



PATHWAYS FOR A LOW-EMISSION INDUSTRY FUTURE IN INDIA

Working Paper

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Table of Contents

1. Introduction	5
1.1. Context Setting	6
1.2. Literature Review	7
2. Rationale	11
3. Objectives	13
4. Research Question	15
5. Methodology	16
5.1. Iron and Steel Sector	17
5.1.1. <i>Technology Pathways Represented in the Model</i>	18
5.1.2. <i>Scenario Descriptions</i>	18
5.2. Cement Sector	19
5.2.1. <i>Technology Pathways Represented in the Model</i>	20
5.2.2. <i>Scenario Descriptions</i>	20
5.3. Aluminium Sector	21
5.3.1. <i>Technology Pathways Represented in the Model</i>	22
5.3.2. <i>Scenario Descriptions</i>	23
6. Key Insights	24
6.1. Iron and Steel Sector	24
6.2. Cement Sector	25
6.3. Aluminium Sector	26
7. Policy Recommendations	27
7.1. Reorienting Industrial Strategy from Efficiency to Structural Change	27
7.2. Creating Enabling Markets for Low Carbon Materials	28
7.3. Aligning Energy Infrastructure with Industrial Transition	28
7.4. Mobilising Finance for First Movers	28
7.5. Strengthening Circular Economy Frameworks	29
8. Conclusion	29
9. References	29

List Of Figures

Figure 1: Share Emissions by different sectors in FY 2021-22	5
Figure 2: Final Energy Consumption by different sectors in FY 2021-22	6
Figure 3: Technologies considered	7
Figure 4: Share of Technologies in Iron and Steel in FY 2021-22	8
Figure 5: Share of Technologies in Cement Sector in FY 2021-22	9
Figure 6: Share of Technologies in Aluminium Sector in FY 2021-22	10
Figure 7: Considered Rationale	12
Figure 8: Integrated Analytical Framework used	14
Figure 9: India's Sectoral Transition to a Low Emission Future	15
Figure 10: Industrial Decarbonisation Framework	16
Figure 11: Technologies in Iron and Steel under different scenarios	18
Figure 12: Share of Technologies for Iron and Steel under different scenarios	19
Figure 13: Technologies considered in Cement Sector	20
Figure 14: Cement Sector Technology Scenarios	21
Figure 15: Technologies Considered in Aluminium Sector	22
Figure 16: Cement Sector Technology Scenarios	23
Figure 17: Final Energy Demand for Iron and Steel Sector	24
Figure 18: Final Energy Demand for Cement Sector	26
Figure 19: Final Energy Demand for Aluminium Sector	27

1. Introduction

The industrial sector, which promotes urbanisation, constructs infrastructure, and boosts employment and GDP, is the cornerstone of India's economic expansion. The energy-intensive sub-sectors, such as cement, Aluminium, chlor-alkali (caustic soda and soda ash), iron and steel, and others, enhance India's competitive position in manufacturing, construction, and exports.

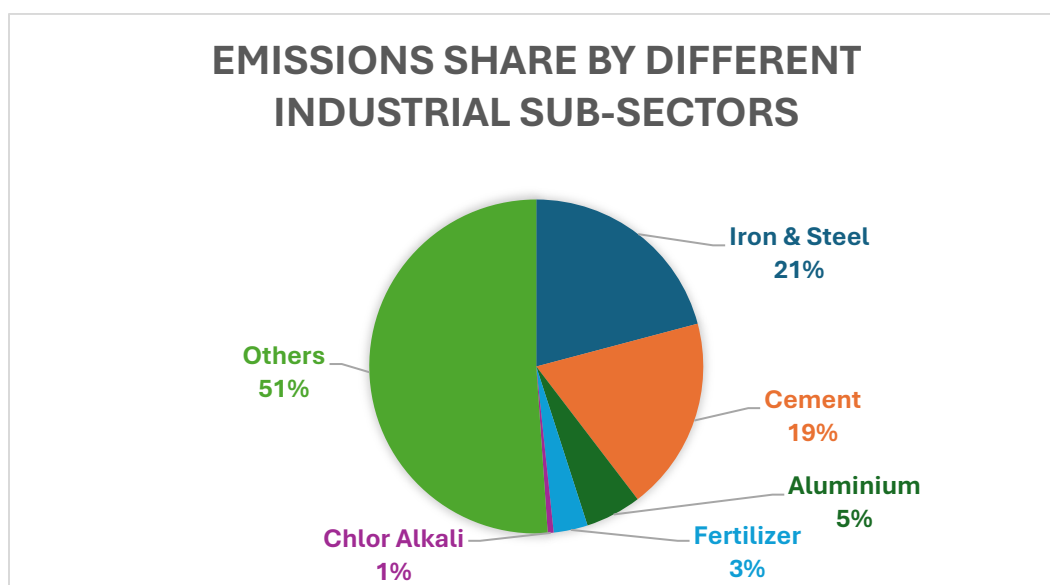


Figure 1: Share Emissions by different sectors in FY 2021-22

Approximately 35% of India's total final energy consumption was derived from the industrial sector, the second-largest energy-consuming sector after the power sector (IEA, 2023). The Industry Sector emitted approximately 803 million metric tonnes of CO₂e (MMtCO₂e), equivalent to 30 per cent of national emissions in 2019 (MoEFCC, 2023). As India is moving towards a low-carbon economy and net-zero emissions by 2070, lowering the energy intensity and the carbon footprint of this sector has become an essential part of National Climate Action. The industrial sector's energy consumption is projected to increase steadily due to factors such as urbanisation, demographic shifts, and rising output. However, there is also a unique opportunity to transition to low-carbon technologies and fuels and alter the industrial value chain for the long run.

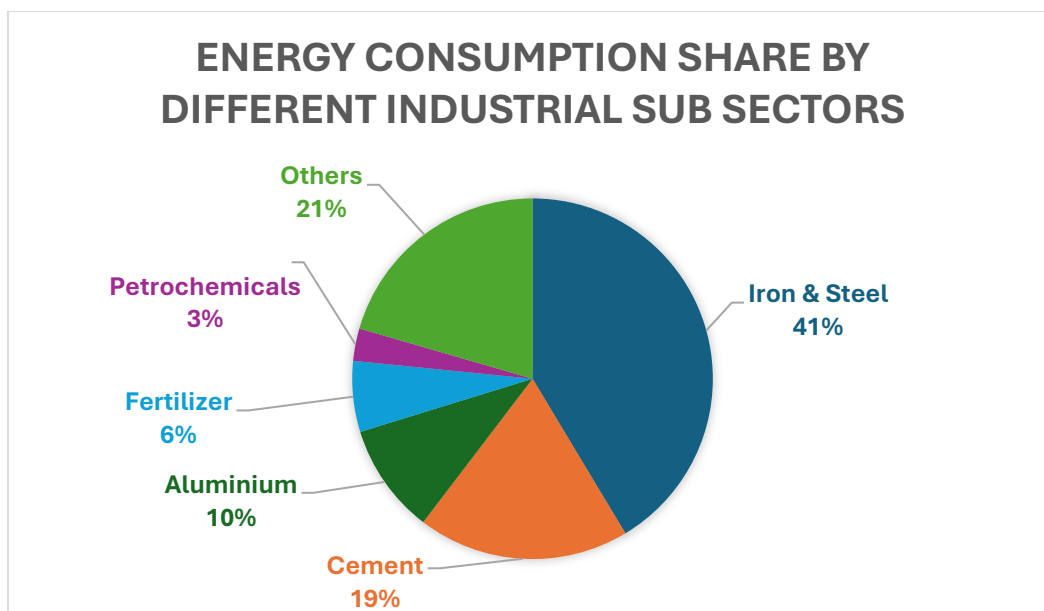


Figure 2: Final Energy Consumption by different sectors in FY 2021-22

In 2019, the aggregate emissions from the steel, cement, and chemicals industries totalled 678 MMtCO₂e, accounting for almost 68 per cent of the overall emissions from the industrial sector (MoEFCC 2023). The increasing demand from infrastructure development, housing, and transportation is projected to more than triple steel output (IBEF 2023) and double cement production (Kumar 2023) by 2050. In a Business-As-Usual scenario that assumes no further low-carbon economy efforts, emissions across the different industrial sectors may rise to 2,657 MMtCO₂e by 2050. The increase in emissions renders these industries essential to India's low-carbon economy policy.

