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This report is intended to communicate research results and improve public understanding of global environment and energy challenges, thereby contributing to informed debate about climate change and the economic and social implications of policy alternatives.

—Ronald G. Prinn,
Joint Program Director

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Economic Analysis of the Hard-to-Abate Sectors in India

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Abstract: We assess the contribution of India's hard-to-abate sectors to the country's current emissions and their likely future trajectory of development under different policy regimes. We employ an enhanced version of the MIT Economic Projection and Policy Analysis (EPPA) model to explicitly represent the following hard-to-abate sectors: iron and steel, non-ferrous metals (copper, aluminum, zinc, etc.), non-metallic minerals (cement, plaster, lime, etc.), and chemicals. We find that, without additional policies, the Paris Agreement pledges made by India for the year 2030 still can lead to an increasing use of fossil fuels and corresponding greenhouse gas (GHG) emissions, with projected CO_2 emissions from hard-to-abate sectors growing by about 2.6 times from 2020 to 2050. Scenarios with electrification, natural gas support, or increased resource efficiency lead to a decrease in emissions from these sectors by 15-20% in 2050, but without carbon pricing (or disruptive technology changes) emissions are not reduced relative to their current levels due to growth in output. Carbon pricing that makes carbon capture and storage (CCS) economically competitive is critical for achieving substantial emission reductions in hard-to-abate sectors, enabling emission reductions of 80% by 2050 relative the scenario without additional policies.

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1. Introduction

India is facing a serious threat from global climate change and local air pollution. To make a viable contribution to the internationally agreed goal of limiting the global temperature rise to less than 2 degrees Celsius relative to the pre-industrial temperature, India will require a transformation of its energy system over the upcoming decades. To meet India's growing demand for energy amid efforts to stabilize the climate impacts and reduce air pollution will require the deployment of low carbon energy sources on a massive scale, but mobilizing the financial resources, technological advances, public opinion and political determination needed to move toward net zero emissions will be a challenging undertaking. To avert dangerous climate change, emissions from every sector should be reduced.

There are several global studies related to the decarbonization of industry. For example, the International Energy Agency (IEA) recently issued an Iron and Steel Technology Roadmap (IEA, 2020a), Habert *et al* (2020) looked at decarbonization strategies in the cement and concrete industries, and Rissman *et al* (2020) provided a review of technologies and policies to decarbonize global industry. There are also studies that focus exclusively on India's industries. In particular, The Energy and Resource Institute assessed the options for the Indian steel sector (TERI, 2020) and the World Business Council for Technology Development provided a roadmap for the Indian cement sector (WBCSD, 2018). However, the details for mitigation options in the hard-to-abate sectors (cement, iron and steel, non-ferrous metals, chemicals) in India have not been explored for their interdependencies, costs, and impacts.

In this study, we employ an enhanced version of the MIT Economic Projection and Policy Analysis (EPPA) model (Paltsev *et al.*, 2005; Chen *et al.*, 2016, Morris *et al.*, 2019) to explicitly explore hard-to-abate sectors in India—their existing emission contributions, their near-term (i.e., up to 2030) and medium-term (i.e., up to 2050) options for emissions reductions, and projections of their future trajectories of development under different scenarios. We provide a consistent view of decarbonization options to quantify the magnitude of the changes in energy use and emissions for several pathways that include electrification, natural gas support, resource efficiency, carbon pricing, and carbon capture and storage (CCS) deployment. We also consider the potential for hydrogen use in steel production. Our findings can be used to help decision-makers to design efficient pathways to reduce emissions in hard-to-abate sectors.

The paper is organized in the following way. In Section 2 we describe the current energy use and emissions from the hard-to-abate sectors in India. Section 3 presents the model and scenarios. Section 4 discusses the results of projections under different scenarios. Section 5 concludes.

2. Historic Trends for Energy Use and Emissions from Hard-to-Abate Sectors in India

India's economy is fast growing. In the period from 1981 to 2000, India's GDP grew at an annual average rate of 5.6%/year. Between 2001–2020, India's GDP grew even faster, at an annual average rate of 6.4%/year (IMF, 2021). This economic growth was fueled by an increase in energy use. Since fossil fuels have been dominating India's energy mix, economic growth also resulted in the rising greenhouse gas (GHG) emissions. India's GHG emissions grew from about 1,000 Megatonnes of CO_2-equivalent ($MtCO_2e$) in 1990 to about 1,600 $MtCO_2e$ in 2000, to about 2,175 $MtCO_2e$ in 2010, and to about 3,000 $MtCO_2e$ in 2018 (Climate Action Tracker, 2021). While India's GHG emissions have been growing slower than India's economy, GHG emissions are projected to increase for several decades, in particular due to the continuing reliance on coal for India's energy needs (IEA, 2020; MIT Joint Program, 2021). De-coupling the economic growth from GHG growth would require a clear pathway for a transition from unabated coal use to low-carbon regulations.

India's official GHG emissions are reported in National Communications and Biennial Updates to the United Nations Framework Convention on Climate Change (UNFCCC). The detailed data in these reports are available for 2000, 2007, 2010, 2014, and 2016 (MoEF, 2012; MoEFCC, 2015, 2018, 2021). CO_2 emissions make up a significant portion of the total GHG emissions. For example, in 2016 India's CO_2 emissions were about 2,230 $MtCO_2$, while total GHG emissions were about 2,840 $MtCO_2e$.

Emission reporting for industry in the official submissions to UNFCCC is divided into those related to energy use (i.e., combustion of fossil fuels) and process-related emissions (e.g., from the calcination process in cement production or from the feedstock in chemical production). **Figure 1** shows that in 2016, industrial emissions were about 27% of India's total CO_2 emissions (fuel emissions were 19% and process emissions were 8%).

Industrial emissions increased substantially over time. As shown in **Table 1**, energy use (fuel) related CO_2 emissions increased from 228 $MtCO_2$ in 2000 to 396 $MtCO_2$ in 2016. Process CO_2 emissions increased from 73 $MtCO_2$ in 2000 to 166 $MtCO_2$ in 2016. As a result, the total CO_2 emissions from India's industry increased from about 300 $MtCO_2$ in 2000 to about 560 $MtCO_2$ in 2016. It should be noted that the official data have a large portion of industrial emissions that is not assigned to a specific sector. For our sectoral analysis, we rely on the data from the Global Trade Analysis Project (GTAP), that provides the global data, including the data for India (Aguiar *et al.*, 2019).

A substantial share of India's emissions come from the so called "hard-to-abate sectors" (production of iron and steel,

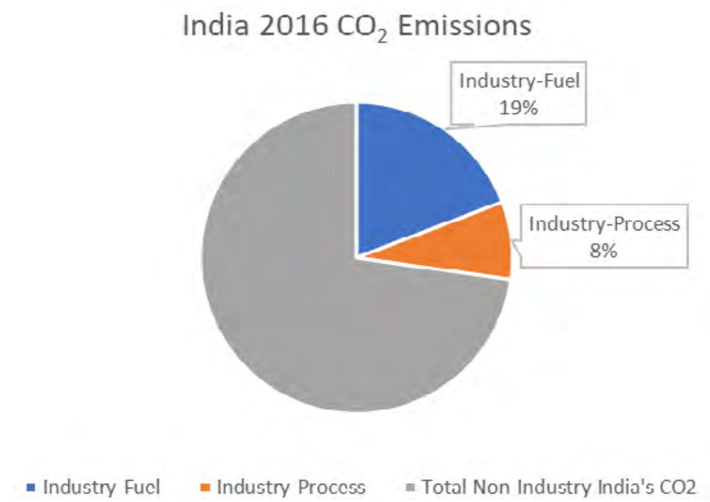

Figure 1. India's CO_2 Emissions in 2016. Data Source: MoEFCC (2021).

Table 1. Industry CO_2 emissions in India. Data source: MoEF (2012), MoEFCC (2015, 2018, 2021).

Mt CO2	2000	2010	2014	2016
Total CO_2 Emissions in India	1024.8	1574.4	1997.9	2231.0
Energy Use Related Emissions in India (Fuel)	952.2	1441.9	1844.7	2064.8
Energy Use in Industry ("Industry-Fuel")	**228.2**	**299.2**	**350.2**	**395.9**
Iron and Steel (Fuel)	52.4	95.5	153.9	134.7
Cement (Fuel)	39.7	40.5	46.9	53.5
Non-Ferrous Metals (Fuel)	1.9	1.9	1.7	7.7
Chemicals (Fuel)	34.5	7.9	2.0	2.0
Pulp and Paper (Fuel)	5.3	6.7	3.9	2.6
Unspecified/Other Small Items (Fuel)	94.4	146.7	141.8	195.4
Industrial Processes and Product Use ("Industry-Process")	**72.6**	**132.5**	**153.2**	**166.2**
Mineral Products	53.6	104.5	126.9	135.5
Cement (Process)	44.1	83.8	115.3	106.6
Chemical Industry	15.8	19.5	18.5	21.3
Ammonia (Process)	11.1	12.6	10.2	11.5
Ethylene (Process)	3.3	5.1	6.2	7.6
Metal Production	**2.5**	**6.8**	**5.7**	**7.2**
FerroAlloys (Process)	1.5	3.7	2.5	2.7
Aluminum (Process)	1.0	3.1	3.1	4.5
Total Industry Emissions (Fuel+Process)	**300.8**	**431.7**	**503.4**	**562.1**

cement, non-ferrous metals and chemicals), where decarbonization options are limited and more expensive in comparison to other sectors of economy (such as power generation and transport). Emissions from these "hard-to-abate" industries are notoriously difficult to reduce because, in addition to emissions associated with energy use, a significant portion of industrial emissions come from the process itself. For example, in the cement industry, about half of the emissions come from the decomposition of limestone into lime and CO_2. While a shift to zero-carbon energy sources such as solar or wind-powered electricity could lower CO_2 emissions in the power sector and other energy needs, there are no easy substitutes for emissions-intensive industrial processes.

Figure 2 shows energy use (by type of fuel) in the hard-to-abate sectors in 2014 as represented in the GTAP dataset (Aguiar *et al.*, 2019). Coal use has a large share in iron and steel and cement production. All sectors have electricity inputs, and currently the electricity production is coal-based as well (in 2019 about 72% of India's electricity generation was coal-based, according to IEA (2020)). The majority of

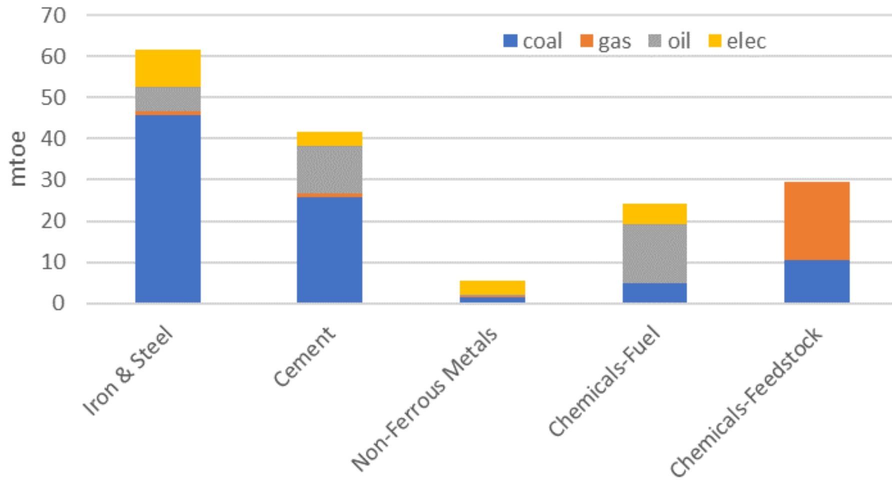

Figure 2. Fuel Use in Industry in 2014. Data Source: GTAP (Aguiar *et al.*, 2019)

Table 2. Shares of Fossil Fuels in 2014.

	Use in Hard-to-Abate Sectors (mtoe)	Share of Fuel Type Relative to Total Fossil Fuel Use in Hard-to-Abate Sectors (%)	Total Primary Energy Use (mtoe)	Share of Fuel Use in Hard-to-Abate Sectors Relative to Total Use of This Fuel (%)
Coal	89	63	378	23
Oil	32	23	185	17
Gas	21	15	43	48

natural gas in industry is used as a feedstock rather than as a fuel. Oil use is also quite sizable in industry. Following GTAP, the oil category includes refined oil and processed coal (i.e., petcoke and coke). Decarbonizing energy inputs to the industrial sectors requires higher electrification where possible (provided that the electricity sector is moving to low-carbon options), various energy efficiency measures, and novel technological routes, such as carbon capture and storage (CCS) and the use of zero-carbon hydrogen as a heat source and chemical feedstock. We explore some of these options in our scenarios described in Section 3.

In terms of shares of fossil fuels, about a half of India's natural gas, about a quarter of coal and about one-fifth of oil are used in the hard-to-abate sectors (**Table 2**). The remaining use of fossil fuels in India are in electricity production (about 70% of coal is used in power generation) and transportation (more than 40% of oil use is in the transport sector). Natural gas is also used in the electricity sector (about 30% of total natural gas is used for power generation).

3. Analytical Approach

To explore the energy mix and the resulting emissions in the hard-to-abate sectors and to analyze energy and emission pathways for decarbonization of industry in India, we employ the MIT Economic Projection and Policy Analysis (EPPA) model – the part of the MIT Integrated Global Systems Model (IGSM) that represents the human systems (Paltsev *et al,* 2005, Chen *et al.*, 2016). The EPPA model is a recursive-dynamic, multi-region, multi-sector, dynamic general equilibrium model of the world economy, which is built on the GTAP dataset and additional data for GHG and urban gas emissions, taxes and details of selected economic sectors. Provision is made for analysis of uncertainty in key human influences, such as the growth of population and economic activity and the pace and direction of technological advances.

The EPPA model is designed to develop projections of economic growth, energy transitions and anthropogenic emissions of greenhouse gases and air pollutants. The model projects economic variables (GDP, energy use, sectoral output, consumption, etc.) and emissions of greenhouse gases (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) and other air pollutants (CO, VOC, NOx, SO_2, NH_3, black carbon, and organic carbon) from combustion of carbon-based fuels, industrial processes, waste handling, agricultural activities and land use change.

Table 3 presents the scenarios up to 2050 that we have considered, with a focus on electrification, natural gas support, resource efficiency, carbon pricing, and carbon capture and storage. We consider four scenarios without carbon pricing and four scenarios with carbon pricing. The scenarios differ by their assumptions about policy support and technology options available in the future.

The *Reference* scenario is based on the current policy setting in India and an assumption that the Covid-19 pandemic is brought under control in 2021. In this scenario we impose India's emission intensity pledge for the Paris Agreement process (reducing India's emission intensity of GDP by 33–35% by 2030 relative to 2005 level). In this scenario, India's GDP returns to the pre-Covid levels in 2022 and India's average annual GDP growth rates are: 4.5% from 2020 to 2024, 6.4% from 2025 to 2029 and 4.5% from 2030 to 2050 (see Appendix for details).

In the *Electrification* scenario, we assume support for a wider use of electricity in industry by providing a subsidy for electricity inputs to incentivize deployment of electric boilers, electric arc furnaces, and wider use of solar and wind power. We also assume that coal use in industry is penalized (a tax is imposed on coal inputs at a rate of 35%) in this scenario. For electricity, we assume a subsidy of 10% to the cost of electricity in industrial use. The level of the subsidy was chosen for illustrative purposes as a simplified way to represent public incentives toward electrification; we are not aware of any plans by the government for such policy. Higher levels of support were also explored. Directionally, larger subsidies lead to similar outcomes in terms of energy mixes, but they would require substantial government revenue to be raised, hence we focus on the levels of manageable electrification support in our scenarios.

In the *Natural Gas Support* scenario, price incentives are introduced to expand natural gas infrastructure and the use of natural gas as an energy input. For example, in steelmaking it incentivizes a natural gas-based direct reducing iron process. For illustrative purposes, we assume a subsidy of 10% to the cost of natural gas in industrial use. We also assume that coal use in industry is penalized in this scenario (tax is imposed on coal inputs as in the electrification scenario).

The *Resource Efficiency* scenario is based on movement to a more resource efficient and circular economy. In this scenario, we assume an increase in the lifetime of products through improved production processes, higher quality input materials and a higher recycling rate that reduces the amount of virgin materials. Following TERI (2019), we assume an increase of 10% in the lifetime of steel products and an increase by 10% of the recycle rate. Processing of recycled steel requires less energy. Steel intensity can be reduced in products by greater substitution with other materials (e.g., aluminum or plastics). In this scenario, we made similar assumptions for other industrial sectors (e.g., use of plastics in chemicals, aluminum in non-ferrous metals, higher-quality cement and concrete).

