once successfully demonstrated, technologies to electrify industry can reach the market only if there are firms that can manufacture and supply them. GoI can encourage domestic manufacturing of electric industrial heating equipment (e.g., heat pumps, e-boilers, thermal batteries) by offering PLIs, potentially modeled on existing PLIs for high-efficiency solar PV modules. GoI can also offer tax incentives to domestic manufacturers, like reduced corporate income tax rates, exemptions for customs or GST, or accelerated depreciation. Requiring that foreign firms wishing to sell novel technologies like thermal batteries in India establish in-country manufacturing facilities can help ensure the local workforce gains experience producing and maintaining this equipment while driving down its manufacturing costs.

Workforce Training and Development Policies

Transitioning industry to new technologies will require workers skilled in the installation, operation, and maintenance of those technologies. GoI can play an important role in upskilling students and existing industrial workers to meet the needs of clean industry. For one, it can incorporate industrial electrification curricula into India's existing industrial training institutes, which offer vocational training that prepares youth for careers in manufacturing or industrial trades.¹³³ GoI can also create educational and vocational training programs centered around industrial

electrification, whether university-based programs that train students off-site or apprenticeship programs that train them on-site. Governments can also partner with industrial firms to create upskilling programs for existing workers, and they can create tools and informational materials that keep workers up to date on the latest electrification technologies.

CONCLUSION

Industry will be critical to India's future, providing goods like steel, cement, cars, and textiles that the country needs to accelerate along its development path and pull millions out of poverty. However, Indian industry is at an energy crossroads—industrial coal use is blanketing cities in life-threatening smog, and other fossil fuels like oil and natural gas must be imported, driving up costs and exposing firms to global energy price volatility.

India's clean energy boom could not have come at a better time. With access to the world's lowest-cost solar and storage, Indian industry can preserve its competitiveness—today and in the future—by electrifying its processes. Our analysis finds that solar-powered industry can already compete with oil and gas combustion in almost all industrial processes, even when waste heat is recovered. It can even compete with coal combustion in some cases, like low-temperature processes that can use heat pumps or high-temperature processes where fuel combustion is highly inefficient.

Our analysis also finds that transitioning to solar-powered industry can avert nearly 794,000 premature deaths per year by reducing India's air pollution. Along with that cleaner air comes a carbon emissions reduction of 51 percent, getting India closer to its decarbonization goals without sacrificing economic development or competitiveness.

In industries that currently rely on expensive, imported fuels, industrial electrification can start today, though additional policy support can accelerate the transition. Accelerated solar development and open-access policy reforms, for example, can help more firms take advantage of low-cost solar. For industries that currently rely on coal, additional policy support is critical to drive clean energy adoption that cleans up the air. This support includes air pollution regulations, carbon pricing, and fossil fuel subsidy reforms that hold firms responsible for the negative impacts of their pollution, as well as subsidies that reward firms for manufacturing products cleanly.

With its record-low solar prices and limitations on fossil fuel use, India has a unique opportunity to be a global leader in clean industry. With targeted policies and deployment efforts, India can reap the economic, environmental, and public health benefits of solar-powered industry and set its economy up for success for decades to come.

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