1.1. Context Setting

India's industrial sector is entering a decisive phase of transformation. As the backbone of infrastructure development, urban expansion, and manufacturing growth, industry plays a central role in the country's economic trajectory. At the same time, it represents one of the largest sources of energy consumption and greenhouse gas emissions, accounting for approximately 35 percent of final energy use and close to 30 percent of national emissions in recent years [IEA, 2023; MoEFCC, 2023]. Energy-intensive subsectors such as iron and steel, cement, aluminium, and bulk chemicals dominate this footprint.

Material demand is expected to rise rapidly over the coming decades, driven by housing construction, transport infrastructure, electrification, and broader industrialisation. National development strategies envision sustained high economic growth through mid-century, implying substantial expansion in steel, cement, and aluminium production [NITI

Aayog, 2023; IBEF, 2023; Kumar, 2023]. Under current production structures, this growth trajectory risks locking the industrial sector into a high-energy and high-emissions pathway, increasing future transition costs and placing additional pressure on energy supply systems.

India’s climate commitments, including its updated Nationally Determined Contribution and net-zero target for 2070, require a fundamental shift in how industrial output is produced. Unlike other sectors, industrial decarbonisation involves not only energy substitution but also deep changes in production technologies, material efficiency, recycling systems, and infrastructure planning. Process emissions in cement and primary metals, reliance on coal for high-temperature heat, and long-lived capital assets further complicate the transition [IPCC, 2022].

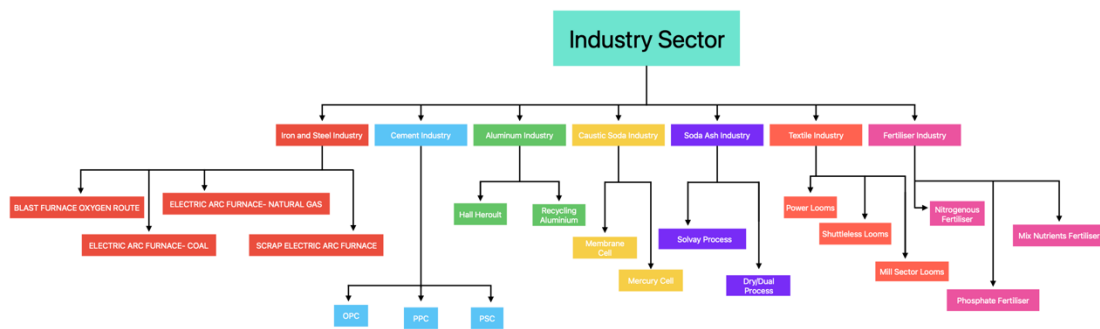


Figure 3: Technologies considered

Recent policy initiatives, including the National Green Hydrogen Mission and expanding renewable electricity capacity, signal growing momentum toward industrial decarbonisation. However, the pace and scale of change required extend beyond incremental efficiency improvements. Achieving alignment with long-term climate objectives demands coordinated action across multiple sectors, combining demand-side moderation with structural transformation of supply chains and production routes.

Within this context, there is a need for integrated, sector-spanning assessments that link material demand growth with technology transitions and energy system evolution. This working paper responds to that need by examining alternative development pathways for key industrial subsectors using a unified modelling framework, with particular attention to energy demand trajectories and the role of circular economy strategies

1.2. Literature Review

Industry accounts for approximately 35 percent of India’s total final energy consumption and nearly 30 percent of national greenhouse gas emissions, making it the second-largest energy-consuming sector after power [IEA, 2023; MoEFCC, 2023]. In absolute terms, industrial emissions reached roughly 803 MtCO₂e in 2019, with steel,

cement, and chemicals contributing close to 68 percent of this total. Under business-as-usual trajectories, emissions from Indian industry are projected to exceed 2.6 GtCO₂e by 2050, driven primarily by rapid growth in material demand associated with urbanisation and infrastructure expansion.

Global mitigation assessments consistently identify industry as one of the most challenging sectors to decarbonize due to the coexistence of fuel combustion emissions, process emissions, and long-lived capital stock [IPCC, 2022]. Integrated modelling studies show that incremental energy efficiency improvements typically deliver only 10 to 20 percent reductions in sectoral emissions by mid-century, whereas deep decarbonization pathways require structural shifts toward electrification, hydrogen, material efficiency, and circular economy strategies [IRENA, 2022; Van Vuuren et al., 2011].

India’s iron and steel industry exemplifies this structural challenge. In 2022, crude steel production hit 125.3 million tonnes, making India the second-largest global producer. However, per capita steel consumption remains low at about 93.5 kg, indicating significant hidden demand [World Steel Association, 2023]. The current output mainly relies on coal-based blast furnace-basic oxygen furnace and DRI methods, which produce emissions over 2.5 tCO₂ per tonne of crude steel above the global average of around 1.9 tCO₂ [IEA, 2020]. Technology roadmaps suggest that hydrogen-based DRI with electric arc furnaces could cut emissions by 85-95% compared to traditional BF-BOF routes. Additionally, scrap-based EAF approaches save 60-65% of final energy per tonne of steel [IEA, 2020; TERI, 2020]. Still, scrap accounts for less than a third of India’s steel feedstock due to fragmented collection systems and limited processing infrastructure, even after the implementation the Steel Scrap Recycling Policy [Ministry of Steel, 2019; Joint Plant Committee, 2023].

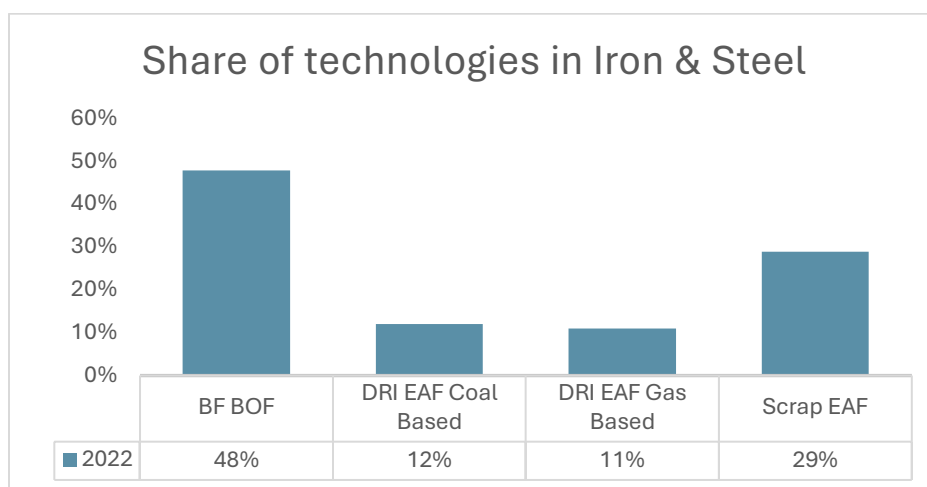


Figure 4: Share of Technologies in Iron and Steel in FY 2021-22

A similar pattern emerges in cement. India produced over 390 million tonnes of cement in 2022, ranking second globally, with production expected to double by 2050 under current development trajectories [CMA, 2022; Kumar, 2023]. Unlike metals, approximately 60 percent of cement emissions arise from clinker calcination rather than energy use. Although India already achieves blended cement shares exceeding 70 percent, average clinker factors remain around 0.70, leaving limited scope for marginal improvements [GCCA India, 2023].