For carbon pricing, we assume two profiles (**Figure 3**), where the higher carbon price is consistent with the assumption from the Sustainable Development Scenario of the IEA World Energy Outlook (IEA, 2020b). Note that currently India does not have carbon pricing and we are not aware of any immediate plans by the government of India to introduce carbon prices. We consider our carbon price scenarios for illustrative purposes.

In the *Low Carbon Price* scenario, an economy-wide carbon price is imposed in 2025 at a level of 5\$/tCO_2. It grows linearly over time to reach 80\$/tCO_2 by 2050. The carbon price is paid on all fossil inputs based on their carbon content. We do not allow carbon capture and storage (CCS) technology in industry in this scenario.

In the *High Carbon Price* scenario, we impose a similar economy-wide carbon pricing policy, but the price level is higher. The carbon price is imposed in 2025 at 43\$/tCO_2. It grows linearly over time to reach 175\$/tCO_2 by 2050. We do not allow CCS technology in industry in this scenario.

In the *CCS and Low Carbon Price* scenario, we assume the carbon prices from the *Low Carbon Price* scenario, but in addition we allow CCS to be built when it is economic

Table 3. Scenarios.

Name	Paris Pledge	Carbon Price in 2025	Carbon Price in 2050	CCS Available	Additional Comments
Reference	Yes	No	No	No	Base GDP growth
Electrification	Yes	No	No	No	EAF in iron and steel, electric boilers, solar and wind support
Natural Gas Support	Yes	No	No	No	Price incentives for natural gas, gas-based DRI, gas infrastructure
Resource Efficiency	Yes	No	No	No	Increase durability, materials substitution, increased energy efficiency
Low Carbon Price	Yes	5	80	No	CCS not allowed; *Reference* setting for other technologies
High Carbon Price	Yes	43	175	No	CCS not allowed; *Reference* setting for other technologies
CCS and Low Carbon Price	Yes	5	80	Yes	CCS enters when economic; *Reference* setting for other technologies
CCS and High Carbon Price	Yes	43	175	Yes	CCS enters when economic; *Reference* setting for other technologies

Figure 3. Carbon price assumptions. Dots for 2025 and 2040 reflect carbon prices from the Sustainable Development Scenario from IEA's 2020 World Energy Outlook.

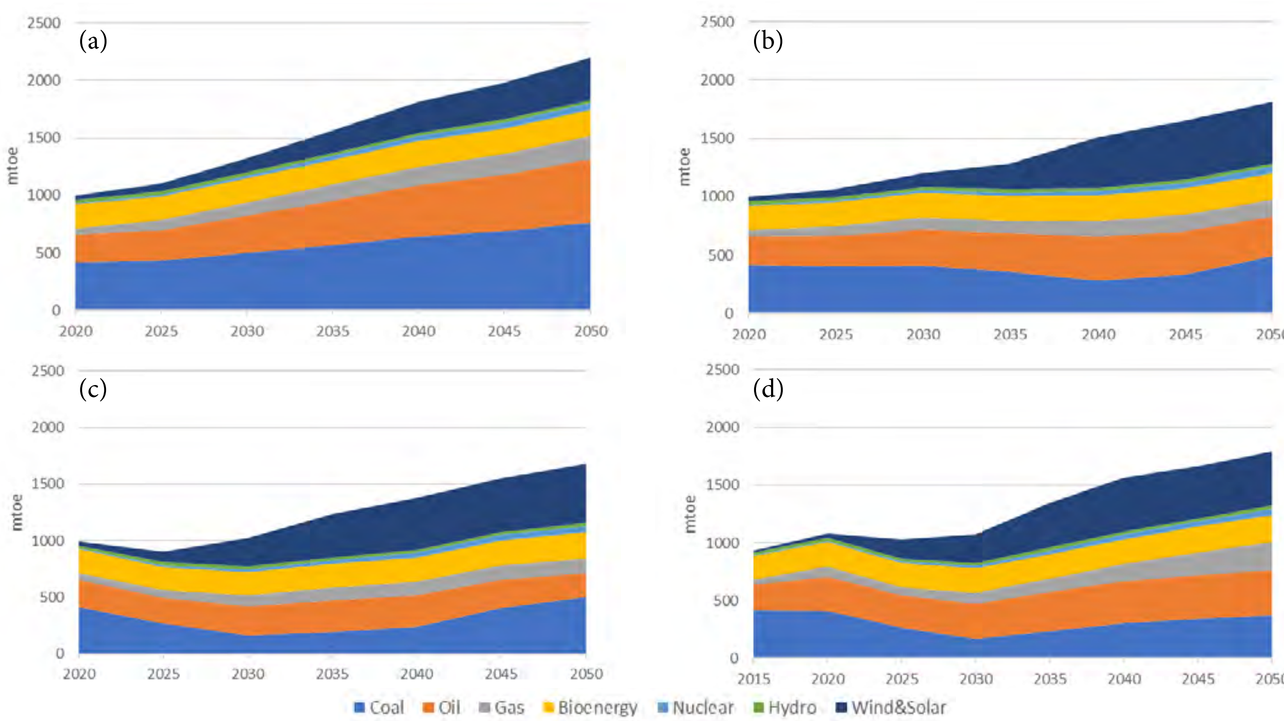

Figure 4. Primary Energy Use in India in Selected Scenarios: (a) *Reference*, (b) *Low Carbon Price*, (c) *High Carbon Price*, (d) *CCS and High Carbon Price*.

to do so. For the costs of CCS in industry, we rely on assessments by Farrell (2018) and Paltsev *et al* (2021) and assume that production costs increase by 25% when carbon capture is deployed in the cement and chemicals sectors. In the steel and aluminum sectors, the cost increases due to CCS are 15%.

In the *CCS and High Carbon Price* Scenario, we assume the carbon prices from the *High Carbon Price* scenario and in addition we allow CCS to be built when economic. We use the same assumptions for CCS costs as in the previous scenario.

4. Results

4.1 Primary Energy Use in India

We project substantial growth in energy consumption in India in all scenarios. **Figure 4** presents the results for total primary energy use in selected scenarios (reporting for 2020–2050 for all scenarios is provided in the Appendix). In the *Reference* setting, energy use more than doubles from 2020 to 2050. It grows from about 1,000 million tonnes of oil equivalent (mtoe) in 2020 to about 2,200 mtoe in 2050.

Without additional policies, use of all fossil fuels continues to expand, with natural gas being the fastest growing fossil fuel (from 2020 to 2050, natural gas use increases 3.4 times). At the same time, the growth of variable renewables (solar and wind) is even greater. By 2050, they exhibit an almost 10-fold increase from the 2020 levels.

Scenarios of technology support in the hard-to-abate sectors (not shown in Figure 4) do not substantially change the trajectories for economy-wide primary use, while carbon pricing scenarios slow down fossil fuels growth and incentivize variable renewables even more. The share of fossil fuels in primary energy use stays about the same over time in the *Reference* scenario (72% in 2020 vs 69% in 2050), while carbon pricing reduces the share of fossil fuels in the total energy mix. By 2050 it is reduced to 54% in the *Low Carbon Price* scenario and to 50% in the *High Carbon Price* scenario.

In the *Low Carbon Price* scenario, variable renewables grow almost 14-fold between 2020 and 2050, which is faster growth in comparison to the scenarios without carbon pricing. In 2050, variable renewables are 45% larger (530 mtoe vs 370 mtoe) in comparison to the *Reference* scenario. In the other carbon pricing scenarios (which include *High Carbon Price*, *CCS and Low Carbon Price*, *CCS and High Carbon Price*), variable renewables show a similar growth pattern, where by 2050 they increase to about 470–530 mtoe. We estimate that this level of power generation requires about 750 GW of solar capacity and about 250 GW of wind capacity in 2050.

We estimate that the land required for installing the variable renewables might create a challenge. For our calculations of the land requirement for solar and wind power generation, we make the following assumptions. According to NREL (2019), installing 1 Megawatt (MW) of solar power capacity requires 1 hectare (ha, 0.01 sq.km) and installing 1MW of wind requires 24.3 ha (0.243 sq.km). For wind, only 2% of that area is used directly by turbines and other supporting infrastructure, the remaining area might be used for other purposes (e.g., farming). Applying these assumptions, we can estimate the land requirements for wind and solar in 2050. 750 GW of solar capacity would need 7,500 sq.km of land, while the land for 250 GW of wind farms would take 60,750 sq.km, with 1,200 sq.km of land directly used by wind turbines.

To put these numbers into perspective, the area needed for solar panels in 2050 would be twice the size of the state of Goa. Total area required for wind farms in 2050 is larger than the state of Kerala. Even with only 1–2% of wind farm area directly dedicated to wind turbines (and other space usable for farms, roads, etc.), the change in land usage is quite substantial.

4.2 Energy Intensity and Emission Intensity of India's GDP

Energy intensity of GDP (i.e., how much energy is used to produce a unit of GDP) and emission intensity of GDP (i.e., how many tonnes of CO_2 are emitted to produce a unit of GDP) are improving over time in all scenarios. **Table 4** presents energy intensity expressed in mtoe per billion 2015 US dollars of GDP. The amount of energy needed to produce a unit GDP decreases from 0.35 mtoe/billion USD in 2020 to 0.16–0.19 mtoe/billion USD in different scenarios.

As a pledge for the Paris Agreement's Nationally Determined Contribution (NDC), India's main target is to reduce its emission intensity of GDP by 33–35% by 2030, relative to the 2005 level. In all scenarios, India over-achieves its Paris Agreement pledge. Even in the *Reference* scenario, emission intensity is about 40% below the 2005 level. **Table 5** shows that emission intensity of GDP without carbon pricing is reduced by 50–55% from 2020 to 2050. In the same period, in the low carbon pricing scenarios, emission intensity is reduced by about 75% and in the high carbon pricing scenario it declines by about 90%.

4.3 Energy Use in the Hard-to-Abate Sectors

We begin with the major results for a combined hard-to-abate sector, which includes iron and steel, cement, non-ferrous metals, and chemicals. A detailed look at individual sectors is provided in Sections 4.5–4.8. Energy use in the hard-to-abate sectors grows at a higher rate than India's primary energy use. **Figure 5** illustrates energy use inputs to the hard-to-abate sectors in selected scenarios (information for all scenarios is provided in the Appendix). In the *Reference* scenario, energy use in the hard-to-abate sectors grows 2.8 times from 2020 to 2050. For a comparison, total primary energy in India is projected to grow 2.2 times in the same period. Technology support scenarios push their corresponding fuels (electricity and natural gas). Carbon pricing reduces coal use and overall energy use, and also brings more electricity into the mix.

While technology support and carbon policy impositions increase the use of particular types of fuels and result in overall demand responses, the overall fuel mix does not change substantially in any scenario in the next 10 years due to a large share of production from the existing fleet of facilities. However, by 2050, the changes are pronounced. In particular, the electricity share increases, but electricity use in cement and chemicals is limited by process and feedstock requirements. Coal use is not eliminated in any scenario (as discussed later, mostly due to steel and cement sectors that continue to use coal). Moreover, enabling CCS technology increases coal use in these sectors in comparison to carbon pricing without CCS. The shares of natural gas grow, but they remain limited, especially in the cement and aluminum production sectors.

Table 4. Energy Intensity of GDP in India (mtoe/billion of 2015 USD).

Name	2020	2025	2030	2035	2040	2045	2050
Reference	0.35	0.31	0.28	0.25	0.23	0.20	0.19
Electrification	0.35	0.31	0.27	0.25	0.23	0.20	0.19
Natural Gas Support	0.35	0.31	0.27	0.24	0.22	0.20	0.19
Resource Efficiency	0.35	0.31	0.26	0.23	0.21	0.19	0.17
Low Carbon Price	0.35	0.30	0.25	0.21	0.20	0.18	0.17
High Carbon Price	0.35	0.27	0.23	0.21	0.19	0.18	0.16
CCS and Low Carbon Price	0.35	0.30	0.25	0.21	0.20	0.18	0.16
CCS and High Carbon Price	0.35	0.27	0.23	0.21	0.19	0.18	0.17

Table 5. Emission Intensity of GDP in India (Mt CO_2/billion of 2015 USD).

Name	2020	2025	2030	2035	2040	2045	2050
Reference	0.83	0.71	0.62	0.54	0.49	0.44	0.41
Electrification	0.83	0.70	0.60	0.53	0.47	0.42	0.40
Natural Gas Support	0.83	0.70	0.60	0.53	0.47	0.42	0.39
Resource Efficiency	0.83	0.69	0.56	0.49	0.44	0.39	0.36
Low Carbon Price	0.83	0.68	0.56	0.42	0.32	0.27	0.22
High Carbon Price	0.83	0.49	0.31	0.25	0.17	0.13	0.10
CCS and Low Carbon Price	0.83	0.68	0.56	0.42	0.32	0.27	0.20
CCS and High Carbon Price	0.83	0.49	0.31	0.22	0.14	0.10	0.07

Figure 5. Energy Use in Hard-to-Abate Sectors in Selected Scenarios: (a) *Reference,* (b) *Natural Gas Support,* (c) *Low Carbon Price,* (d) *CCS and High Carbon Price.*

Total energy use in the hard-to-abate sectors grows from about 200 mtoe in 2020 to about 200–300 mtoe in 2030 (lower range numbers are for the high carbon pricing scenarios) and to about 300–550 mtoe in 2050 (the lower range numbers are for the high carbon pricing scenarios). Technology support does not substantially change energy input shares for the aggregate hard-to-abate sector. Deployment of CCS leads to an increase in energy use in carbon pricing scenarios by mid-century.

Figure 6 focuses on the results for natural gas use in the hard-to-abate sectors in 2030 and 2050 (information for all energy inputs is provided in Appendix). The use of natural gas increases from 24 mtoe in 2020 to 40–73 mtoe in 2030 (lower range numbers are for the carbon pricing scenarios and resource efficiency scenario) and to 46–182 mtoe in 2050 (lower range number is for the high carbon price scenario without CCS). Not surprisingly, the *Natural gas support* scenario leads to the largest increase in gas usage. In this scenario, natural gas use in the hard-to-abate sectors triples from 2020 to 2030 and it grows 7.5-times from 2020 to 2050.

4.4 CO_2 Emissions in the Hard-to-Abate Sectors

Sustaining projected output growth while reducing CO_2 emissions poses immense challenges. **Figure 7** provides an overall picture for emission trajectories in the hard-to-abate sectors in different scenarios. While we explore the results for individual sectors in the later sections, we note that technology support (electrification, natural gas) has rather limited impact on emission reductions because of the long life of the existing assets. Technology support results in more efficient production in terms of emissions, but continuing demand growth and limited economic competitiveness of alternative options (without aggressive targeted measures from the government) makes these achievements insufficient for a low-carbon transition. Imposition of carbon pricing which incentivizes carbon capture and storage (CCS) substantially reduces the resulting emissions for the hard-to-abate sectors (80% reduction), but even with CCS deployment, emissions are not completely eliminated, mostly due to emissions from the chemical sector that currently lacks viable zero-emission options.