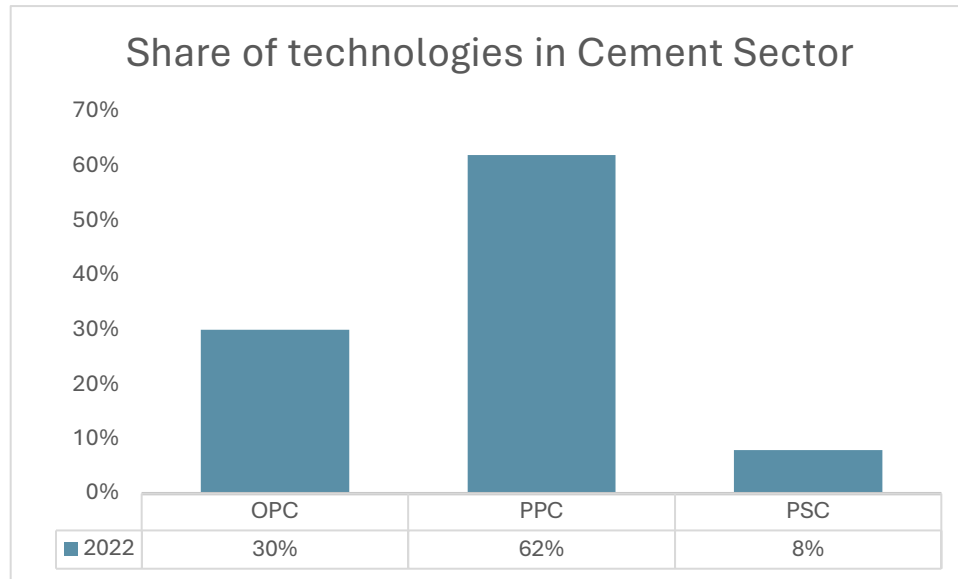


Figure 5: Share of Technologies in Cement Sector in FY 2021-22

Studies by the International Energy Agency and Lawrence Berkeley National Laboratory show that efficiency improvements and alternative fuels can reduce energy intensity by 10 to 15 percent, but achieving emissions reductions beyond 40 percent requires aggressive clinker substitution and eventual deployment of carbon capture technologies [IEA, 2018; LBNL, 2020].

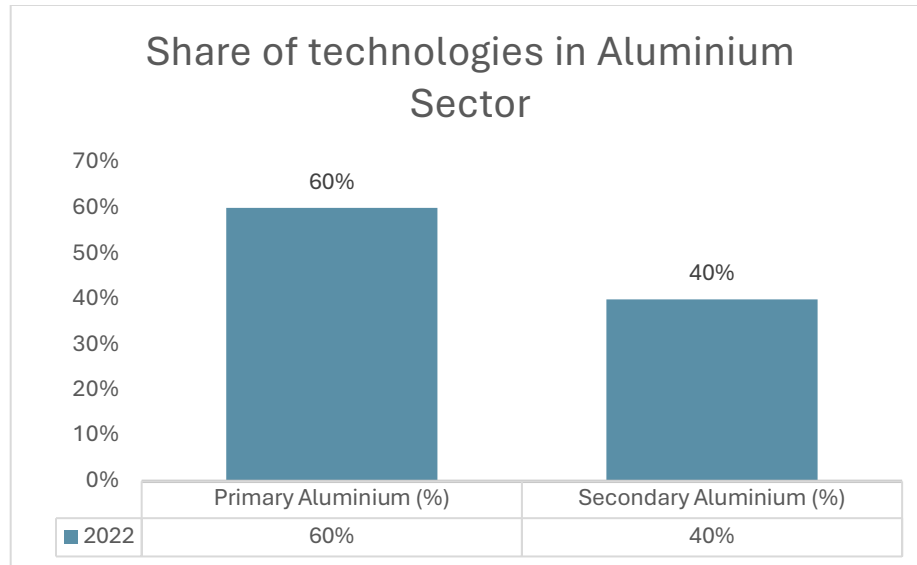


Figure 6: Share of Technologies in Aluminium Sector in FY 2021-22

Aluminium represents one of the most electricity-intensive industrial subsectors. India produced approximately 4 million tonnes of primary aluminium in 2022, with production dominated by the Hall-Héroult process, which typically consumes 13 to 15 MWh of electricity per tonne [IAI, 2022]. Secondary aluminium production requires only about 5 percent of this energy, making recycling the single most effective decarbonisation lever available to the sector [NITI Aayog, 2018; TERI, 2021]. Global pathway studies suggest that increasing recycled content to above 60 percent, combined with low-carbon electricity, could halve aluminium sector emissions by mid-century [IAI, 2021]. In India, however, secondary aluminium still accounts for less than half of total output, reflecting constraints in scrap availability and processing capacity [Ministry of Mines, 2023].

Bulk chemicals add further complexity. India’s caustic soda production exceeded 3 million tonnes in 2022, with electricity consumption typically ranging between 2,200 and 2,500 kWh per tonne under membrane cell technology [AMAI, 2021]. The phase-out of mercury cell electrolysis following the Minamata Convention delivered immediate efficiency gains, yet electricity continues to account for over 80 percent of final energy demand in the sector, making emissions trajectories increasingly dependent on grid decarbonisation [UNEP, 2017; Department of Chemicals and Petrochemicals, 2023]. Soda ash production, exceeding 3.2 million tonnes annually, remains dominated by the Solvay process, with energy intensities typically above 6 GJ per tonne and heavy reliance on coal and natural gas. Incremental efficiency improvements reduce energy use by only 10 to 20 percent, while deeper reductions require adoption of modified processes and cleaner energy inputs [Chemical Weekly, 2023; UNIDO, 2020].

Across these subsectors, a consistent quantitative insight emerges technology substitution and recycling deliver far greater energy and emissions reductions than incremental efficiency measures alone. Circular economy strategies, particularly in metals, are repeatedly identified as among the lowest-cost mitigation options, while hydrogen and electrification become increasingly important beyond 2035 as marginal efficiency gains are exhausted [IRENA, 2022; TERI, 2020].

To analyse these interactions, recent studies increasingly rely on integrated modelling frameworks such as the LEAP system, which enables bottom-up representation of industrial technologies combined with scenario-based policy analysis [Heaps, 2022; SEI, 2022]. Demand-side modelling commonly employs saturation-based approaches, such as Gompertz functions, to capture observed nonlinear relationships between income growth and material consumption, thereby providing more realistic long-term projections than linear extrapolation [Van Vuuren et al., 2011].

Despite this growing evidence base, much of the literature remains fragmented across individual subsectors or focused primarily on emissions outcomes. There is limited work that integrates material demand saturation, technology transitions, circular economy strategies, and electricity decarbonisation within a single analytical framework for India.

Addressing this gap is critical for understanding how alternative development pathways shape long-term industrial energy demand and for identifying policy priorities that can deliver both economic growth and deep emissions reductions.

2. Rationale

India's industrial sector stands at a critical intersection of economic development and climate responsibility. The sector currently accounts for approximately 35 percent of total final energy consumption and nearly 30 percent of national greenhouse gas emissions, with absolute emissions reaching around 803 MtCO_{2e} in 2019. Energy-intensive subsectors such as iron and steel, cement, aluminium, and bulk chemicals alone contribute close to 68 percent of total industrial emissions. At the same time, material demand is projected to rise sharply, with steel output expected to more than triple and cement production expected to double by mid-century, driven by infrastructure expansion, housing demand, and broader industrialisation. Under a Business-As-Usual trajectory, emissions from India's industrial sector could escalate to approximately 2,657 MtCO_{2e} by 2050, placing national climate commitments at significant risk

While India has articulated ambitious long-term goals, including net-zero emissions by 2070 and enhanced Nationally Determined Contributions, existing policy frameworks and sectoral strategies remain fragmented across individual industries and technologies. Much

of the current discourse focuses either on incremental efficiency improvements or on isolated technology pathways, without adequately capturing the combined effects of demand growth, production structure, energy intensity, and circular economy measures. This creates a critical evidence gap for policymakers seeking to design coordinated, system-level interventions.

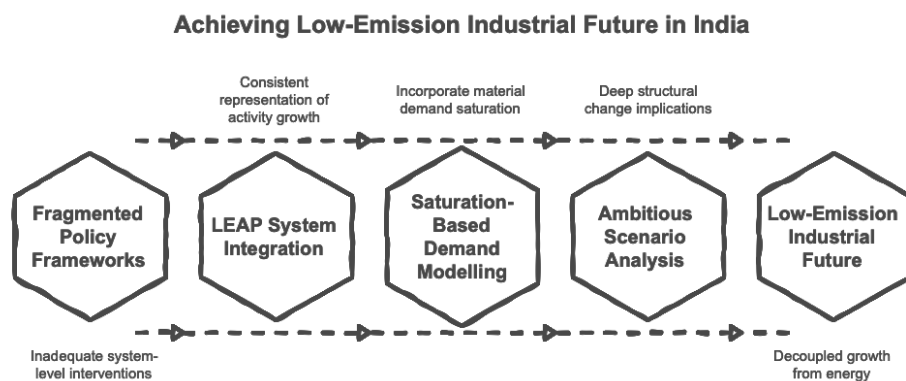


Figure 7: Considered Rationale

Moreover, conventional projections often rely on linear demand growth assumptions, which fail to reflect the observed saturation dynamics of material consumption as economies mature. This limits the ability of existing studies to provide realistic long-term estimates of industrial energy demand and obscures the role of structural transformation in shaping future trajectories. There is therefore a need for modelling approaches that explicitly incorporate material demand saturation alongside technology transitions.

Against this backdrop, the present study adopts an integrated, bottom-up modelling framework using the LEAP system combined with saturation-based demand modelling through Gompertz functions. This approach enables consistent representation of activity growth, technology pathways, and energy intensities across key industrial subsectors, while allowing systematic exploration of alternative futures under varying levels of policy ambition.

By constructing Baseline, Business-As-Usual, and Ambitious scenarios, the analysis moves beyond incremental efficiency narratives to examine the implications of deep structural change, including electrification, green hydrogen deployment, expanded recycling, and circular economy practices. The Ambitious scenario, in particular, demonstrates the potential to reduce end-use industrial energy demand by more than 60 percent relative to the Baseline, highlighting the scale of transformation required to decouple industrial growth from energy consumption.

3. Objectives

India's industrial sector accounts for approximately 35 percent of the total final energy consumption and nearly 30 percent of national greenhouse gas emissions with absolute emissions reaching to around 803 MtCO₂e in the year 2019. Energy intensive industries like iron and steel, cement, aluminium and bulk chemicals dominate the emission footprint of the sector, contributing to around 68 percent of the total emissions. At the same time, material demand is projected to rise rapidly as India continues to pursue growth in infrastructure, urbanisation and manufacturing expansion. Steel production is expected to increase at a much faster rate, and the demand for cement is expected to double by mid-century. Under a continuation of the current trend without any interventions, emissions from the industrial sector could be escalating to around 2,657 MtCO₂e by the year 2050, creating a substantial gap between the development trajectories and India's long term Net Zero commitments.

In this context, the primary objective of this study is to develop an integrated analytical framework to link material demand growth with production technologies and energy use across five industrial sub-sectors. By combining Gompertz-based saturation modelling for steel, cement, and aluminium with technology-explicit representation in the LEAP system, the study aims to move beyond linear projections and provide a realistic assessment of how industrial energy demand may evolve as the economy **matures**.

A central objective is to examine how alternative development pathways share future trajectories across policy-ambition scenarios. Through the construction of the baseline and the different alternate scenarios, the analysis compares the continued resilience of coal-based production technology routes characterised by gradual efficiency parameters and policy-led structural transformation. For iron and steel, this process involves evaluating transitions from coal-dominated BF, BOF and DRI routes towards scrap production EAF. In the cement sector, the study focuses on shifts from Ordinary Portland Cement (OPC) to Blended Cements like Portland Pozzolana Cement (PPC) and Portland Slag Cement (PSC), which, in turn, reduce clinker intensity.

For aluminium, the analysis examines the implications of expanding secondary production beyond its current 40 per cent share, thereby reducing dependence on electricity-intensive primary smelting. In the chemical sector, the study assesses how electricity intensity and energy sourcing influence caustic soda production following the near-complete transition to membrane cell technology, and how efficiency improvements and limited adoption of alternative processes shape energy use in soda ash production.

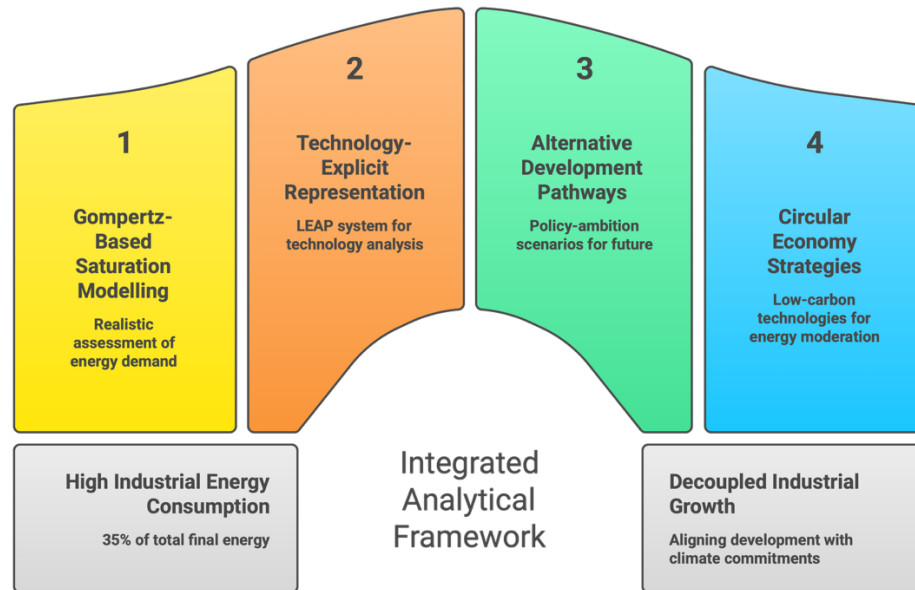


Figure 8: Integrated Analytical Framework used

A central objective is to examine how the alternative development pathways share the future trajectories across the various scenarios of policy ambition. Through the construction of the baseline and the different alternate scenarios, the analysis compares the continued resilience of coal-based production technology routes characterised by gradual efficiency parameters and policy-led structural transformation. For iron and steel, this process involves evaluating transitions from coal dominated BF BOF and DRI routes towards scrap production EAF. In the cement sector, the study focuses on shifts from Ordinary Portland Cement(OPC) towards Blended Cements like Portland Pozzolana Cement(PPC) and Portland Slag Cement (PSC), which in turn reduces the clinker intensity.

The working paper also seeks to quantify the role of circular economy strategies and low-carbon technologies in moderating industrial energy demand. Scrap-based steelmaking, which typically requires 60 to 65 percent less energy than primary routes, secondary aluminium production that bypasses energy-intensive upstream processing, aggressive clinker reduction in cement, electrification of industrial processes, and deployment of green hydrogen are examined as key structural levers. In parallel, the study evaluates how improvements in electricity carbon intensity affect outcomes in highly electricity-dependent subsectors such as aluminium and caustic soda.

Ultimately, the objective is to generate policy-relevant insights that reflect the scale and coordination of interventions required to decouple industrial growth from energy consumption across all five subsectors. By explicitly representing production routes, technology shares, activity growth, and energy intensities within a unified modelling

framework, the analysis aims to clarify the limitations of incremental efficiency measures and highlight the conditions under which integrated deployment of recycling, material efficiency, electrification, and low-carbon technologies can align India's industrial development with its long-term climate commitments while sustaining economic growth.

4. Research Question

This working paper is guided by a set of interconnected research questions aimed at understanding how India's industrial sector can transition toward a low-emission future while sustaining rapid economic growth.

At its core, the study asks how projected growth in material demand across iron and steel, cement, aluminium, caustic soda, and soda ash translates into long-term industrial energy requirements when demand saturation dynamics are explicitly accounted for. By moving beyond linear extrapolation and incorporating Gompertz-based demand modelling, the analysis seeks to clarify how per capita consumption trajectories shape aggregate industrial activity over time.

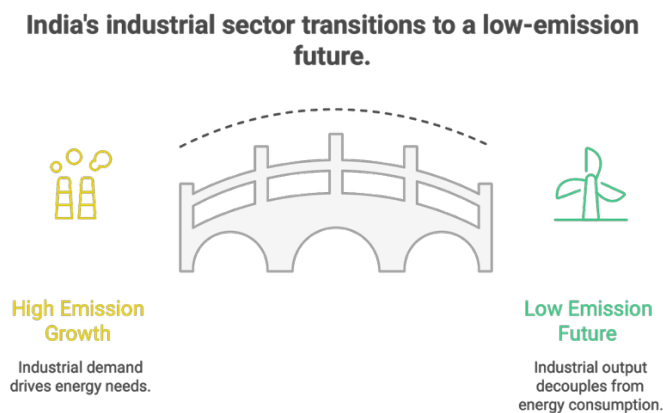


Figure 9: India's Sectoral Transition to a Low Emission Future

Building on this demand perspective, the paper examines how alternative production pathways influence future energy demand under varying levels of policy ambition. It asks how continued reliance on coal-based technologies compares with scenarios characterised by gradual efficiency improvements and policy-led structural transformation, including hydrogen-based steelmaking, expanded recycling in metals, low-clinker cement pathways, electrification of industrial processes, and cleaner electricity supply.