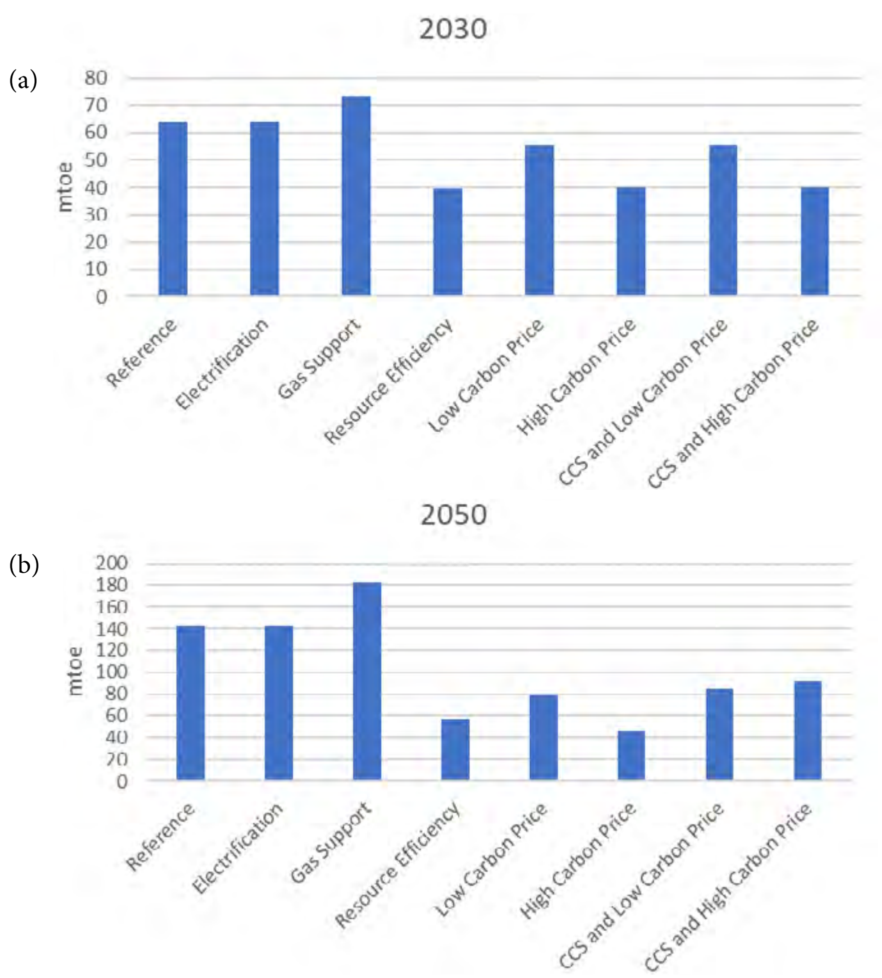

Figure 6. Natural Gas Use in Hard-to-Abate Sectors in: (a) 2030, (b) 2050.

Figure 8 shows the CO_2 contribution of individual sectors for the *Reference* and *CCS and High Carbon Price* scenarios (detailed sectoral results are discussed in Sections 4.5–4.8 and the results for all scenarios are provided in Appendix). In the *Reference* scenario, substantial shares of emissions are projected to come from cement (fuel and process), iron and steel, and chemicals. As seen in Figure 8, imposition of carbon pricing that incentivizes CCS substantially reduces the resulting emissions from iron and steel and cement. In the chemical sector, CCS becomes economic only by mid-century. Industrial CCS plays a smaller role in non-ferrous metals production due to its heavy reliance on electricity for energy input.

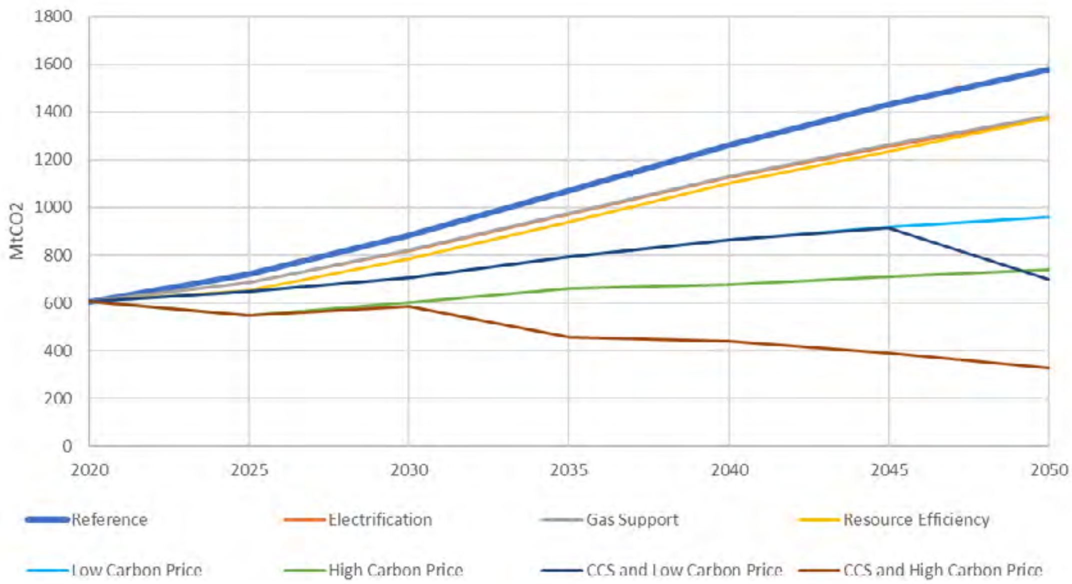

Figure 7. CO_2 Emissions in Hard-to-Abate Sectors.

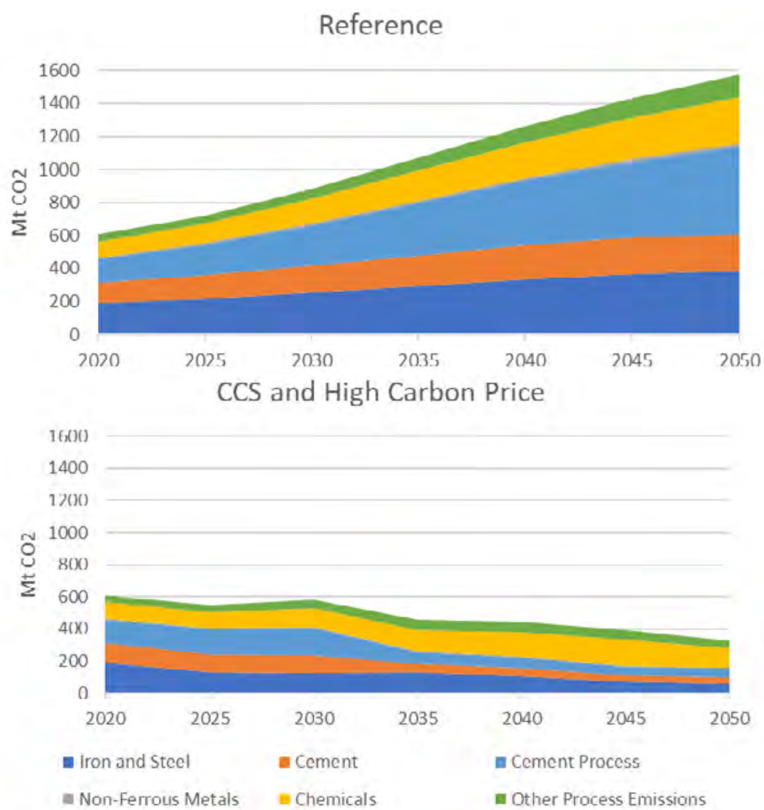

Figure 8. CO_2 Emissions in Hard-to-Abate Sectors in Extreme Scenarios: *Reference* and *CCS and High Carbon Price*.

4.5 Iron and Steel Production

Steel production in India has been growing fast—from 27 Mt in 2000, to 68 Mt in 2010, and to 90 Mt in 2015. According to the World Steel Association, now India is the second-largest world producer with 111 Mt of steel produced in 2019 (WSA, 2020) and 142 Mt of steel production capacity (TERI, 2020). India has an ambitious target for future steel capacity growth. The National Steel Policy envisions that steelmaking capacity in India would double in the next 10 years and reach 300 Mt by 2030 (IBEF, 2021).

In terms of energy inputs, steelmaking in India is mostly coal-based (see Figure 2) and about half of steel is produced with blast furnace-basic oxygen furnace (BF-BOF) technology (TERI, 2020). Another half of the steel production is done with direct reduced iron (DRI) – electric arc furnace (EAF) and electric induction furnace (IF) technology. In contrast to many countries (Russia, Iran) where DRI process is natural gas-based, in India DRI is coal-based.

The transition to a low-carbon economy would require a portfolio of steel-making technologies. Among the shorter-term options for emission reductions are an increase in energy efficiency, increase in recycled steel scrap, and replacement of coal with natural gas in the DRI process. Several options are feasible in the longer-term: deployment of carbon capture and storage (CCS) on BF-BOF; advanced low-carbon (LC) processes (like the Hisarna process developed by Tata Steel), which are emission-reducing and also attractive for CCS; use of hydrogen for high-temperature heat and/or the reducing agent in DRI; further increases in use of scrap (less need for DRI); and enhancing resource efficiency (increasing durability, materials substitution in construction, etc.). IEA (2020a) provides a detailed description of the challenges and opportunities associated with low-carbon steelmaking options.

Our projections for India's steel production are represented in **Figure 9**. In 30 years, India's steel production grows 3.8–3.9-times in the non-carbon pricing scenarios, except for the *Resource Efficiency* scenario, where it grows 5-times due to an increase in scrap availability. Carbon policy impacts steel production, where it grows slower, only 3.4–3.6 times between 2020 and 2050.

Figure 10 provides the projections of steel production by technology routes (BF-BOF and EAF/IF/LC). In the *Reference* scenario the shares of BF-BOF and EAF/IF do not change much between 2020 and 2050 with BF-BOF still contributing 42% to the total steel production (because of lack of economic incentives to substantially change the production processes. However, in all other scenarios EAF technology grows faster. Steelmaking with CCS reaches a 67% share in 2050 with high carbon prices (discussion of CCS costs is provided in Section 5).

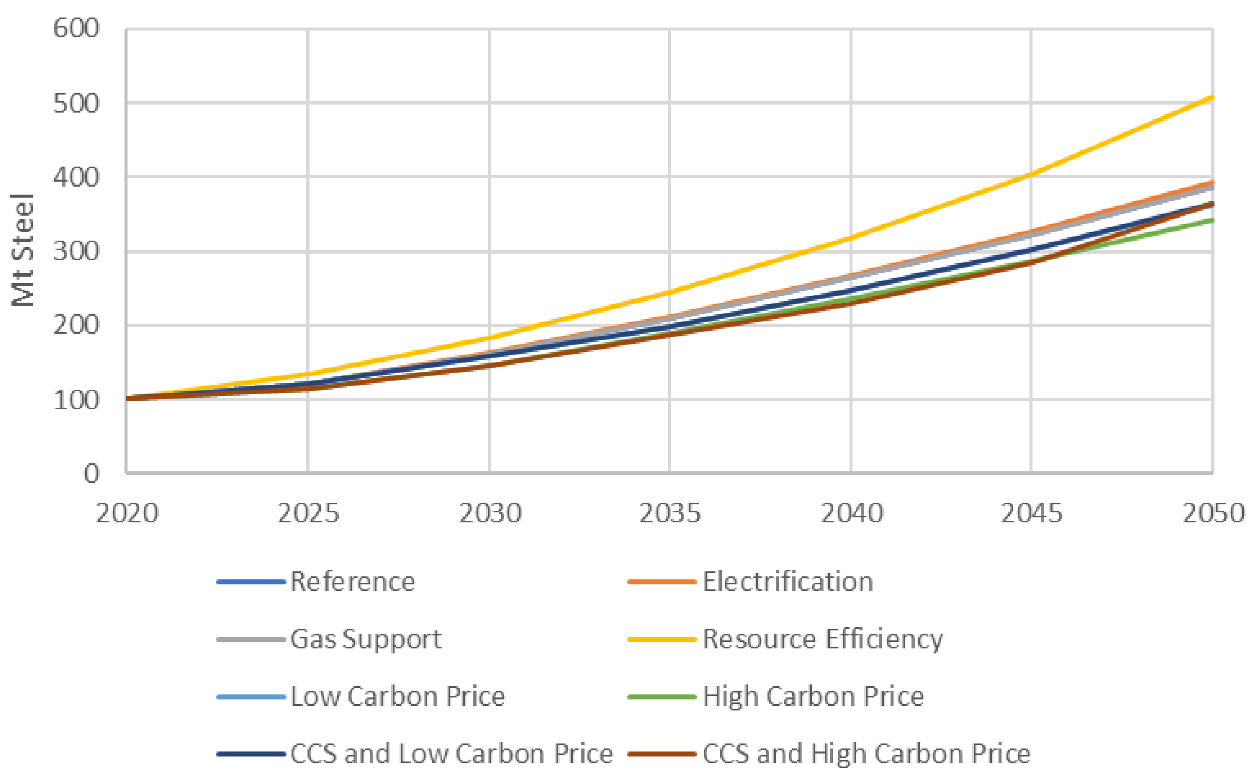

Figure 9. India's Steel Production in Different Scenarios.

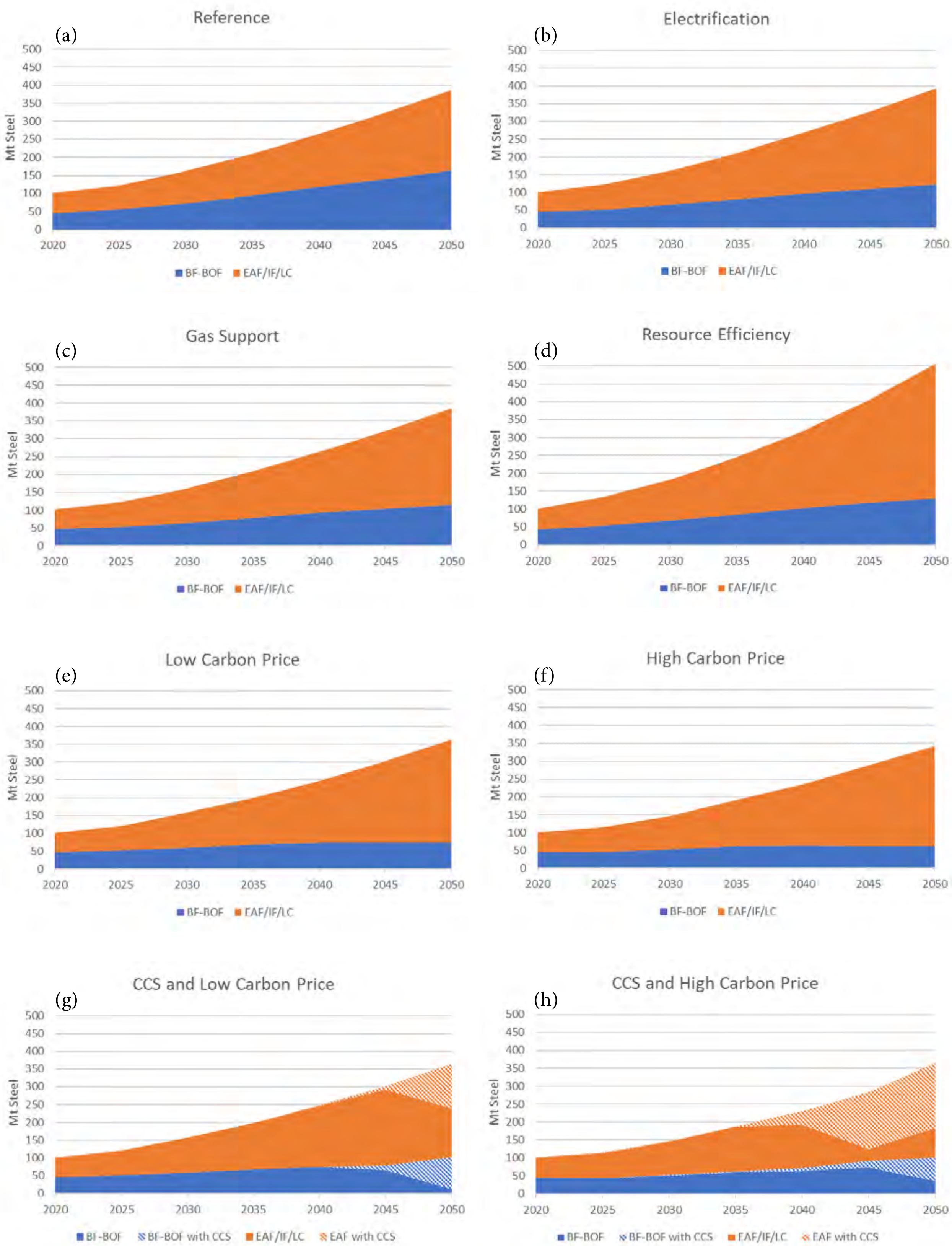

Figure 10. India's Steel Production by Technology in Different Scenarios.

Energy use in steel production varies between different scenarios. **Figure 11** shows the fuel mix in 2030, when coal is still a dominant energy input. **Figure 12** provides this information for 2050, when coal use is substantially reduced in several scenarios (*Resource Efficiency*, *Low Carbon Price*, *High Carbon Price*) and electricity use is increased in all scenarios.

In the *Reference* scenario, CO_2 emissions from iron and steel production more than double between 2020 and 2050 (**Figure 13**). *Electrification* and *Natural Gas Support* reduce 2050 emissions by 35% relative to the *Reference*. Carbon pricing scenarios without CCS reduce 2050 emissions by 40–50% relative to 2020 levels. Development of CCS decreases emissions further: in the *CCS and High Carbon Price* scenario, they are lower by almost 70% in 2050 relative to 2020 levels.