A central research question concerns the role of circular economy strategies in moderating industrial energy growth. The study investigates to what extent increased scrap-based steel production, expansion of secondary aluminium beyond current levels, and

greater use of industrial by-products in cement can reduce energy intensity and support decoupling of industrial output from energy consumption.

The paper further explores how electricity-intensive subsectors such as aluminium and caustic soda respond to improvements in electricity efficiency and decarbonisation, and how fuel switching and process optimisation affect energy trajectories in soda ash production. These questions address the extent to which power sector transitions and industrial technology choices must evolve in parallel to enable deep structural change.

Finally, the study asks what combination of policy interventions, technology deployment, and structural shifts is required across all five subsectors to align India's industrial development with its long-term climate commitments. Rather than identifying a single optimal pathway, the research seeks to compare alternative futures and highlight the scale, timing, and coordination of actions necessary to move from incremental efficiency gains toward systemic transformation of the industrial sector.

5. Methodology

To capture the diversity of production processes, energy use patterns, and decarbonisation pathways across India's industrial landscape, the analysis adopts a subsector-specific modelling approach within a unified LEAP framework. While all subsectors share common macroeconomic and demand assumptions, each is represented through technology-explicit activity trees that reflect sector-specific production routes, material characteristics, and energy intensity profiles.

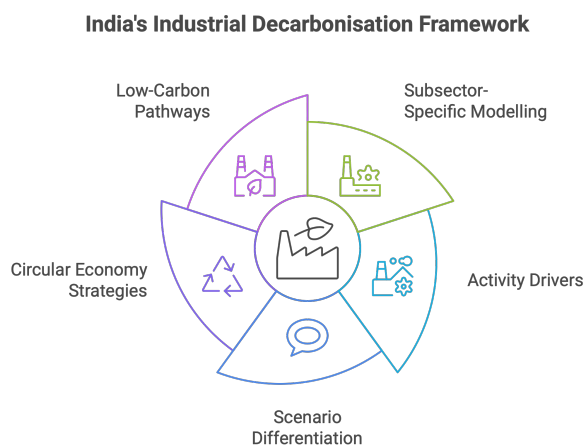


Figure 10: Industrial Decarbonisation Framework

The modelling framework covers five key industrial subsectors: iron and steel, cement, aluminium, caustic soda, and soda ash. Together, these account for the majority of industrial energy consumption and emissions in India. For each subsector, activity levels are

driven either by saturation-based demand projections (steel, cement, aluminium) or exogenously defined production growth trajectories (caustic soda and soda ash). These activity drivers are applied consistently across all scenarios to isolate the effects of technology choice, efficiency improvements, and structural change.

Scenario differentiation is implemented through time-varying technology shares, pathway-specific energy intensities, and fuel substitution assumptions. The Baseline Scenario assumes no additional policy intervention beyond current practices, with technology structures frozen at base-year levels. The Business-As-Usual Scenario incorporates gradual, market-driven efficiency improvements and limited structural shifts. The Ambitious Scenario represents a policy-led transformation characterised by accelerated deployment of low-carbon technologies, expanded recycling, electrification of industrial processes, and integration of green hydrogen.

Circular economy strategies are embedded across relevant subsectors through increased scrap-based steelmaking, expanded secondary aluminium production, and greater utilisation of industrial by-products in cement. Low-carbon production pathways, including hydrogen-based DRI-EAF in steel, low-clinker cement formulations, and electrification of chemical processes, are introduced as distinct technology branches with scenario-specific adoption trajectories.

This consistent modelling structure allows for systematic comparison of alternative development pathways while preserving the technological and operational specificity of each subsector. The following sections describe in detail the methodological treatment of each industrial subsector, beginning with iron and steel, which represents the largest source of industrial energy demand and emissions.

5.1. Iron and Steel Sector

The iron and steel sector plays a critical role in India's industrial growth and infrastructural development. India is the world's second-largest producer of crude steel with a production of 125.3 million tonnes of crude steel in 2022 (World Steel Report, 2022). Despite this scale in production, the per capita consumption of steel is substantially low for India, i.e., 93.5 kg per person, indicating significant growth potential.

At the same time, the sector is one of the most carbon intensive in the economy, accounting more than 30 percent of the total industrial emissions. The emission intensity exceeds the global average due to a coal-dominated production route, scrap availability and a carbon-intensive electricity mix. Aligning this to the climate goals of India requires fundamental technological shifts and also structural changes within the sector.

5.1.1. Technology Pathways Represented in the Model

The modelling framework represents four principal steelmaking routes. The Blast Furnace Basic Oxygen Furnace route remains the most energy intensive as well as emission intensive technology. It currently dominates the large-scale production of steel in India. Coal-based Direct Reduced Iron (DRI), when coupled with Electric Arc Furnaces, is widely used due to the domestic availability of coal, but it still exhibits high emissions. Gas based DRI EAF is less emission intensive but is constrained by the limited supply of natural gas in India. Scrap-based EAF is the least energy intensive pathway and is central to the circular economy-driven decarbonization.

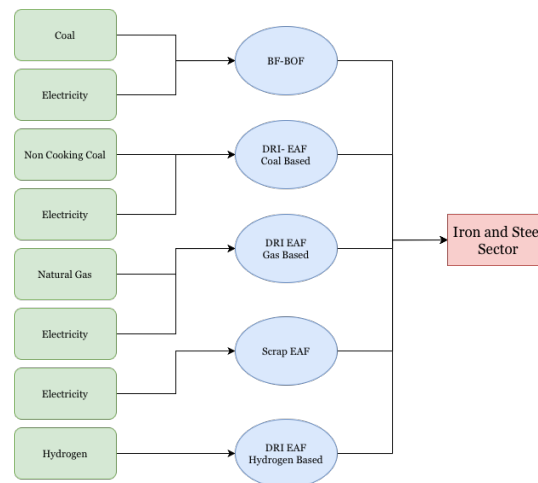


Figure 11: Technologies in Iron and Steel under different scenarios

These technological routes underpin the sectoral activity structure within the LEAP modelling framework.

5.1.2. Scenario Descriptions

Baseline Scenario

The Baseline scenario assumes no additional policy interventions or technological advancements beyond current levels. Technology shares are held constant at their base year values through 2070. Coal-based BF-BOF and DRI routes continue to dominate production, while hydrogen-based steelmaking remains absent. This scenario results in strong fossil-fuel lock-in, rapidly rising energy demand, and emissions trajectories incompatible with long-term climate objectives.

Business-As-Usual Scenario / Current Policy Scenario (CPS)

The Business-As-Usual scenario reflects gradual, market-driven efficiency improvements and compliance with existing energy efficiency regulations. Incremental technological upgrades reduce energy intensity and moderate demand growth, with coal

consumption peaking around midcentury. However, structural change remains limited, and the deployment of hydrogen and circular economy pathways occurs only at marginal levels. As a result, emissions reductions are insufficient to meet long-term decarbonization targets.

Ambitious Scenario

The Ambitious scenario represents a policy-led transformation aligned with India’s long-term climate commitments. Strong support for green hydrogen, electrification, scrap recycling, and enabling infrastructure drives a substantial shift away from coal-based production routes. Hydrogen-based DRI-EAF and scrap-based EAF expand significantly by 2047, leading to a sharp reduction in coal use and a more than 50 per cent reduction in final energy demand relative to the Baseline scenario. This pathway achieves a clear decoupling of industrial growth from energy consumption and emissions.

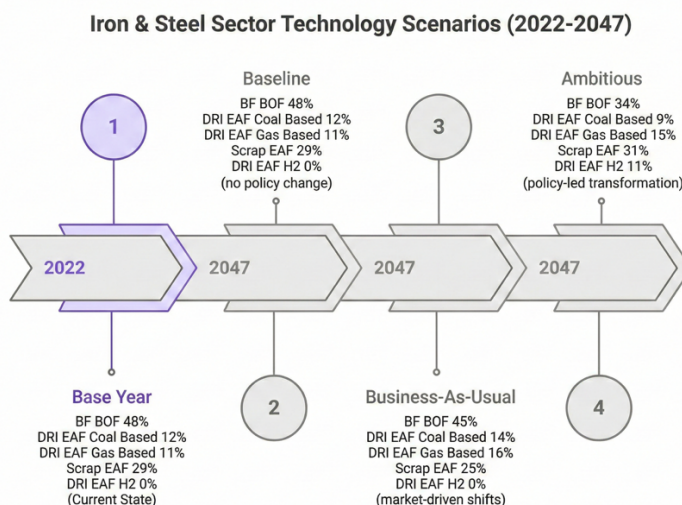


Figure 12: Share of Technologies for Iron and Steel under different scenarios

5.2. Cement Sector

The cement sector is a critical component of India’s industrial activity and infrastructural development. Demand for cement is closely linked to housing construction, transport infrastructure, urban expansion, and public investment, making the sector one of the drivers of economic growth in the country. At the same time, cement production is among the most energy- and emission-intensive sectors. A defining character of this sector is that a substantial amount of emission in this sector arises from the chemical process of clinker production rather than just from energy use alone. As the demand for cement is projected to rise sharply in the near future, understanding how energy technology choices and policy interventions influence energy demand trajectories is a pivot to aligning sectoral growth with long-term low-carbon objectives.

5.2.1. Technology Pathways Represented in the Model

The cement sector is represented in the LEAP modelling framework through three dominant cement production pathways, differentiated by clinker content and associated energy intensity.

Ordinary Portland Cement (OPC) is the most clinker-intensive cement type and exhibits the highest energy and emissions intensity. Its production relies heavily on coal for thermal energy, resulting in the highest final energy demand per tonne of cement.

Portland Pozzolana Cement (PPC) partially substitutes clinker with pozzolanic materials such as fly ash. This reduces clinker requirements and lowers both energy consumption and emissions intensity relative to OPC.

Portland Slag Cement (PSC) blends clinker with granulated blast furnace slag and represents the lowest-energy-intensity pathway among the three cement types. Due to its low clinker content, PSC has the greatest potential for reducing energy demand and emissions at the sector level.

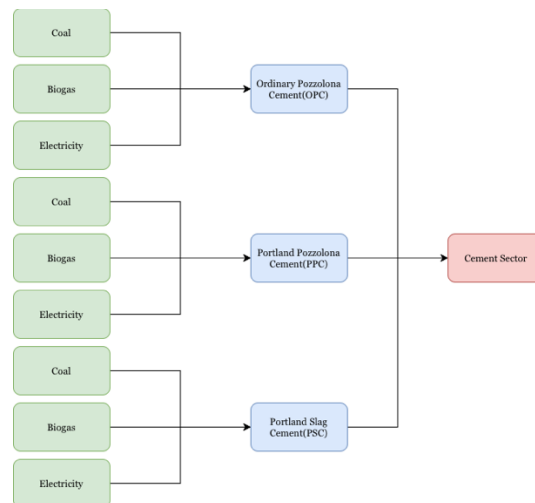


Figure 13: Technologies considered in Cement Sector

These three cement types form the activity structure in LEAP and determine final energy demand through their distinct clinker factors and fuel requirements. India already exhibits a relatively high share of blended cements, providing a strong structural base for further decarbonization, while also implying that future reductions depend on deeper shifts toward low clinker products rather than marginal efficiency gains.

5.2.2. Scenario Descriptions

Three scenarios are used to evaluate alternative development pathways for the cement sector.

The Baseline Scenario assumes no additional policy interventions or structural changes beyond existing practices. The production mix remains largely unchanged over time, with OPC retaining a significant share, PPC remaining dominant, and limited expansion of PSC. Coal continues to dominate thermal energy use across all cement types. Under this scenario, energy demand increases almost proportionately with cement output.

The Business-As-Usual Scenario reflects gradual, market driven shifts in production structure and incremental efficiency improvements. The share of OPC declines steadily, while PSC expands to a moderate extent. PPC continues to account for a large share of production. These changes reduce the average clinker factor and moderate energy demand growth relative to the Baseline Scenario, but do not fundamentally alter the sector’s dependence on clinker-based production.

The Ambitious Scenario represents a policy led transformation aligned with long term climate objectives. Blended cements dominate production, OPC is aggressively phased down, and PSC penetration increases substantially. In parallel, alternative fuels expand and preparations for large scale deployment of carbon capture technologies are introduced. This scenario delivers the strongest reduction in energy intensity and constrains long term energy demand growth despite continued expansion in cement production.

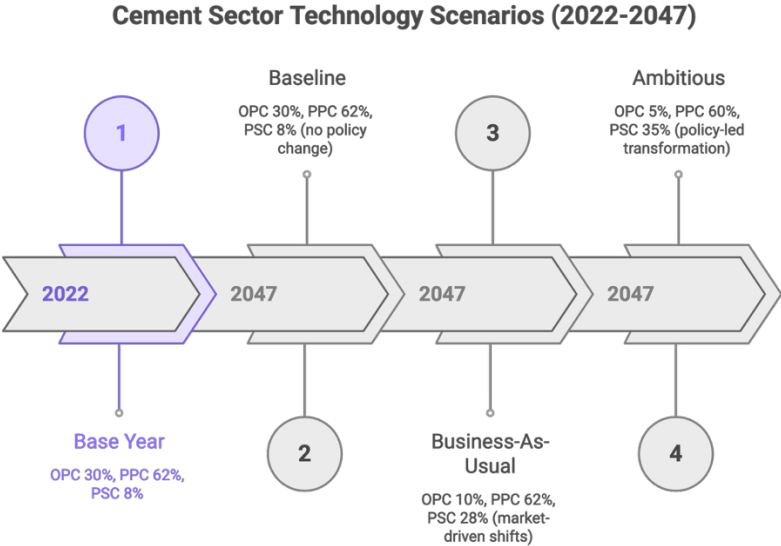


Figure 14: Cement Sector Technology Scenarios

5.3. Aluminium Sector

The aluminium sector occupies a strategically important position in India’s industrial landscape, supplying essential inputs to construction, transport, packaging, electrical equipment, and the rapidly expanding renewable energy sector in India. As one of the most

electricity intensive industrial activities, aluminium production plays a disproportionate role in shaping industrial energy demand and emissions trajectories. India is among the world’s largest producers of aluminium, with growth driven primarily by primary smelting through the Hall-Héroult process. While technologically mature, this production route is highly energy intensive and closely tied to the carbon intensity of the electricity grid.

A defining structural challenge for the Indian aluminium industry is the relatively low share of secondary aluminium production. Recycling offers one of the strongest decarbonization levers available to the sector, as secondary aluminium requires only a fraction of the energy needed for primary smelting. This section examines how different levels of policy ambition and technological adoption influence long-term energy demand outcomes for the aluminium sector.

5.3.1. Technology Pathways Represented in the Model

The aluminium sector is represented in the LEAP modelling framework through two principal production pathways with sharply contrasting energy profiles.

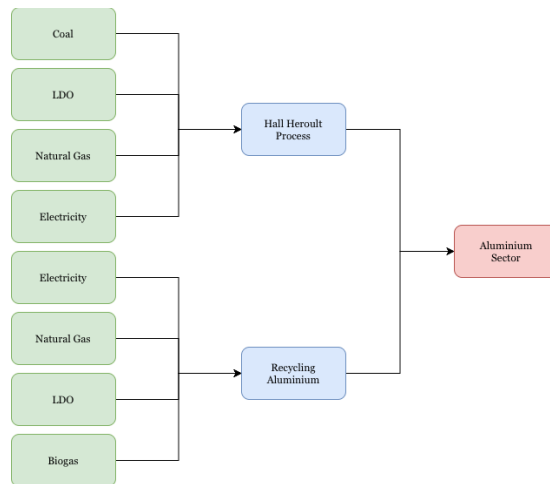


Figure 15: Technologies Considered in Aluminium Sector

Primary aluminium production is modelled through the Hall-Héroult electrolytic smelting process. This pathway is highly electricity intensive and relies on carbon anodes, making it one of the most energy and emissions intensive industrial technologies. Final energy demand under this route is dominated by electricity consumption, and overall emissions are strongly influenced by the carbon intensity of the power system.

Secondary aluminium production represents aluminium recycling from post-consumer and industrial scrap. This pathway bypasses the energy intensive stages of bauxite mining, alumina refining, and electrolytic reduction. As a result, secondary

aluminium requires substantially lower final energy per tonne of output and forms the backbone of a circular economy based decarbonization strategy.

5.3.2. Scenario Descriptions

All scenarios share a common demand trajectory derived from the saturation-based demand model but differ in the evolution of the production mix between primary and secondary aluminium.