Emission intensity of output (measured as tonne of CO_2 emitted per tonne of steel) gradually declines in all scenarios from 2020 to 2050 for steel production (**Figure 14**). Carbon pricing and resource efficiency have a larger impact on emission intensity of steel production. In these scenarios, emission intensities of steel output decrease by 80–90% between 2020 and 2050.

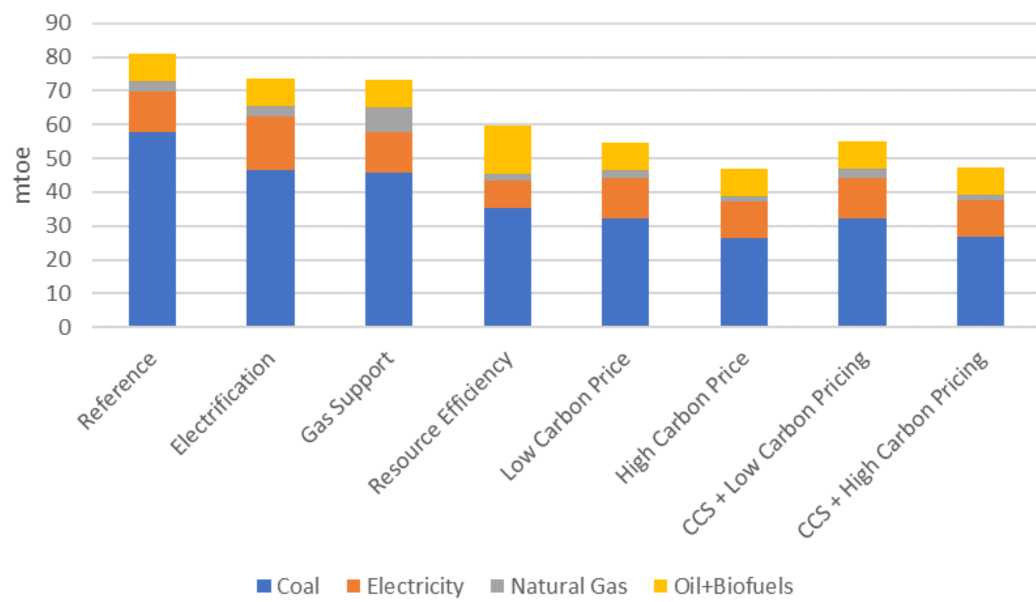

Figure 11. Energy Use in Steel Production in 2030.

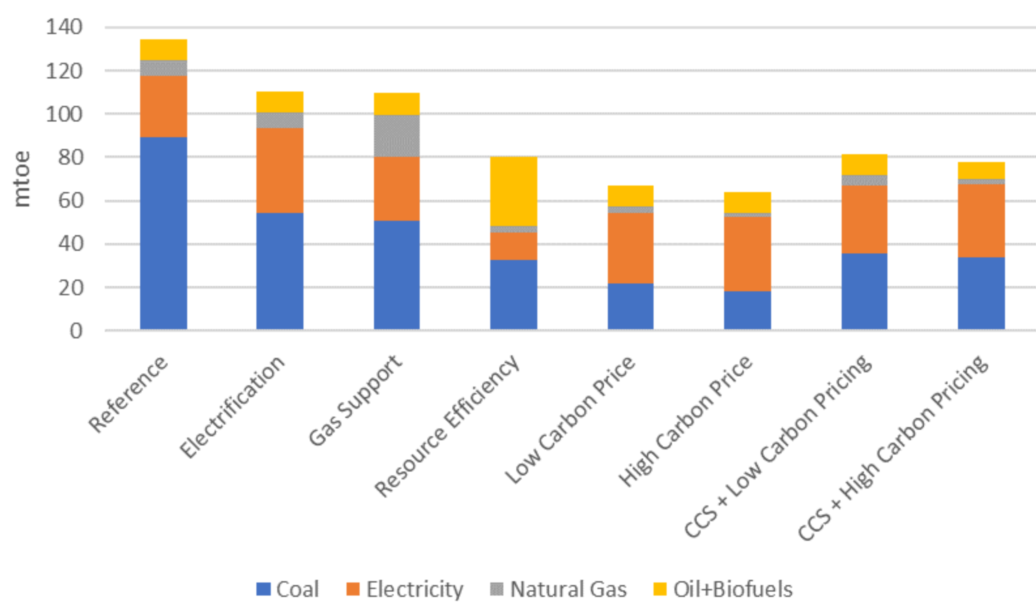

Figure 12. Energy Use in Steel Production in 2050.

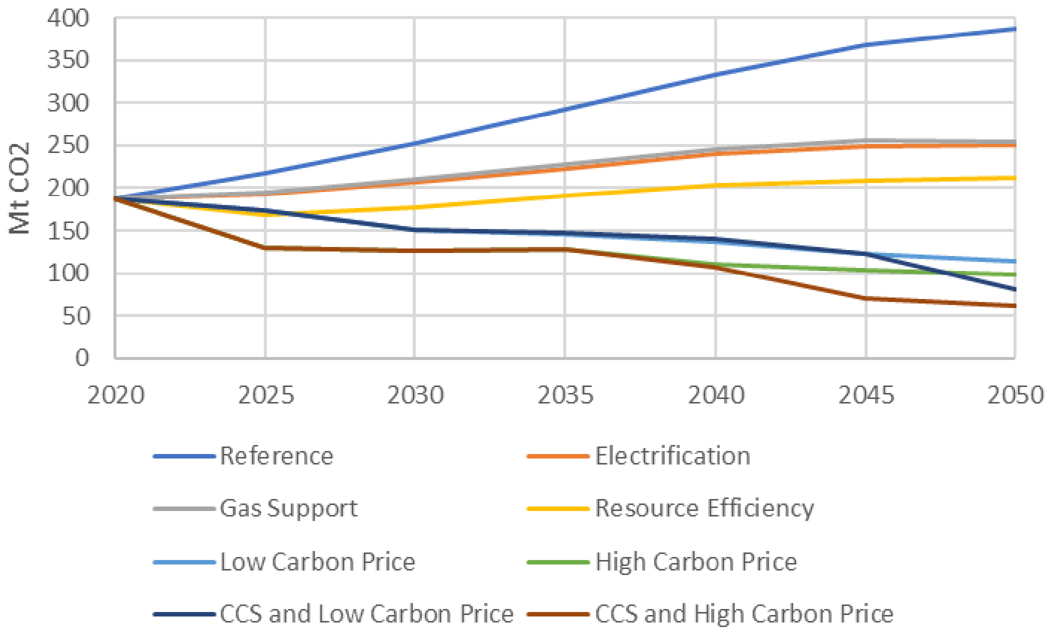

Figure 13. CO_2 Emissions from Iron and Steel Production in Different Scenarios.

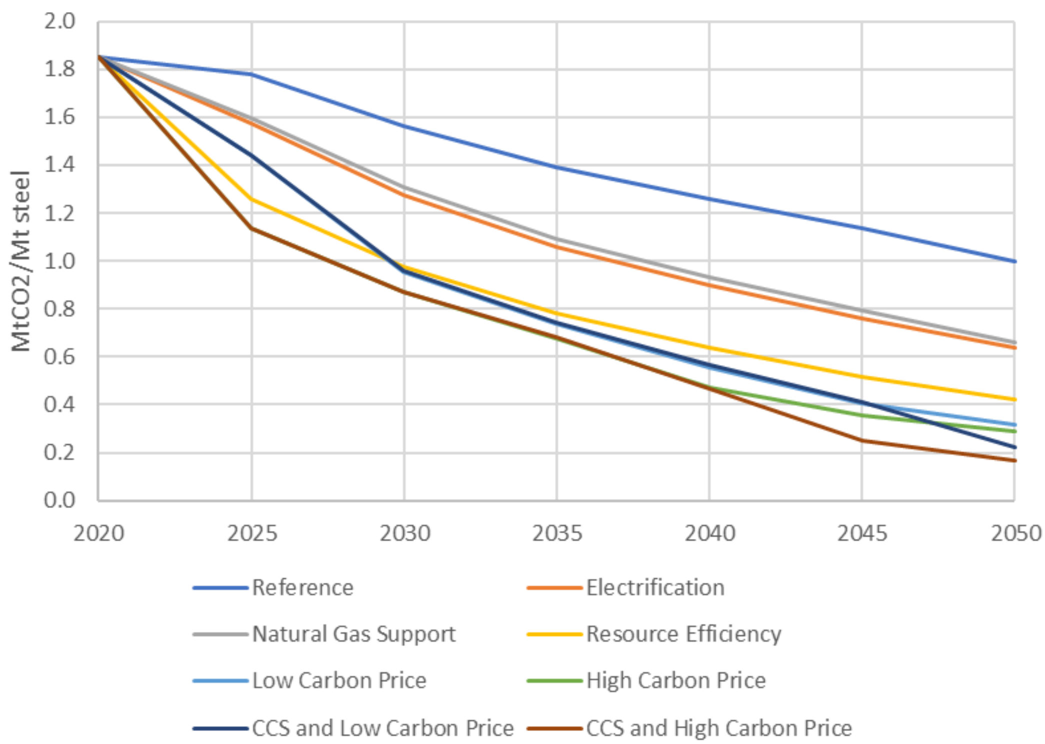

Figure 14. CO_2 Emission Intensity from Iron and Steel Production in Different Scenarios.

4.6 Cement Production

Cement production is a major contributor to the overall emissions in sectors that are hard to decarbonize. As shown in **Figure 15**, cement production in India has been growing steadily, from 175 Mt in 2007 to about 285 Mt in 2015. Production has flattened in 2015–2017, followed by a substantial increase in 2018 to about 340 Mt. After 2018, the production did not grow. As with steel, India is the second-largest cement producer in the world.

Cement production is a localized, low-cost and low-margin industry. The total emissions generated from the cement production process depend on two sources: the process-related emissions resulting from the calcination of the raw meal and the fuel combustion-related emissions generated in the pre-calciner and the kiln (Farrell, 2018). The clinker-cement ratio is one way of measuring the total amount of clinker needed to produce the cement. A low ratio indicates that the cement was formed using less clinker, which inherently emits CO_2 from the calcination process. Various substitutes could be used in place of clinker to produce cement, including fly ash, slag, and limestone, but their applications are extremely limited by their availability (IEAGHG, 2013).

The cost of production substantially affects the profitability of operations and demand for cement. As a result, less efficient but cheaper fuels and production processes are widely employed in different parts of the world, including India. Even in an environmentally-cautious U.S. state of California, the fuel mix in its cement industry in 2015 was dominated by coal, while petroleum coal, electricity, natural gas, tires, and solid waste also provided sizeable contributions (Hasanbeigi and Springer, 2019). For the global fuel combustion-related numbers, Damtoft *et al* (2008) report that modern cement kilns emit approximately 0.31 tCO_2/t clinker, while inefficient kilns emit about 0.6 tCO_2/t clinker. For process-related emissions, CO_2 is determined by the contents of the limestone, which does not change much regardless of the type of process involved. Damtoft *et al* (2008) estimate process-related emissions of 0.53 tCO_2/t clinker, with a world average share of fuel emissions in the total cement CO_2 emissions being equal to 0.41 (and a process-related emission share of 0.59). Hasanbeigi and Springer (2019) report the same percentages (41% for fuel and 59% for process) for fuel and process emissions in California in 2015. The data for India is limited. Based on MoEFCC (2018) and WBSCD (2018), we estimate the shares of fuel emissions and process emissions in India in 2020 as being equal to 0.46 and 0.54.

In terms of CO_2 emission reductions, when about half (to one-third in more efficient settings based on IEA and WBCSD (2018)) of the emissions are related to fuel use and the remaining emissions are related to the calcination process, many decarbonization options that can be applied in other industries (such as a switch from coal to natural gas or hydrogen, expanded electrification, etc.) will have only a partial impact on the overall emission reductions in the cement industry. Shorter-term options for emission reductions in cement production include improving energy efficiency of the process and replacing high emitting inputs like coal with natural gas and biomass. Medium-to-long term solutions include: clinker substitutes; post-combustion CCS; cryogenic CCS; use of hydrogen for high-temperature heat (e.g. "blue hydrogen" from natural gas with CCS or "green hydrogen" from renewables via electrolysis); increased resource efficiency (e.g. increased durability, materials substitution in construction, CO_2 curing, etc.)

We project that between 2020 and 2050 India's cement production grows by 150–280% in different scenarios (**Figure 16**). Even in the *Reference* scenario, we project substantial advances in deploying modern technology in terms of reduction of fuel-related CO_2 emissions. We estimate that by 2050 the shares of fuel emissions and process emissions are 0.3 and 0.7 in the *Reference* scenario (compared to 0.46 and 0.54 in 2020).

We also project slower production growth when carbon prices are imposed. For example, while in the *Reference* scenario cement production reaches 1,260 Mt in 2050, in the *High Carbon Price* scenario, the growth in production is reduced, with 2050 output only at about 800 Mt of cement. The reason for this reduction is that carbon pricing has a substantial impact on the cost of cement, which negatively

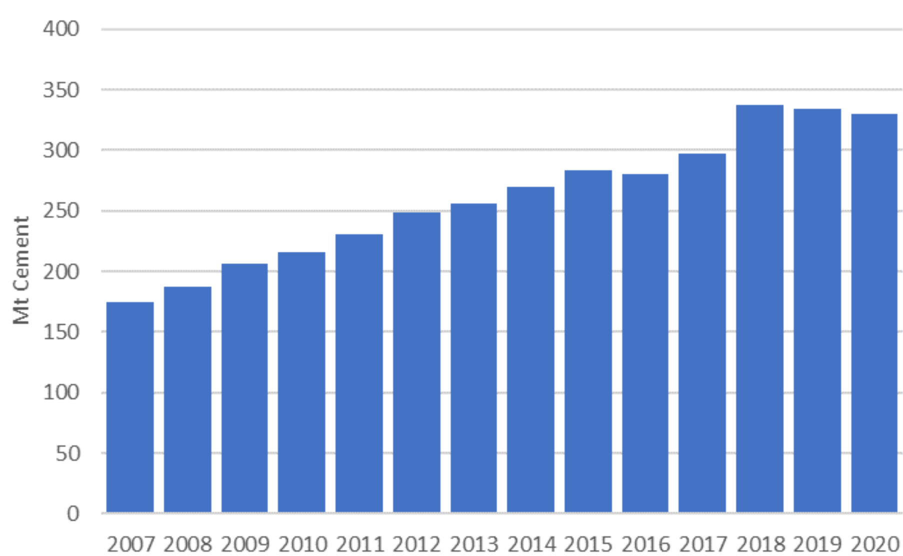

Figure 15. Cement Production in India in 2007-2020.

affects demand. In addition, overall economic activity in India is lower in the high carbon price setting. Thus, demand for construction is also negatively impacted. Deployment of CCS has a positive effect on cement production. When CCS is available, cement production in 2050 grows to about 1,000 Mt.

CCS is the only option that substantially reduces both energy emissions and process emissions in cement production. However, as mentioned above, cement production with CCS is more expensive than traditional technology (discussion of CCS costs is provided in Section 5). **Figure 17** shows our projection of CCS deployment in the cement industry in India. The *CCS and Low Carbon Price* scenario brings CCS only after 2045, while higher carbon prices

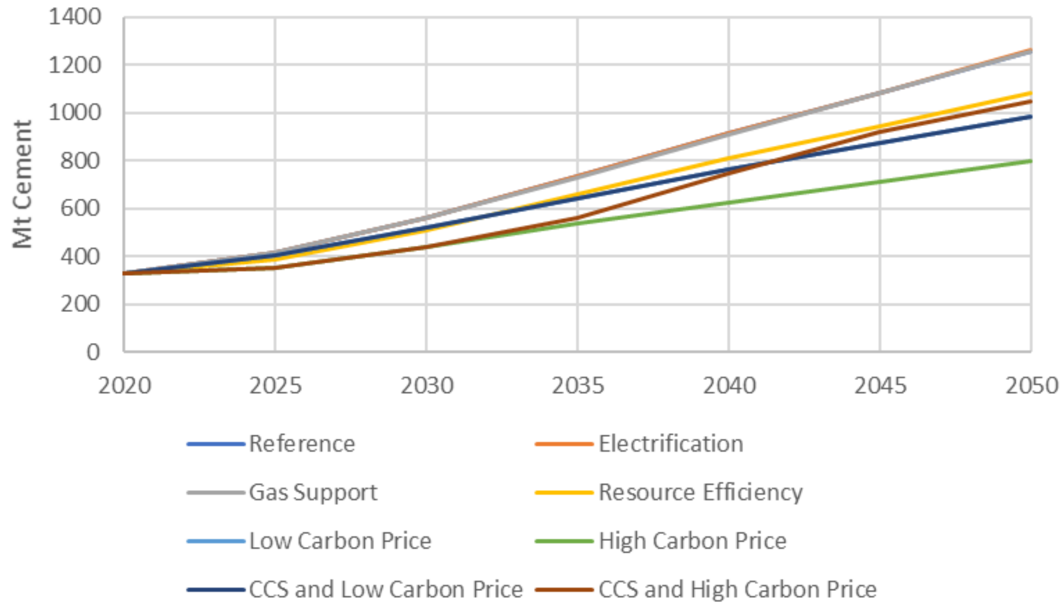

Figure 16. Cement Production in India in Different Scenarios.