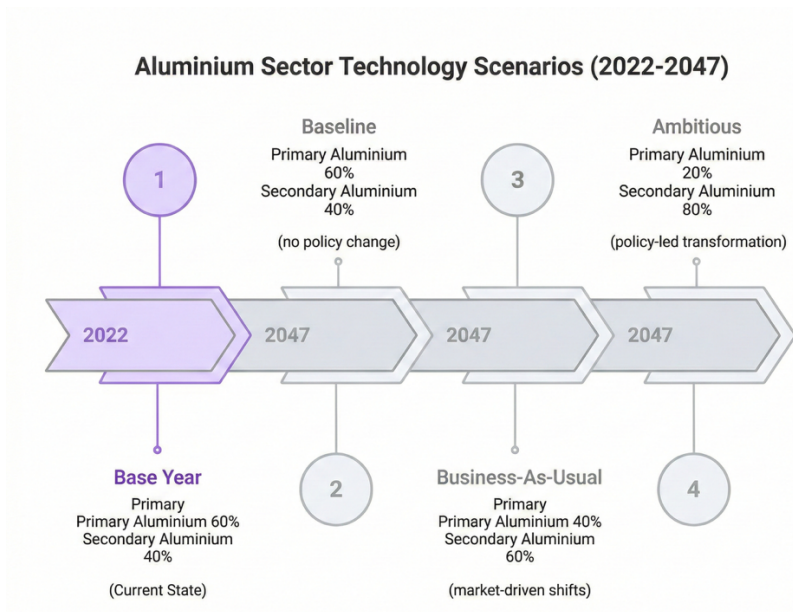


Figure 16: Cement Sector Technology Scenarios

In the **base year 2022**, aluminium production is dominated by primary smelting, with secondary aluminium accounting for approximately **40 percent** of total production and primary production accounting for the remaining **60 percent**. This production structure forms the starting point for all scenarios.

The **Baseline Scenario** assumes no structural change in production technologies. The share of primary aluminium remains fixed at 60 percent, while secondary aluminium remains at 40 percent throughout the projection period. Energy demand, therefore, rises sharply with output growth, reflecting the continued dominance of electricity-intensive primary smelting.

The **Business-As-Usual Scenario** incorporates gradual market driven expansion of recycling. Under this pathway, secondary aluminium increases steadily, reaching approximately **60 percent of total production by 2070**, with primary production declining correspondingly. This shift moderates energy demand growth but does not fundamentally transform the sector's energy profile.

The **Ambitious Scenario** represents a policy led transformation centered on a circular economy. Recycling expands aggressively, with secondary aluminium reaching **around 80 percent of total production by 2070**, and primary smelting reduced to a residual share. This scenario assumes strong policy support for scrap collection, processing infrastructure, and enabling regulations.

6. Key Insights

6.1. Iron and Steel Sector

The evolution of final energy demand in the iron and steel sector reveals how policy ambition and technology choices fundamentally shape long term outcomes. In the base year 2022, final energy demand stands at 3.83 EJ across all scenarios, providing a common reference point for comparison. Beyond this point, the trajectories diverge, reflecting the underlying assumptions embedded in each scenario.

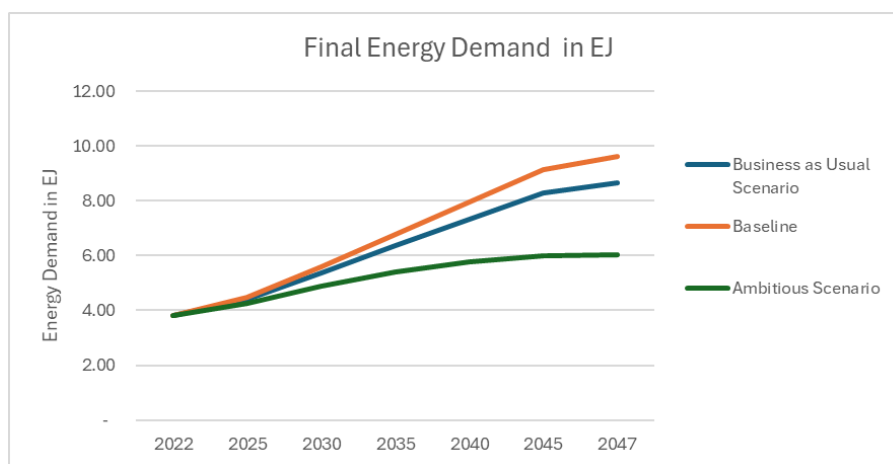


Figure 17: Final Energy Demand for Iron and Steel Sector

In the **Baseline Scenario**, energy demand increases steadily throughout the projection period, reaching 9.62 EJ by 2047. This more than two-and-a-half-fold increase is driven by continued reliance on coal-intensive production routes and the absence of meaningful technological or structural change. As steel output expands to meet growing demand, energy consumption rises almost in proportion, reinforcing fossil-fuel lock-in and resulting in a high-energy, high-emissions pathway.

The **Business-As-Usual Scenario** moderates this growth to some extent. Final energy demand rises to 8.67 EJ by 2047, remaining below the Baseline but still more than double the 2022 level. Incremental efficiency improvements and gradual process optimisation slow the pace of demand growth, particularly after 2035. However, the underlying production structure remains largely unchanged, limiting the potential for deeper reductions in energy use.

A distinctly different pattern emerges under the **Ambitious Scenario**. Here, final energy demand increases more gradually and stabilises after 2040, reaching 6.03 EJ by 2047. This represents a reduction of roughly 37 per cent reduction relative to the Baseline in the same year. The flatter trajectory reflects a structural transformation of the sector, driven by the large-scale adoption of hydrogen-based DRI, expansion of scrap-based EAF production, increased electrification, and improvements in material efficiency. As a result, growth in steel output is increasingly decoupled from energy consumption, aligning the sector with long-term low-carbon transition objectives in India.

6.2. Cement Sector

The LEAP results for the cement sector reveal distinct energy demand trajectories across the three scenarios, reflecting the combined effects of production growth, cement composition, and policy intervention.

In the base year 2022, total final energy demand across all scenarios is 0.86 EJ, representing the existing production structure dominated by blended cements but still reliant on clinker intensive processes and coal based thermal energy.

Under the Baseline Scenario, final energy demand increases steadily over the projection period, reaching 1.02 EJ in 2030, 1.33 EJ in 2040, and 1.53 EJ by 2047. This represents an increase of nearly 79 percent between 2022 and 2047. The strong upward trajectory closely tracks cement production growth and reflects the absence of structural change in cement composition. The persistence of Ordinary Portland Cement and limited expansion of low clinker cement types result in minimal decoupling between output growth and energy demand.

The Business-As-Usual Scenario shows a moderated but still rising energy demand pathway. Final energy demand reaches 1.01 EJ in 2030, 1.29 EJ in 2040, and 1.46 EJ by 2047, remaining consistently below the Baseline Scenario but still increasing by approximately 70 percent relative to 2022. Incremental shifts toward blended cements and gradual efficiency improvements reduce energy intensity but are insufficient to offset the scale effects of rapid production growth.

The Ambitious Scenario exhibits the most pronounced divergence in outcomes. Final energy demand rises more gradually to 0.92 EJ in 2030, 1.04 EJ in 2040, and 1.09 EJ by 2047, representing an increase of only 27 percent over the projection period. Compared to the Baseline Scenario, the Ambitious pathway reduces final energy demand by approximately 29 percent in 2047, demonstrating a clear decoupling of cement production from energy consumption through aggressive clinker reduction and structural transformation of the production mix.