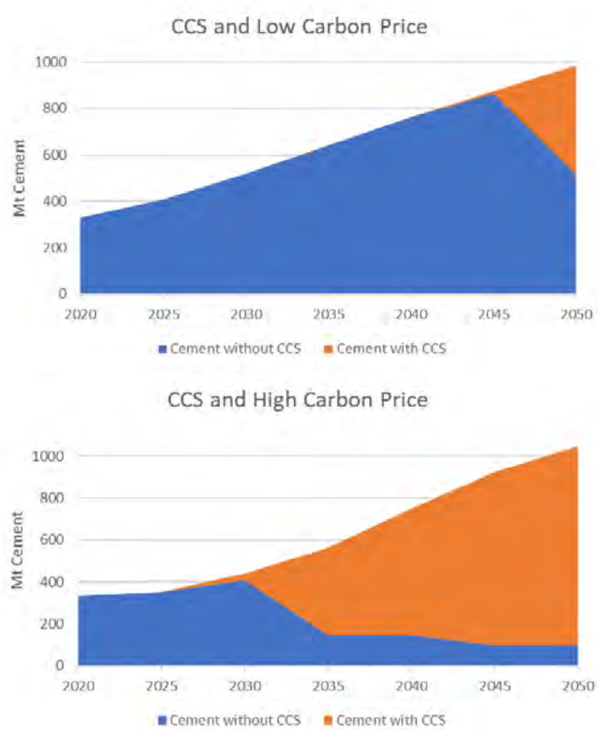

Figure 17. Cement Production with CCS in Different Scenarios.

substantially impact CCS deployment from 2030, with most of the cement after 2035 being produced with CCS.

Energy use in cement production varies between different scenarios. **Figure 18** shows the fuel mix in 2030 and **Figure 19** provides this information for 2050. In all scenarios, coal remains a major component of fuel mix due to its relative cost. Petcoke (reported in oil category) also keeps a sizeable share. Natural gas use is limited, with the largest increases in the *Natural Gas Support* scenario, but even in this scenario it has only a minor share in the total energy use for producing cement.

In the *Reference* scenario, CO_2 emissions (including fuel-related and process-related emissions) from cement production almost triple between 2020 and 2050 (**Figure 20**). Because a large portion of emissions are process-related, fuel switching does not impact the total cement production emissions. CCS is required to make sizeable emission reductions. In the *CCS and High Carbon Price scenario*, CO_2 emissions are reduced by 66% in 2050 relative to 2020 levels. Improvements in capture efficiency are needed for further mitigation.

For cement production, the emission intensity of output (measured as tonne of CO_2 emitted per tonne of cement) only gradually declines (unless CCS is employed) because a large portion of emissions are process-related and fuel switching does not greatly impact the total cement production emissions (**Figure 21**). In the *CCS and High Carbon Price* scenario, deployment of CCS reduces the emission intensity of cement output by 91% from 2020 to 2050.

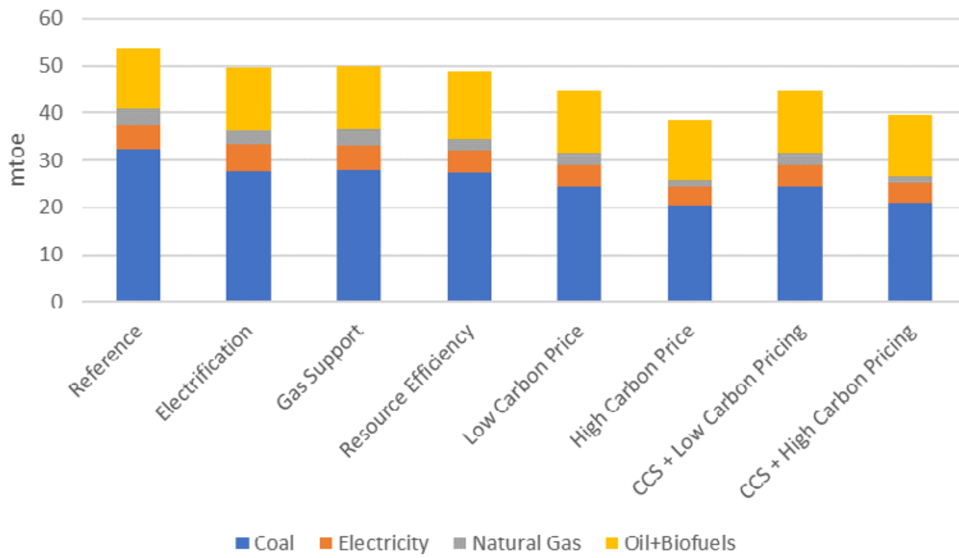

Figure 18. Energy Use in Cement Production in 2030.

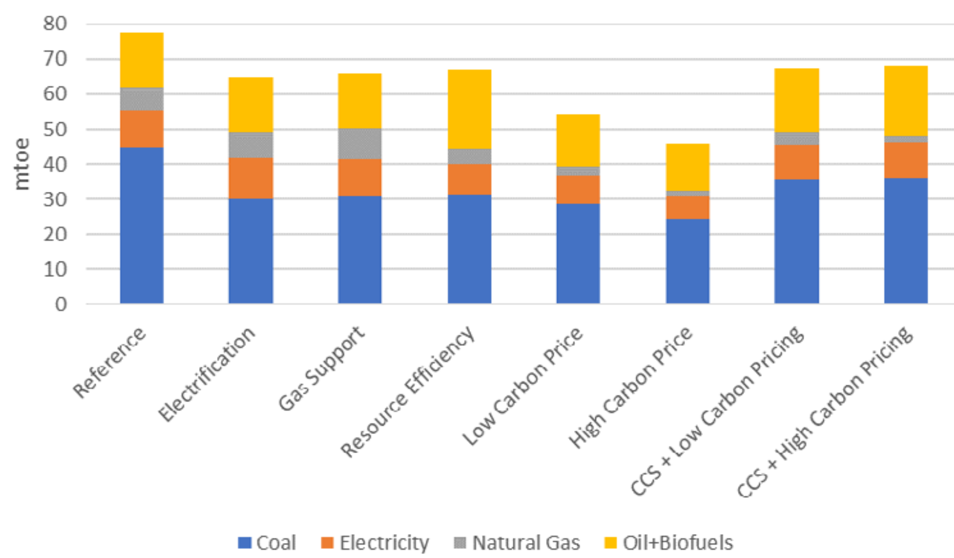

Figure 19. Energy Use in Cement Production in 2050.

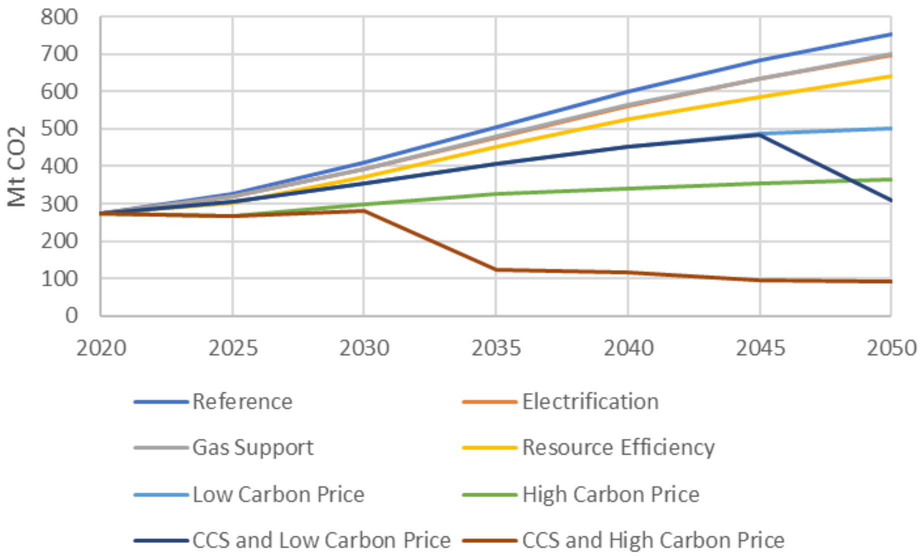

Figure 20. CO_2 Emissions from Cement Production in Different Scenarios.

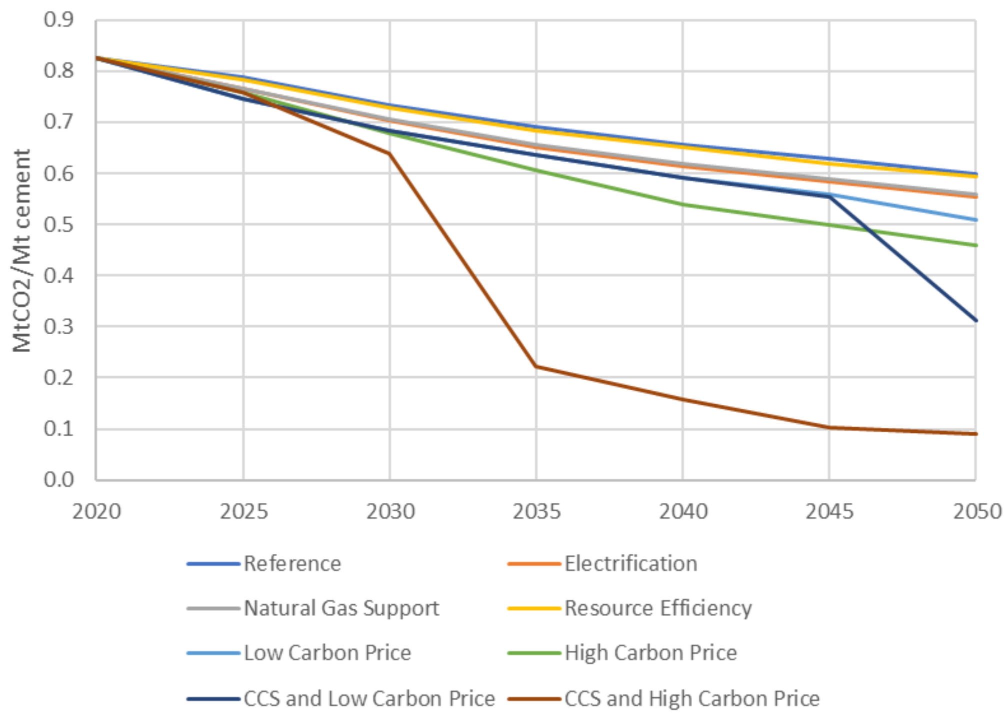

Figure 21. CO_2 Emission Intensity from Cement Production in Different Scenarios.

4.7 Non-Ferrous Metals

The majority of India's non-ferrous metals production is aluminum production. The major energy input in this sector is electricity. **Figures 22 and 23** show energy inputs in 2030 and 2050 in different scenarios. In all scenarios, electricity remains the main energy component in this sector. The *Resource Efficiency* scenario reduces the most the overall energy use in non-ferrous metals production in 2050 relative to the *Reference* scenario. Since electricity used for non-ferrous metals production is predominantly grid-based, we project a very limited deployment of CCS in this sector (while electricity is mostly moving to solar and wind resources by 2050).

Decarbonizing electricity generation (grid-based and own generation) is essential for emission reductions in the non-ferrous metals sector. Direct (i.e., non-electricity) CO_2 emissions in the non-ferrous metals sector are relatively small. As shown in **Figure 24**, they are in the range of 4–15 $MtCO_2$ in 2050 (compared to India's total 2020 CO_2 emissions of 2,300 $MtCO_2$).

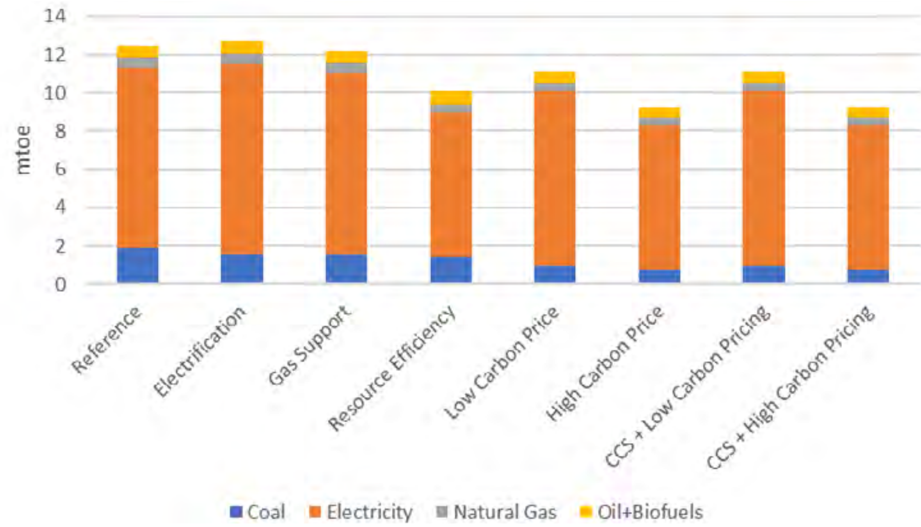

Figure 22. Energy Use in Non-Ferrous Metals Production in 2030.

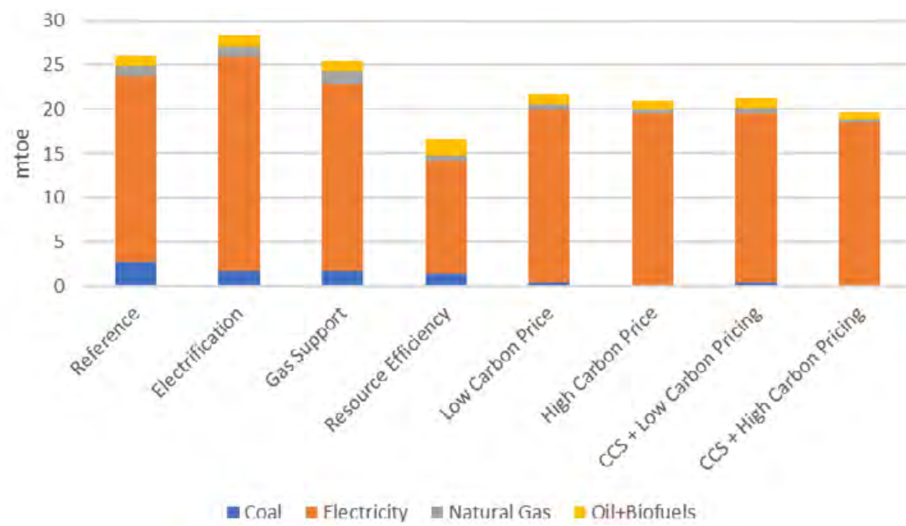

Figure 23. Energy Use in Non-Ferrous Metals Production in 2050.

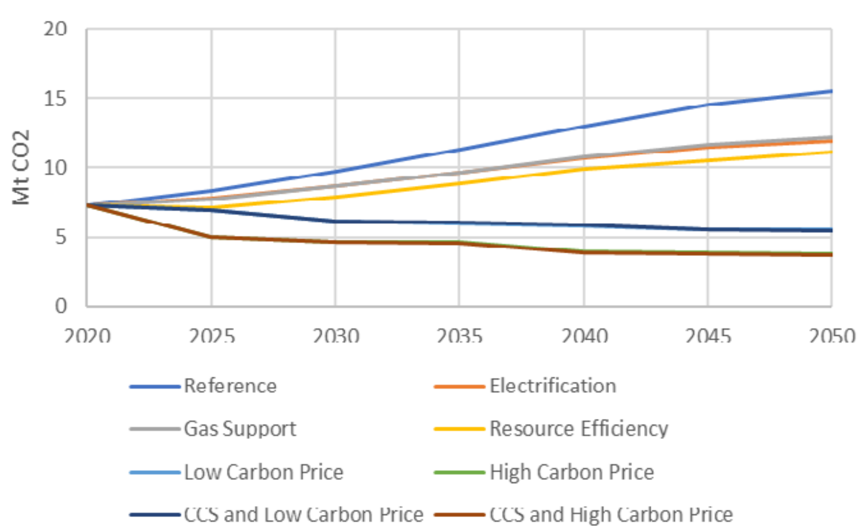

Figure 24. CO_2 Emissions from Non-Ferrous Metals Production in Different Scenarios.

4.8 Chemicals

Projections of chemical production is a more challenging task in comparison to other hard-to-abate sectors because the chemical sector produces numerous heterogeneous products: Ammonia, Ethylene, Propylene, Soda Ash, Caustic Soda, Chlorine, Calcium Carbide, Carbon Black, Potassium Chlorate, Titanium dioxide, Hydrogen Peroxide, Acetic Acid, Methanol, and many others. **Figure 25** presents our projections for an index of output of the chemical sector in different scenarios. In most scenarios, the output grows 3.1–3.8 times between 2020 and 2050. In the *Resource Efficiency* scenario, the output growth is larger due to a larger availability of recycled products, eco-design of chemical production and products, and an increased substitution of other products for plastics.

Another important characteristic of the chemical sector is a substantial use of fossil fuels as feedstock (Kapsalyamova and Paltsev, 2020). In India, in 2015 about 25 mtoe of fossil fuels were used as feedstock, which is slightly more than fossil fuels used for energy needs in the chemical sector. **Figures 26 and 27** show total energy inputs into chemical sector in 2030 and 2050 in different scenarios. Natural gas keeps its relatively large share in all scenarios.

In the *Reference* scenario, CO_2 emissions from chemicals almost triple between 2020 and 2050 (**Figure 28**). CCS is required to make sizeable emission reductions in the chemicals sector. We find that CCS is deployed by mid-century in the *CCS and High Carbon Price* scenario. Since the model represents the sector as aggregate, additional exploration is needed to quantify mitigation options at the level of individual products of the chemical industry.

5. CCS and Hydrogen

As discussed above, CCS is an important option for industry decarbonization in India. We project that in the *CCS and High Carbon Price* scenario, about 70% of steel, 90% of cement, and 35% of chemicals will be produced using CCS by 2050. Carbon capture becomes economic under the high carbon pricing from 2030 onwards. We estimate that between 2030 and 2050 a cumulative amount of about 6 $GtCO_2$ will be captured from the hard-to-abate sectors, which translates to an average annual CO_2 capture of about 300 $MtCO_2$ per year during this period. After 2050, the amount of carbon capture in India's industry might increase to about 500 $MtCO_2$ per year. If this carbon would not be utilized as an input to fuel and chemicals production (see IEA (2020c) for a discussion of carbon utilization prospects), would India have enough geologic storage for captured CO_2 from its industry?

Kearns *et al* (2017) have estimated a practically accessible geologic storage capacity for CO_2 for the major world regions. While India's carbon storage capacity is relatively small in comparison to other regions like Russia, USA, Africa, or the Middle East, it is estimated that India's carbon storage capacity is between 100 and 700 $GtCO_2$. Even if the annual amount of captured carbon will be twice as high as in our estimates, India would have more than 100 years of storing industrial CO_2. These estimates are subject to further research and they do not include technical offshore capacity and mineralization options for storing carbon in India.

Smith *et al* (2021) have explored the costs of CO_2 transportation options in the major world regions, including India, and they have also considered an option for transporting CO_2 by sea tankers as currently discussed in Europe

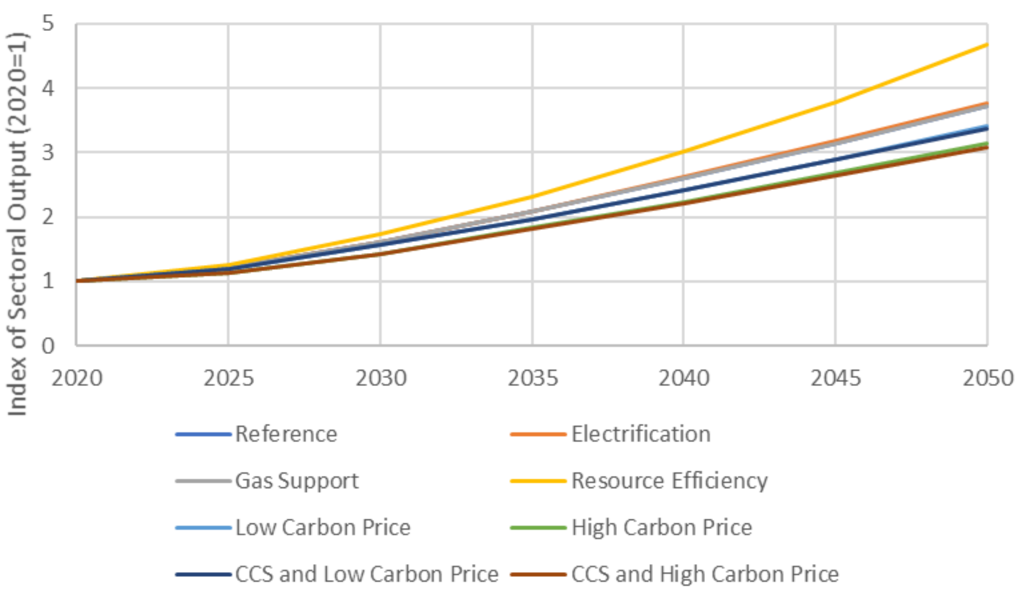

Figure 25. Index of Sectoral Output of Chemicals Production in Different Scenarios.

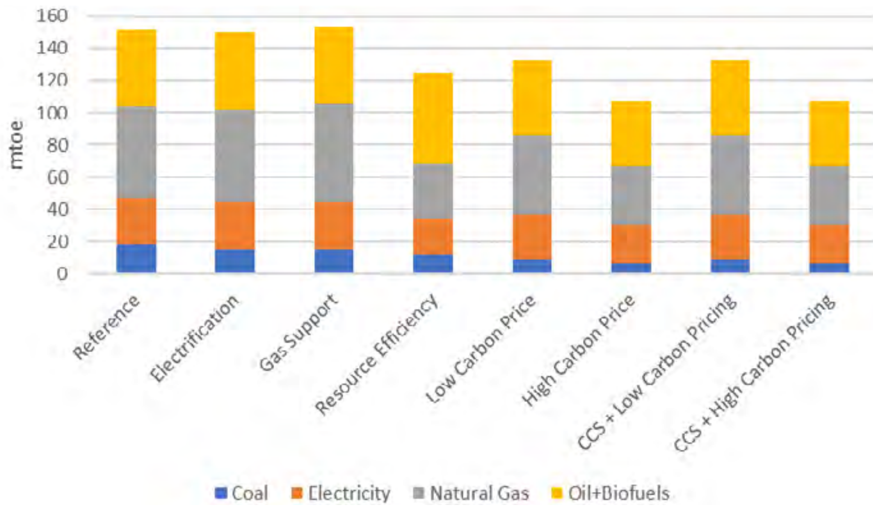

Figure 26. Energy Use in Chemicals Production in 2030.

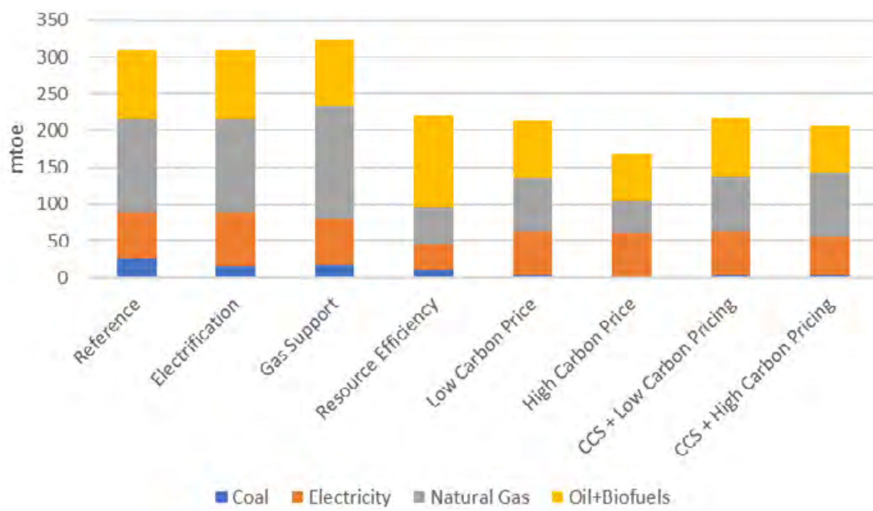

Figure 27. Energy Use in Chemicals Production in 2050.

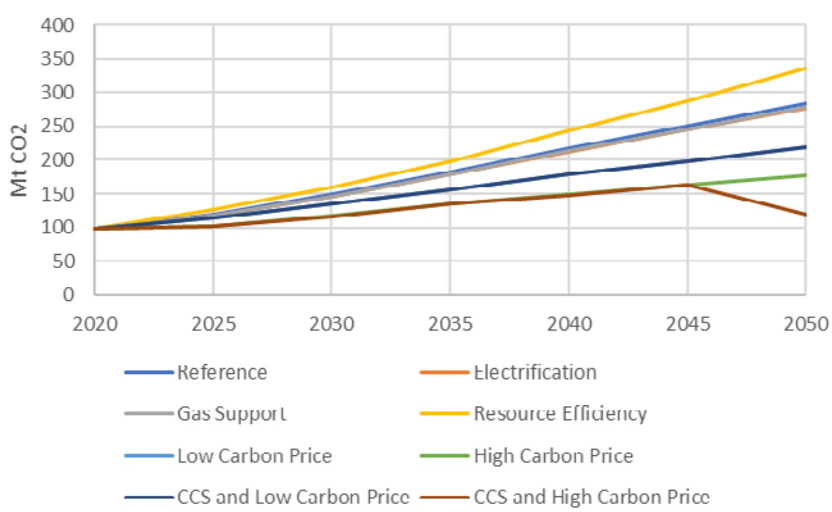

Figure 28. CO_2 Emissions from Chemicals Production in Different Scenarios.

and Japan. Qualitatively it is known that CCS transport networks and storage hubs can significantly reduce CO_2 transport and storage costs, and that these will develop in different locations at different paces. Regulatory regimes can enable or create barriers for certain CO_2 transport and storage options and can impose or remove significant costs accordingly. More research is needed to quantify the impact of these factors on CO_2 transport, utilization, and storage.

Other important options for decarbonizing industry are based on using low-carbon and zero-carbon hydrogen inputs. In our modeling for this study, we have not explicitly represented hydrogen-based options. Hence, here we provide only indicative estimates and we call for a need for a detailed study of hydrogen pathways in India. In several pathways, CCS and hydrogen options are complementary if hydrogen is produced from natural gas or biomass with CCS.

IEA (2020c) provides a comparison of costs for CCS and hydrogen options in industry. IEA's cost assessments for CCS are consistent with our analysis (as described in Section 3, we estimate that production cost increases due to CCS are 25% for cement and chemicals and 15% for steel and aluminum). IEA reports that producing one tonne of steel via CCS-equipped DRI is about 10% more expensive than today's main commercial production routes and the cost of CCS-equipped ammonia and methanol production is around 20–40% higher than that of their unabated counterparts.

While hydrogen is a subject of our active research, our current cost estimates do not favor hydrogen options in industry because they are more expensive than applying CCS to existing or new plants. In comparison to CCS, hydrogen-based steelmaking raises costs by 35–70% and electrolytic hydrogen-based ammonia and methanol production increases the cost by 50–115% (IEA, 2020c). In the IEA report that outlines the roadmap to net-zero emissions in the global energy sector by 2050 (IEA, 2021), hydrogen deployment is substantial. However, it relies on extremely aggressive reductions in hydrogen production costs and high capacity factors for variable renewables. The assumed 1–2.5\$/kg H_2 range for hydrogen production from renewables ("green hydrogen") in 2050 does not include costs for battery storage.

IEA (2020a) provides an example for hydrogen-based steelmaking in India that directly uses variable renewables and outlines substantial requirements for its viability, mostly in terms of flexibility either on the supply side (through the use of hydrogen buffer storage or battery electricity storage) or on the demand side (a tolerance of a certain degree of ramping or periods of ceasing production). Both options result in additional costs, either in the form of additional equipment (e.g., hydrogen or electricity storage) or lower utilization and increased maintenance costs for core process equipment (e.g., the hydrogen-based DRI furnace).

While these illustrative examples are informative of the challenges and opportunities, currently hydrogen pathways offer more expensive decarbonization options for India than CCS. We have evaluated indicative conditions for green H_2 steel to be competitive with the CCS option. Based on Vogl *et al* (2018), we found that the cost of electrolysis needs to be reduced by about 75% in addition to a carbon price in the range of \$70–150/tCO_2. Our findings are consistent with the levelized cost of different options for steel production reported in IEA (2020a).

In terms of government support for different decarbonization options, we argue that it is important to advance electrification and wider natural gas use. We show that these options provide emission reduction benefits. Imposition of economy-wide carbon prices in India would establish even greater environmental benefit while providing revenue that could be used to compensate the most affected segments of the society. CCS and hydrogen options are both at a low technology readiness level and they require substantial research and development (R&D) spending. India can help advance these technologies by establishing financial incentives for them (like a provision of the tax code in the USA – section 45Q to stimulate investment in CCS by providing financial incentives for CO_2 stored permanently in saline reservoirs or via enhanced oil recovery).

The exact pathways for CCS and hydrogen in India are highly speculative at this point (especially for green hydrogen that requires dramatic cost reductions from the current levels to be economically-competitive), but it is clear that industry needs support from government either in the form of reasonable carbon prices and/or financial incentives for low-carbon options. Action in the forms of R&D, technology deployment, infrastructure development, policy incentives and business practices will all be essential to speed up the transition to a low-carbon industry in India.

6. Concluding Remarks

The Paris Agreement pledges made by India for the year 2030 still can lead to increasing use of fossil fuels and the corresponding greenhouse gas (GHG) emissions. Without additional policies, primary energy use grows from about 1,000 mtoe in 2020 to 2200 mtoe in 2050. The share of fossil fuels in primary energy declines from 72% in 2020 to 69% in 2050. India's energy and industry-related CO_2 emissions are projected to grow from about 2,300 MtCO_2 in 2020 to about 4,700 MtCO_2 in 2050.

About a quarter of India's total CO_2 emissions come from the "hard-to-abate sectors" (iron and steel, cement, non-ferrous metals and chemicals), where decarbonization options are limited and more expensive in comparison to other sectors of economy (such as power generation and transport). Currently, about a half of India's natural gas, about a quarter of coal and about one-fifth of oil is used in the hard-to-abate sectors. Decarbonizing India's hard-to-abate sectors is crucial for a successful low-carbon transformation.

We evaluated several pathways for emission reductions in hard-to-abate sectors. Scenarios with electrification, natural gas support, and resource efficiency lead to emission reductions of 15–20%, but without carbon pricing (or disruptive technology changes) emissions are not reduced relative to their current levels due to growth in outputs of hard-to-abate sectors. Thus, additional policy actions will be critical to accelerate the energy transition towards low-carbon sources.

We project that the use of natural gas increases in several scenarios, especially in the natural gas support scenario where its use in the hard-to-abate sectors triples from 2020 to 2030 and it grows 7.5-times between 2020 to 2050. However, carbon pricing substantially affects growth in natural gas use. High carbon pricing leads to growth from 24 mtoe in 2020 to 40 mtoe in 2030 and to only 46 mtoe in 2050, which is substantially lower than the 2050 levels projected in the natural gas support scenario.

Electrification offers emission reductions, but with substantial land requirements for solar energy production. CCS is projected to play an important role for the cement and iron and steel industries in the carbon price scenarios. We also project some CCS deployment in the chemical and non-ferrous metals industries. Green hydrogen (produced by electrolysis from renewable energy) can be used to reduce direct emissions during steel production. However, the process requires more energy inputs than the traditional process and the cost is higher than traditional steelmaking or a CCS option.

For decarbonizing individual hard-to-abate sectors, we find that in cement production fuel switching does not much impact the total cement emissions because a large portion of emissions are process-related. Deploying CCS is critical for India's cement industry and in combination with carbon pricing it lowers the emission intensity of cement output by 90% from 2020 to 2050 and the overall cement CO_2 emissions by 66% in 2050 relative to 2020 levels. We also project a substantial use of CCS in steelmaking by mid-century, when about 70% of steel in India is produced with carbon capture. For non-ferrous metals, the key is decarbonizing electricity generation (grid-based and own generation). Declining costs of variable renewables provide a viable opportunity for a substantial reduction and eventual elimination in unabated coal generation. The chemicals sector requires heterogeneous decarbonization solutions due to a vast variety of products and processes. While CCS also provides a practical option, reductions in process energy intensity and enhancing resource efficiency and circular economy are critical for chemicals.