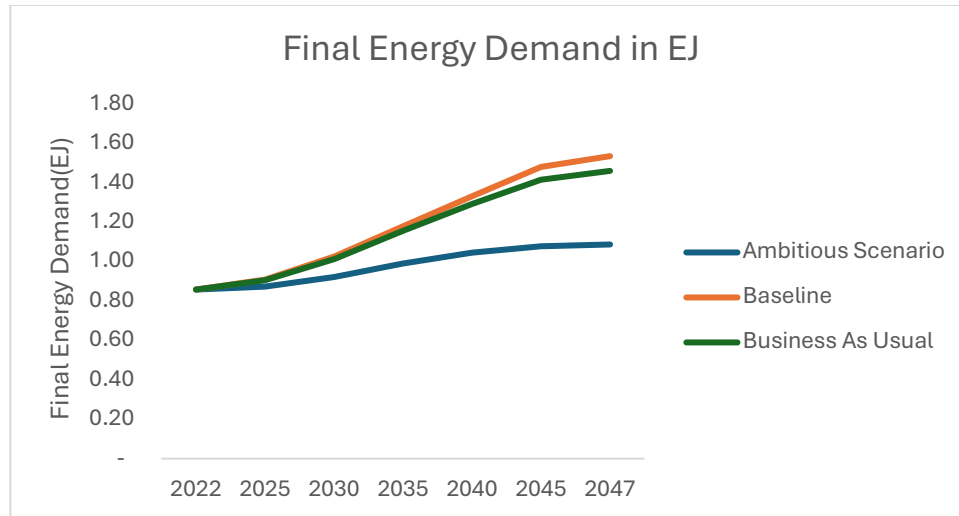


Figure 18: Final Energy Demand for Cement Sector

Across all scenarios, differences in energy demand outcomes are driven primarily by changes in cement type shares rather than by efficiency improvements within individual technologies. Fuel-wise results further show that coal remains the dominant energy source throughout the projection period, accounting for more than 90 percent of final energy demand even in later years. Biomass and electricity increase in absolute terms but remain secondary contributors, underscoring that fuel substitution alone delivers limited gains without clinker reduction.

6.3. Aluminium Sector

LEAP results reveal sharply diverging energy demand trajectories across the three scenarios.

In the base year **2022**, final energy demand in the aluminium sector is **0.87 EJ** across all scenarios. Under the **Baseline Scenario**, final energy demand increases rapidly to **1.44 EJ by 2030, 2.68 EJ by 2040, and 3.77 EJ by 2047**. This represents more than a **fourfold increase** over the projection period and reflects the continued dominance of electricity intensive primary aluminium production.

The **Business-As-Usual Scenario** moderates but does not reverse this trend. Final energy demand reaches **1.45 EJ in 2030, 2.62 EJ in 2040, and 3.59 EJ by 2047**. Although increased recycling reduces average energy intensity relative to the Baseline Scenario, absolute energy demand continues to rise sharply due to strong growth in aluminium output.

The **Ambitious Scenario** exhibits the strongest divergence in outcomes. Final energy demand rises to **1.28 EJ by 2030, 2.03 EJ by 2040, and 2.54 EJ by 2047**. Compared to the Baseline Scenario, the Ambitious pathway reduces final energy demand by approximately

33 percent in 2047, demonstrating a clear decoupling of aluminium production growth from energy consumption through aggressive expansion of secondary aluminium.

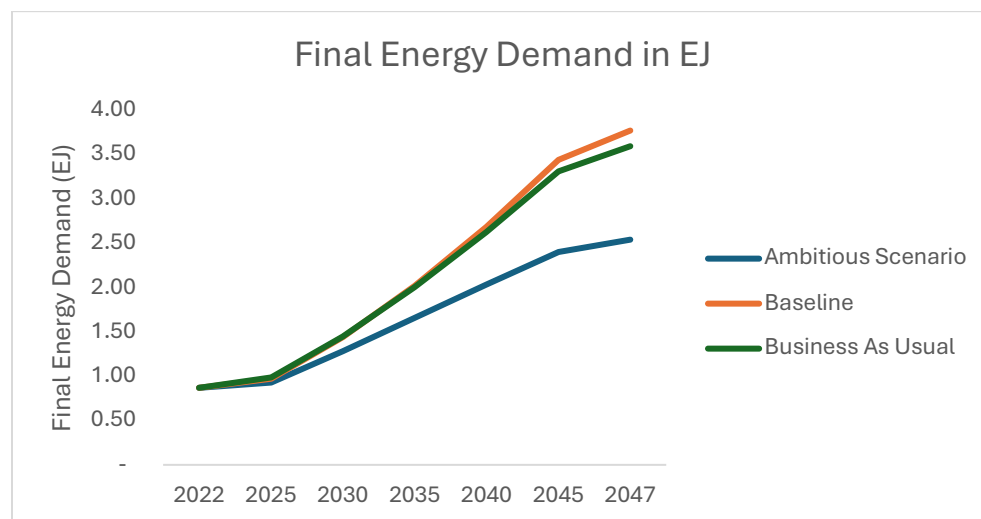


Figure 19: Final Energy Demand for Aluminium Sector

Across scenarios, the results confirm that **production mix is the dominant driver of energy outcomes**. Efficiency improvements within primary smelting play a limited role, while large scale substitution toward secondary aluminium delivers substantial reductions in long term energy demand.

7. Policy Recommendations

The modelling work done for the select industries provides a clear structural message for India's industrial transition towards Viksit Bharat 2047 and Net Zero 2070. The future of energy demand in hard-to-abate sectors like iron and steel, cement and aluminium will not be determined by marginal efficiency gains alone, but by deliberate shifts in production and technological process pathways, material composition, and circularity. The policy challenge, therefore, is not incremental optimisation but managed structural transformation with a developmental outcome in the backdrop of Viksit Bharat and India's Net Zero goals.

7.1. Reorienting Industrial Strategy from Efficiency to Structural Change

Across iron and steel, cement, and aluminium, incremental improvements within incumbent technologies yield only modest change in long term energy demand. What fundamentally alters trajectories is a change in production mix and technological change. This implies that policy instruments must move beyond traditional energy efficiency frameworks and actively shape technology adoption and material flows by thinking of leapfrogging technologies for the industrial transformation for Viksit Bharat 2047 and Net Zero 2070.

Industrial policy must explicitly support transition technologies that are currently cost intensive but are also critical for an energy and social system of India. In steel, this means enabling hydrogen based direct reduction and accelerating the expansion of scrap based electric arc furnaces by emphasizing on the circular economy imperatives. In cement, the priority lies in structurally lowering clinker intensity through blended cement standards and material substitution. In aluminium, the dominant lever is a rapid scale up of secondary production supported by a robust recycling ecosystem.

The implication is clear. Energy transition in industry must be embedded within broader industrial, economic, environmental and development goals, not as a peripheral environmental objective for long-term climate goals.

7.2. Creating Enabling Markets for Low Carbon Materials

A recurring barrier across sectors is the absence of strong demand signals for low carbon alternatives. Without assured markets, market based incentives private investment in hydrogen steel, low clinker cement, or recycled aluminium will remain cautious.

Public procurement can play a catalytic role. Government funded infrastructure projects can incorporate embodied carbon disclosure and preferential sourcing requirements. Over time, such measures can evolve into performance-based standards that reward lower carbon intensity rather than prescribing specific technologies. This has to be incentivized with sustained government support and public – private partnerships. Complementary measures such as green product certification, voluntary disclosure frameworks, and alignment with emerging global carbon border mechanisms and market creation must therefore be viewed as a central policy pillar rather than a supplementary measure.

7.3. Aligning Energy Infrastructure with Industrial Transition

Energy infrastructure and industrial transition by aligning hydrogen production, transport infrastructure and its clustering, alignment with steel clusters needs to be implemented through coordinated planning between renewable energy expansion, grid infrastructure development, and industrial cluster strategy. Dedicated renewable corridors for industrial hubs, streamlined access to long term power purchase agreements, and support for captive renewable systems will be essential.

7.4. Mobilising Finance for First Movers

Low-carbon industrial technologies are capital-intensive and face cost uncertainties during early deployment stages. Without financial de-risking instruments, private actors may delay investment decisions. This needs to be done through blended financing frameworks

and execution structures. Carbon pricing needs to be legitimised for long-term investment signaling.

7.5. Strengthening Circular Economy Frameworks

Circularity emerges as a cross cutting theme, particularly for steel and aluminium. Expanding scrap availability, formalising collection systems, and improving material recovery rates require institutional reforms beyond plant level interventions by integrating informal recycling networks, establishing digital material tracking systems, and setting recycled content benchmarks in downstream sectors such as construction, automotive, and packaging.

8. Conclusion

India's industrial expansion over the coming decades will be substantial. The central question is whether this expansion locks the country into energy intensive pathways or catalyses a new generation of low carbon production systems. The energy economy model based analysis demonstrates that structural transformation offers a viable pathway to moderate energy demand growth while sustaining output expansion. Hydrogen-based steelmaking, clinker reduction in cement, and recycling-driven aluminium production are not marginal adjustments but foundational shifts in industrial architecture. The policy implication is therefore strategic rather than incremental by aligning technology innovation, infrastructure development, market creation, and financial support into a coherent transition framework.

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