Hydrogen offers another decarbonization option that needs further exploration. Current options are expensive and require robust government support for research, development and deployment. International technology transfers are also needed. Even if costs are dramatically reduced, hydrogen imposes substantial additional infrastructure requirements. If green hydrogen is used, we project that generation from solar and wind would almost double in comparison to the levels discussed earlier in Section 4.1, including doubling land requirements (and all issues related to permitting of projects and purchasing of land). If blue hydrogen is used, costs are lower, but the requirements for LNG, pipeline infrastructure and carbon storage are elevated. All these considerations call for additional detailed investigations of hydrogen-based decarbonization options in the hard-to-abate sectors in India.

Our analysis shows the magnitude of the mitigation challenge in the hard-to-abate sectors in India. While we explore key mitigation options, the exact numerical values should be treated with a great degree of caution because many aspects of the market and industry details are simplified or beneath the level of model aggregation. With all inherent uncertainty about the potential cost reductions for existing technologies and deployment of new technological options, one message is clear: without substantial government actions decarbonization will not be achievable.

The costs of low-carbon technologies might come down with additional research and scale, but these cost reductions alone will not be sufficient to decarbonize the industry sector in India. Strategic, well-designed policy is required. We have shown that high-value policies include carbon pricing. While we have not explored distributional impacts of these policies, it should be noted that the government should also develop a safety net to ensure a just transition for displaced workers and affected communities. Industrial decarbonization actions should also be designed to help low- and middle-income segments of Indian society that use the products of these sectors. Our illustrative scenarios do not provide exact predictions, but they can be used for a qualitative analysis of decision-making risks associated with different pathways.

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Appendix. Scenario Results

Scenario:	Reference							
Indicators								
Production	units	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Iron and Steel	Mt	101.0	121.9	161.5	209.7	264.9	322.8	387.5
Cement	Mt	330.8	415.9	561.0	733.8	914.3	1084.8	1259.5
Non-Ferrous Metals	index (2020=1)	1.00	1.18	1.56	2.02	2.58	3.19	3.90
Chemicals	index (2020=1)	1.00	1.21	1.61	2.08	2.61	3.14	3.72
Share of Production with CCS								
Iron and Steel	%	0	0	0	0	0	0	0
Cement	%	0	0	0	0	0	0	0
Non-Ferrous Metals	%	0	0	0	0	0	0	0
Chemicals	%	0	0	0	0	0	0	0
Energy Use								
Iron and Steel								
Coal	mtoe	42.2	49.4	57.8	67.4	77.3	85.2	89.3
Electricity	mtoe	8.1	9.4	12.1	15.6	19.4	23.6	28.2
Natural Gas	mtoe	1.9	2.4	3.1	3.9	4.9	6.0	7.0
Oil+Biofuels	mtoe	7.4	7.7	8.1	8.5	9.0	9.4	9.9
Cement								
Coal	mtoe	23.9	27.9	32.4	37.2	41.5	44.2	44.7
Electricity	mtoe	3.5	4.1	5.2	6.5	7.9	9.2	10.5
Natural Gas	mtoe	2.0	2.4	3.2	4.1	5.1	6.0	6.9
Oil+Biofuels	mtoe	12.0	12.3	12.9	13.6	14.3	14.9	15.4
Non-Ferrous Metals								
Coal	mtoe	1.4	1.7	1.9	2.1	2.4	2.6	2.7
Electricity	mtoe	6.6	7.5	9.4	11.8	14.6	17.6	21.0
Natural Gas	mtoe	0.3	0.4	0.5	0.6	0.8	1.0	1.2
Oil+Biofuels	mtoe	0.4	0.5	0.6	0.8	0.9	1.1	1.2
Chemicals								
Coal	mtoe	13.7	15.9	18.0	20.6	23.1	25.0	25.7
Electricity	mtoe	19.6	22.6	28.8	36.3	44.7	53.8	64.0
Natural Gas	mtoe	19.3	43.7	57.0	72.4	89.7	109.0	126.7
Oil+Biofuels	mtoe	33.0	38.2	48.0	59.0	70.8	81.6	93.0
Total Hard-to-Abate Sectors								
Coal	mtoe	81.3	94.8	110.1	127.4	144.2	157.0	162.5
Electricity	mtoe	37.8	43.5	55.5	70.2	86.5	104.1	123.6
Natural Gas	mtoe	23.6	48.9	63.8	81.1	100.5	122.0	141.7
Oil+Biofuels	mtoe	52.8	58.7	69.6	81.9	95.0	107.0	119.5
CO2 Emissions		**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Fuel Combusiton Emissions								
Iron and Steel	Mt CO2	187.2	217.1	252.2	292.3	333.5	367.4	386.4
Cement	Mt CO2	127.2	144.5	164.7	187.0	206.8	220.4	225.1
Non-Ferrous Metals	Mt CO2	7.3	8.3	9.7	11.3	13.0	14.5	15.5
Chemicals	Mt CO2	98.6	119.0	148.5	181.9	217.7	251.1	284.4
Process Emissions								
Cement	Mt CO2	145.5	183.0	246.8	319.2	393.2	461.0	529.0
Other Process Emissions	Mt CO2	40.1	48.5	63.0	80.1	98.7	117.0	136.6
Total Hard-to-Abate Sectors								
Fuel Combusiton Emissions	Mt CO2	420.2	488.9	575.1	672.6	770.9	853.3	911.4
Process Emissions	Mt CO2	185.7	231.5	309.9	399.3	491.8	578.1	665.6
Total Emissions	Mt CO2	605.9	720.4	885.0	1071.9	1262.8	1431.4	1577.0

Scenario:	Electrification							
Indicators								
Production	units	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Iron and Steel	Mt	101.0	122.3	162.4	211.3	267.5	327.0	393.6
Cement	Mt	330.8	415.8	560.9	733.9	914.7	1085.5	1260.9
Non-Ferrous Metals	index (2020=1)	1.00	1.20	1.59	2.08	2.68	3.35	4.12
Chemicals	index (2020=1)	1.00	1.21	1.61	2.09	2.63	3.18	3.77
Share of Production with CCS								
Iron and Steel	%	0	0	0	0	0	0	0
Cement	%	0	0	0	0	0	0	0
Non-Ferrous Metals	%	0	0	0	0	0	0	0
Chemicals	%	0	0	0	0	0	0	0
Energy Use								
Iron and Steel								
Coal	mtoe	42.2	43.1	46.4	49.9	53.3	54.9	54.6
Electricity	mtoe	8.1	11.4	15.9	21.2	26.9	32.8	39.1
Natural Gas	mtoe	1.9	2.4	3.1	4.0	5.0	6.1	7.1
Oil+Biofuels	mtoe	7.4	7.7	8.1	8.5	9.0	9.4	9.9
Cement								
Coal	mtoe	23.9	25.5	27.8	30.0	31.4	31.4	30.0
Electricity	mtoe	3.5	4.2	5.4	6.9	8.5	10.1	11.8
Natural Gas	mtoe	2.0	2.5	3.3	4.3	5.3	6.4	7.3
Oil+Biofuels	mtoe	12.0	12.3	13.0	13.8	14.5	15.2	15.8
Non-Ferrous Metals								
Coal	mtoe	1.4	1.5	1.6	1.7	1.8	1.8	1.8
Electricity	mtoe	6.6	7.7	9.9	12.7	16.0	19.8	24.2
Natural Gas	mtoe	0.3	0.4	0.5	0.7	0.8	1.0	1.2
Oil+Biofuels	mtoe	0.4	0.5	0.6	0.8	0.9	1.1	1.3
Chemicals								
Coal	mtoe	13.7	14.3	15.1	16.0	16.8	16.8	16.2
Electricity	mtoe	19.6	23.2	30.1	38.7	48.6	59.7	72.5
Natural Gas	mtoe	19.3	43.8	57.0	72.4	89.7	108.7	126.7
Oil+Biofuels	mtoe	33.0	38.2	48.0	59.1	70.8	81.7	93.0
Total Hard-to-Abate Sectors								
Coal	mtoe	81.3	84.4	90.9	97.5	103.3	104.9	102.5
Electricity	mtoe	37.8	46.5	61.4	79.6	100.1	122.5	147.5
Natural Gas	mtoe	23.6	49.1	64.0	81.4	100.9	122.2	142.3
Oil+Biofuels	mtoe	52.8	58.8	69.8	82.1	95.3	107.4	119.9
CO2 Emissions		**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Fuel Combusiton Emissions								
Iron and Steel	Mt CO2	187.2	192.6	207.4	223.4	239.7	248.6	250.0
Cement	Mt CO2	127.2	135.0	147.2	159.1	168.4	171.4	168.9
Non-Ferrous Metals	Mt CO2	7.3	7.8	8.7	9.6	10.7	11.5	11.9
Chemicals	Mt CO2	98.6	117.8	146.4	178.5	212.9	244.8	277.0
Process Emissions								
Cement	Mt CO2	145.5	183.0	246.8	319.2	393.3	461.3	529.6
Other Process Emissions	Mt CO2	40.1	48.6	63.3	80.7	99.6	118.4	138.6
Total Hard-to-Abate Sectors								
Fuel Combusiton Emissions	Mt CO2	420.2	453.2	509.7	570.6	631.6	676.4	707.9
Process Emissions	Mt CO2	185.7	231.6	310.2	399.9	492.9	579.8	668.2
Total Emissions	Mt CO2	605.9	684.8	819.8	970.6	1124.6	1256.1	1376.1

Scenario:	Natural Gas Support						
Indicators							
Production	units	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Iron and Steel	Mt	101.0	121.7	161.2	209.3	264.3	322.0	386.5
Cement	Mt	330.8	415.3	559.9	732.0	911.8	1081.3	1255.2
Non-Ferrous Metals	index (2020=1)	1.00	1.18	1.56	2.02	2.58	3.20	3.90
Chemicals	index (2020=1)	1.00	1.21	1.61	2.08	2.61	3.15	3.73
Share of Production with CCS								
Iron and Steel	%	0	0	0	0	0	0	0
Cement	%	0	0	0	0	0	0	0
Non-Ferrous Metals	%	0	0	0	0	0	0	0
Chemicals	%	0	0	0	0	0	0	0
Energy Use								
Iron and Steel								
Coal	mtoe	42.2	42.8	45.7	48.7	51.5	52.5	50.9
Electricity	mtoe	8.1	9.4	12.2	15.8	19.9	24.4	29.5
Natural Gas	mtoe	1.9	4.6	7.3	10.3	13.5	16.5	19.2
Oil+Biofuels	mtoe	7.4	7.7	8.1	8.5	9.0	9.4	9.9
Cement								
Coal	mtoe	23.9	25.5	27.9	30.2	31.9	32.1	30.8
Electricity	mtoe	3.5	4.1	5.2	6.6	7.9	9.2	10.5
Natural Gas	mtoe	2.0	2.6	3.6	4.8	6.2	7.6	8.9
Oil+Biofuels	mtoe	12.0	12.3	13.0	13.8	14.5	15.1	15.8
Non-Ferrous Metals								
Coal	mtoe	1.4	1.5	1.6	1.7	1.8	1.8	1.8
Electricity	mtoe	6.6	7.5	9.4	11.8	14.6	17.7	21.1
Natural Gas	mtoe	0.3	0.4	0.6	0.7	0.9	1.2	1.4
Oil+Biofuels	mtoe	0.4	0.5	0.6	0.8	0.9	1.1	1.2
Chemicals								
Coal	mtoe	13.7	14.2	15.1	16.0	16.8	17.0	16.4
Electricity	mtoe	19.6	22.6	28.8	36.4	44.8	54.0	64.2
Natural Gas	mtoe	19.3	46.1	61.9	81.0	103.2	128.4	152.8
Oil+Biofuels	mtoe	33.0	38.0	47.6	58.4	69.8	80.3	91.2
Total Hard-to-Abate Sectors								
Coal	mtoe	81.3	84.0	90.3	96.6	101.9	103.4	99.8
Electricity	mtoe	37.8	43.6	55.7	70.6	87.2	105.3	125.3
Natural Gas	mtoe	23.6	53.8	73.4	96.9	123.7	153.7	182.4
Oil+Biofuels	mtoe	52.8	58.6	69.4	81.4	94.2	105.9	118.0
CO2 Emissions		**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Fuel Combusiton Emissions								
Iron and Steel	Mt CO2	187.2	194.6	211.2	228.5	245.5	255.2	254.5
Cement	Mt CO2	127.2	135.5	148.2	160.9	171.2	175.9	174.2
Non-Ferrous Metals	Mt CO2	7.3	7.7	8.6	9.6	10.8	11.6	12.2
Chemicals	Mt CO2	98.6	117.8	146.5	178.8	213.5	245.9	278.5
Process Emissions								
Cement	Mt CO2	145.5	182.7	246.3	318.4	392.1	459.6	527.2
Other Process Emissions	Mt CO2	40.1	48.5	63.0	80.1	98.6	117.0	136.5
Total Hard-to-Abate Sectors								
Fuel Combusiton Emissions	Mt CO2	420.2	455.7	514.5	577.9	641.0	688.6	719.4
Process Emissions	Mt CO2	185.7	231.2	309.3	398.5	490.7	576.5	663.7
Total Emissions	Mt CO2	605.9	686.9	823.9	976.4	1131.6	1265.2	1383.1

Scenario:	Resource Efficiency							
Indicators								
Production	units	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Iron and Steel	Mt	101.0	133.8	182.4	244.0	319.0	405.2	507.2
Cement	Mt	330.8	384.2	511.1	658.9	808.3	944.8	1080.5
Non-Ferrous Metals	index (2020=1)	1.00	1.21	1.67	2.26	3.01	3.91	4.97
Chemicals	index (2020=1)	1.00	1.25	1.73	2.32	3.02	3.79	4.67
Share of Production with CCS								
Iron and Steel	%	0	0	0	0	0	0	0
Cement	%	0	0	0	0	0	0	0
Non-Ferrous Metals	%	0	0	0	0	0	0	0
Chemicals	%	0	0	0	0	0	0	0
Energy Use								
Iron and Steel								
Coal	mtoe	42.2	34.9	35.2	35.9	36.5	34.7	32.6
Electricity	mtoe	8.1	7.2	8.3	9.6	10.7	11.8	12.9
Natural Gas	mtoe	1.9	1.6	1.8	2.1	2.3	2.5	2.6
Oil+Biofuels	mtoe	7.4	11.3	14.5	18.3	22.7	27.1	32.0
Cement								
Coal	mtoe	23.9	24.5	27.3	30.3	32.4	32.3	31.5
Electricity	mtoe	3.5	3.7	4.7	5.7	6.6	7.5	8.4
Natural Gas	mtoe	2.0	2.0	2.5	3.1	3.6	4.1	4.5
Oil+Biofuels	mtoe	12.0	13.1	14.4	16.1	18.1	20.1	22.3
Non-Ferrous Metals								
Coal	mtoe	1.4	1.3	1.4	1.4	1.5	1.5	1.4
Electricity	mtoe	6.6	6.4	7.6	8.9	10.2	11.5	12.8
Natural Gas	mtoe	0.3	0.3	0.3	0.4	0.5	0.5	0.5
Oil+Biofuels	mtoe	0.4	0.6	0.8	1.0	1.3	1.6	1.9
Chemicals								
Coal	mtoe	13.7	12.0	12.2	12.5	12.7	12.1	11.4
Electricity	mtoe	19.6	18.4	21.5	24.8	27.7	30.8	33.7
Natural Gas	mtoe	19.3	30.4	34.9	39.3	43.8	47.2	50.1
Oil+Biofuels	mtoe	33.0	43.2	56.0	71.2	88.5	105.8	124.7
Total Hard-to-Abate Sectors								
Coal	mtoe	81.3	72.8	76.1	80.1	83.1	80.5	76.8
Electricity	mtoe	37.8	35.8	42.1	48.9	55.3	61.6	67.8
Natural Gas	mtoe	23.6	34.2	39.6	44.8	50.2	54.3	57.8
Oil+Biofuels	mtoe	52.8	68.2	85.7	106.7	130.6	154.7	181.0
CO2 Emissions		**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Fuel Combusiton Emissions								
Iron and Steel	Mt CO2	187.2	168.1	177.8	190.4	204.0	208.6	212.7
Cement	Mt CO2	127.2	132.2	147.5	164.3	178.7	183.9	186.9
Non-Ferrous Metals	Mt CO2	7.3	7.2	7.9	8.8	9.9	10.5	11.2
Chemicals	Mt CO2	98.6	125.7	159.1	198.8	243.7	287.9	335.6
Process Emissions								
Cement	Mt CO2	145.5	169.1	224.9	286.6	347.6	401.5	453.8
Other Process Emissions	Mt CO2	40.1	51.7	69.5	91.3	116.6	144.1	175.1
Total Hard-to-Abate Sectors								
Fuel Combusiton Emissions	Mt CO2	420.2	433.1	492.3	562.3	636.3	690.9	746.4
Process Emissions	Mt CO2	185.7	220.7	294.4	377.9	464.2	545.6	628.9
Total Emissions	Mt CO2	605.9	653.9	786.7	940.2	1100.4	1236.5	1375.3

Scenario:	Low Carbon Price							
Indicators								
Production	units	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Iron and Steel	Mt	101.0	121.0	158.1	199.3	247.5	302.5	362.4
Cement	Mt	330.8	406.7	517.7	641.0	763.0	874.6	985.6
Non-Ferrous Metals	index (2020=1)	1.00	1.18	1.54	1.90	2.38	3.04	3.74
Chemicals	index (2020=1)	1.00	1.20	1.57	1.97	2.41	2.89	3.41
Share of Production with CCS								
Iron and Steel	%	0	0	0	0	0	0	0
Cement	%	0	0	0	0	0	0	0
Non-Ferrous Metals	%	0	0	0	0	0	0	0
Chemicals	%	0	0	0	0	0	0	0
Energy Use								
Iron and Steel								
Coal	mtoe	42.2	38.6	32.2	30.8	27.9	24.1	21.7
Electricity	mtoe	8.1	9.3	11.9	15.3	19.5	25.5	32.7
Natural Gas	mtoe	1.9	2.3	2.5	2.8	2.9	2.9	3.0
Oil+Biofuels	mtoe	7.4	7.7	8.1	8.5	9.0	9.4	9.9
Cement								
Coal	mtoe	23.9	22.9	24.3	26.4	28.1	30.8	28.7
Electricity	mtoe	3.5	4.0	4.7	5.5	6.3	7.2	8.1
Natural Gas	mtoe	2.0	2.3	2.6	2.8	2.8	2.7	2.7
Oil+Biofuels	mtoe	12.0	12.3	13.0	13.6	14.1	14.5	14.8
Non-Ferrous Metals								
Coal	mtoe	1.4	1.3	1.0	0.9	0.7	0.5	0.4
Electricity	mtoe	6.6	7.4	9.1	10.7	12.8	16.1	19.4
Natural Gas	mtoe	0.3	0.4	0.5	0.6	0.6	0.7	0.8
Oil+Biofuels	mtoe	0.4	0.5	0.6	0.7	0.8	1.0	1.1
Chemicals								
Coal	mtoe	13.7	11.9	8.9	7.7	6.1	4.4	3.4
Electricity	mtoe	19.6	22.3	27.5	33.0	39.7	48.9	58.7
Natural Gas	mtoe	19.3	42.3	50.0	58.4	63.2	68.0	73.3
Oil+Biofuels	mtoe	33.0	37.8	46.1	54.3	63.1	70.9	78.8
Total Hard-to-Abate Sectors								
Coal	mtoe	81.3	74.7	66.4	65.7	62.9	59.8	54.3
Electricity	mtoe	37.8	43.1	53.3	64.5	78.4	97.7	118.9
Natural Gas	mtoe	23.6	47.3	55.6	64.5	69.6	74.3	79.7
Oil+Biofuels	mtoe	52.8	58.4	67.8	77.1	87.0	95.8	104.6
CO2 Emissions		**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Fuel Combusiton Emissions								
Iron and Steel	Mt CO2	187.2	174.5	150.9	146.6	136.7	122.9	114.9
Cement	Mt CO2	127.2	124.8	132.2	142.2	150.2	161.6	154.2
Non-Ferrous Metals	Mt CO2	7.3	6.9	6.1	6.0	5.8	5.5	5.5
Chemicals	Mt CO2	98.6	114.7	135.1	156.7	178.9	198.3	218.9
Process Emissions								
Cement	Mt CO2	145.5	178.9	220.9	264.9	301.8	327.1	347.7
Other Process Emissions	Mt CO2	40.1	48.1	61.0	75.1	89.7	104.0	117.9
Total Hard-to-Abate Sectors								
Fuel Combusiton Emissions	Mt CO2	420.2	420.9	424.4	451.5	471.6	488.4	493.4
Process Emissions	Mt CO2	185.7	227.1	282.0	340.0	391.6	431.1	465.6
Total Emissions	Mt CO2	605.9	647.9	706.3	791.5	863.2	919.4	959.1

Scenario:	High Carbon Price						
Indicators							
Production	units	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Iron and Steel	Mt	101.0	115.0	146.6	190.8	235.5	287.5	342.6
Cement	Mt	330.8	351.4	439.0	539.5	627.6	713.5	799.4
Non-Ferrous Metals	index (2020=1)	1.00	1.11	1.36	1.87	2.33	3.00	3.64
Chemicals	index (2020=1)	1.00	1.13	1.43	1.84	2.23	2.68	3.14
Share of Production with CCS								
Iron and Steel	%	0	0	0	0	0	0	0
Cement	%	0	0	0	0	0	0	0
Non-Ferrous Metals	%	0	0	0	0	0	0	0
Chemicals	%	0	0	0	0	0	0	0
Energy Use								
Iron and Steel								
Coal	mtoe	42.2	27.6	26.5	26.6	21.8	19.6	18.1
Electricity	mtoe	8.1	8.5	10.8	15.1	19.7	27.2	34.7
Natural Gas	mtoe	1.9	1.6	1.7	1.7	1.6	1.5	1.5
Oil+Biofuels	mtoe	7.4	7.7	8.1	8.5	9.0	9.4	9.9
Cement								
Coal	mtoe	23.9	20.1	20.5	21.8	22.2	23.4	24.2
Electricity	mtoe	3.5	3.3	3.8	4.7	5.3	6.1	6.9
Natural Gas	mtoe	2.0	1.6	1.6	1.6	1.4	1.3	1.2
Oil+Biofuels	mtoe	12.0	12.2	12.6	13.0	13.3	13.5	13.6
Non-Ferrous Metals								
Coal	mtoe	1.4	0.8	0.7	0.6	0.4	0.3	0.2
Electricity	mtoe	6.6	6.7	7.6	10.4	12.5	16.1	19.4
Natural Gas	mtoe	0.3	0.3	0.3	0.4	0.4	0.4	0.5
Oil+Biofuels	mtoe	0.4	0.5	0.5	0.6	0.7	0.8	0.9
Chemicals								
Coal	mtoe	13.7	8.0	6.7	5.6	3.3	2.4	1.8
Electricity	mtoe	19.6	20.2	23.8	31.7	38.3	48.5	58.8
Natural Gas	mtoe	19.3	34.0	36.2	39.6	39.9	41.5	42.8
Oil+Biofuels	mtoe	33.0	34.7	40.9	48.2	54.2	60.2	65.8
Total Hard-to-Abate Sectors								
Coal	mtoe	81.3	56.6	54.4	54.7	47.7	45.7	44.4
Electricity	mtoe	37.8	38.8	46.1	61.9	75.7	97.9	119.7
Natural Gas	mtoe	23.6	37.6	39.8	43.3	43.3	44.8	46.0
Oil+Biofuels	mtoe	52.8	55.1	62.2	70.4	77.2	83.9	90.3
CO2 Emissions		**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Fuel Combusiton Emissions								
Iron and Steel	Mt CO2	187.2	130.5	127.2	128.8	110.5	103.0	98.4
Cement	Mt CO2	127.2	112.0	114.7	120.8	123.0	128.0	131.4
Non-Ferrous Metals	Mt CO2	7.3	5.0	4.7	4.6	3.9	3.9	3.8
Chemicals	Mt CO2	98.6	101.9	117.0	135.4	148.9	163.6	177.7
Process Emissions								
Cement	Mt CO2	145.5	154.6	183.5	206.5	215.9	227.4	235.0
Other Process Emissions	Mt CO2	40.1	45.5	54.9	65.8	73.3	83.2	91.7
Total Hard-to-Abate Sectors								
Fuel Combusiton Emissions	Mt CO2	420.2	349.4	363.6	389.6	386.3	398.5	411.4
Process Emissions	Mt CO2	185.7	200.1	238.4	272.4	289.2	310.6	326.8
Total Emissions	Mt CO2	605.9	549.5	602.0	661.9	675.5	709.1	738.2

Scenario:	CCS and Low Carbon Price						
Indicators							
Production	units	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Iron and Steel	Mt	101.0	121.0	158.1	199.3	247.5	302.3	365.0
Cement	Mt	330.8	406.7	517.7	641.1	763.0	874.5	984.2
Non-Ferrous Metals	index (2020=1)	1.00	1.18	1.54	1.90	2.38	3.04	3.67
Chemicals	index (2020=1)	1.00	1.20	1.57	1.97	2.41	2.89	3.38
Share of Production with CCS								
Iron and Steel	%	0.0	0.2	0.2	0.3	0.5	7.9	58.8
Cement	%	0.0	0.0	0.0	0.0	0.0	1.1	47.7
Non-Ferrous Metals	%	0.0	0.1	0.1	0.1	0.1	0.1	0.1
Chemicals	%	0.0	0.1	0.1	0.1	0.1	0.1	0.1
Energy Use								
Iron and Steel								
Coal	mtoe	42.2	38.6	32.3	31.0	28.8	26.6	35.9
Electricity	mtoe	8.1	9.3	11.9	15.3	19.5	25.2	31.0
Natural Gas	mtoe	1.9	2.3	2.6	3.0	3.2	3.2	4.9
Oil+Biofuels	mtoe	7.4	7.7	8.1	8.5	9.0	9.4	9.9
Cement								
Coal	mtoe	23.9	22.9	24.3	26.4	28.1	30.9	35.6
Electricity	mtoe	3.5	4.0	4.7	5.5	6.3	7.3	10.0
Natural Gas	mtoe	2.0	2.3	2.6	2.8	2.8	2.8	3.3
Oil+Biofuels	mtoe	12.0	12.3	13.0	13.6	14.1	14.6	18.3
Non-Ferrous Metals								
Coal	mtoe	1.4	1.3	1.0	0.9	0.7	0.5	0.4
Electricity	mtoe	6.6	7.4	9.1	10.6	12.8	16.1	19.1
Natural Gas	mtoe	0.3	0.4	0.5	0.6	0.6	0.7	0.7
Oil+Biofuels	mtoe	0.4	0.5	0.6	0.7	0.8	1.0	1.1
Chemicals								
Coal	mtoe	13.7	11.9	8.9	7.7	6.2	4.4	3.4
Electricity	mtoe	19.6	22.3	27.5	33.0	39.7	48.9	59.0
Natural Gas	mtoe	19.3	42.3	50.0	58.4	63.3	68.0	75.7
Oil+Biofuels	mtoe	33.0	37.8	46.1	54.3	63.1	70.9	78.9
Total Hard-to-Abate Sectors								
Coal	mtoe	81.3	74.8	66.6	66.0	63.7	62.5	75.3
Electricity	mtoe	37.8	43.0	53.3	64.5	78.3	97.4	119.1
Natural Gas	mtoe	23.6	47.4	55.7	64.7	69.9	74.6	84.6
Oil+Biofuels	mtoe	52.8	58.4	67.8	77.1	87.0	95.8	108.1
CO2 Emissions		**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Fuel Combusiton Emissions								
Iron and Steel	Mt CO2	187.2	174.5	151.3	147.7	140.0	123.8	81.5
Cement	Mt CO2	127.2	124.8	132.2	142.2	150.2	160.8	109.0
Non-Ferrous Metals	Mt CO2	7.3	6.9	6.1	6.0	5.8	5.5	5.5
Chemicals	Mt CO2	98.6	114.6	135.0	156.6	178.7	198.2	219.3
Process Emissions								
Cement	Mt CO2	145.5	179.0	221.0	264.9	301.8	323.8	198.2
Other Process Emissions	Mt CO2	40.1	48.1	60.9	75.0	89.5	100.1	85.7
Total Hard-to-Abate Sectors								
Fuel Combusiton Emissions	Mt CO2	420.2	420.8	424.7	452.4	474.7	488.3	415.3
Process Emissions	Mt CO2	185.7	227.0	281.9	339.9	391.3	423.9	283.9
Total Emissions	Mt CO2	605.9	647.9	706.5	792.3	866.0	912.2	699.2

Scenario:	CCS and High Carbon Price						
Indicators							
Production	units	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Iron and Steel	Mt	101.0	115.0	146.5	188.5	230.1	284.3	365.4
Cement	Mt	330.8	351.4	439.1	561.8	749.0	922.9	1049.8
Non-Ferrous Metals	index (2020=1)	1.00	1.11	1.36	1.83	2.24	2.84	3.43
Chemicals	index (2020=1)	1.00	1.13	1.43	1.83	2.21	2.64	3.08
Share of Production with CCS								
Iron and Steel	%	0.0	0.3	0.6	0.8	19.8	62.6	67.7
Cement	%	0.0	0.0	6.8	74.1	80.8	89.2	90.5
Non-Ferrous Metals	%	0.0	0.1	0.1	0.1	0.1	0.1	0.2
Chemicals	%	0.0	0.1	0.1	0.1	0.1	0.2	35.2
Energy Use								
Iron and Steel								
Coal	mtoe	42.2	27.7	26.7	26.9	27.4	35.5	34.1
Electricity	mtoe	8.1	8.5	10.8	14.9	18.4	23.8	33.3
Natural Gas	mtoe	1.9	1.7	1.7	1.7	2.0	2.7	2.7
Oil+Biofuels	mtoe	7.4	7.7	8.1	8.5	8.0	7.6	7.9
Cement								
Coal	mtoe	23.9	20.1	21.1	28.9	31.0	34.4	35.9
Electricity	mtoe	3.5	3.3	3.9	6.2	7.4	9.0	10.2
Natural Gas	mtoe	2.0	1.6	1.6	2.1	2.0	1.9	1.8
Oil+Biofuels	mtoe	12.0	12.2	13.0	17.2	18.6	19.9	20.2
Non-Ferrous Metals								
Coal	mtoe	1.4	0.9	0.7	0.6	0.4	0.3	0.2
Electricity	mtoe	6.6	6.7	7.6	10.2	12.0	15.2	18.2
Natural Gas	mtoe	0.3	0.3	0.3	0.4	0.4	0.4	0.4
Oil+Biofuels	mtoe	0.4	0.5	0.5	0.6	0.7	0.8	0.9
Chemicals								
Coal	mtoe	13.7	8.0	6.7	5.7	3.3	2.5	3.3
Electricity	mtoe	19.6	20.2	23.8	31.4	37.7	47.3	52.7
Natural Gas	mtoe	19.3	34.1	36.2	39.3	38.9	39.2	87.2
Oil+Biofuels	mtoe	33.0	34.7	40.9	48.1	54.1	60.2	64.1
Total Hard-to-Abate Sectors								
Coal	mtoe	81.3	56.7	55.2	62.1	62.1	72.7	73.6
Electricity	mtoe	37.8	38.7	46.1	62.7	75.4	95.3	114.5
Natural Gas	mtoe	23.6	37.6	39.9	43.5	43.3	44.2	92.1
Oil+Biofuels	mtoe	52.8	55.1	62.5	74.4	81.4	88.5	93.1
CO2 Emissions		**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Fuel Combusiton Emissions								
Iron and Steel	Mt CO2	187.2	130.6	127.4	129.0	107.4	71.2	61.7
Cement	Mt CO2	127.2	112.0	110.0	53.2	46.9	37.1	36.2
Non-Ferrous Metals	Mt CO2	7.3	5.0	4.7	4.6	3.9	3.8	3.7
Chemicals	Mt CO2	98.6	101.8	116.9	134.8	148.0	162.8	119.8
Process Emissions								
Cement	Mt CO2	145.5	154.6	171.0	71.6	70.3	58.0	57.3
Other Process Emissions	Mt CO2	40.1	45.4	54.7	64.9	65.5	58.2	47.9
Total Hard-to-Abate Sectors								
Fuel Combusiton Emissions	Mt CO2	420.2	349.4	358.8	321.6	306.2	274.9	221.4
Process Emissions	Mt CO2	185.7	200.1	225.7	136.5	135.8	116.3	105.2
Total Emissions	Mt CO2	605.9	549.4	584.5	458.1	442.0	391.1	326.6

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