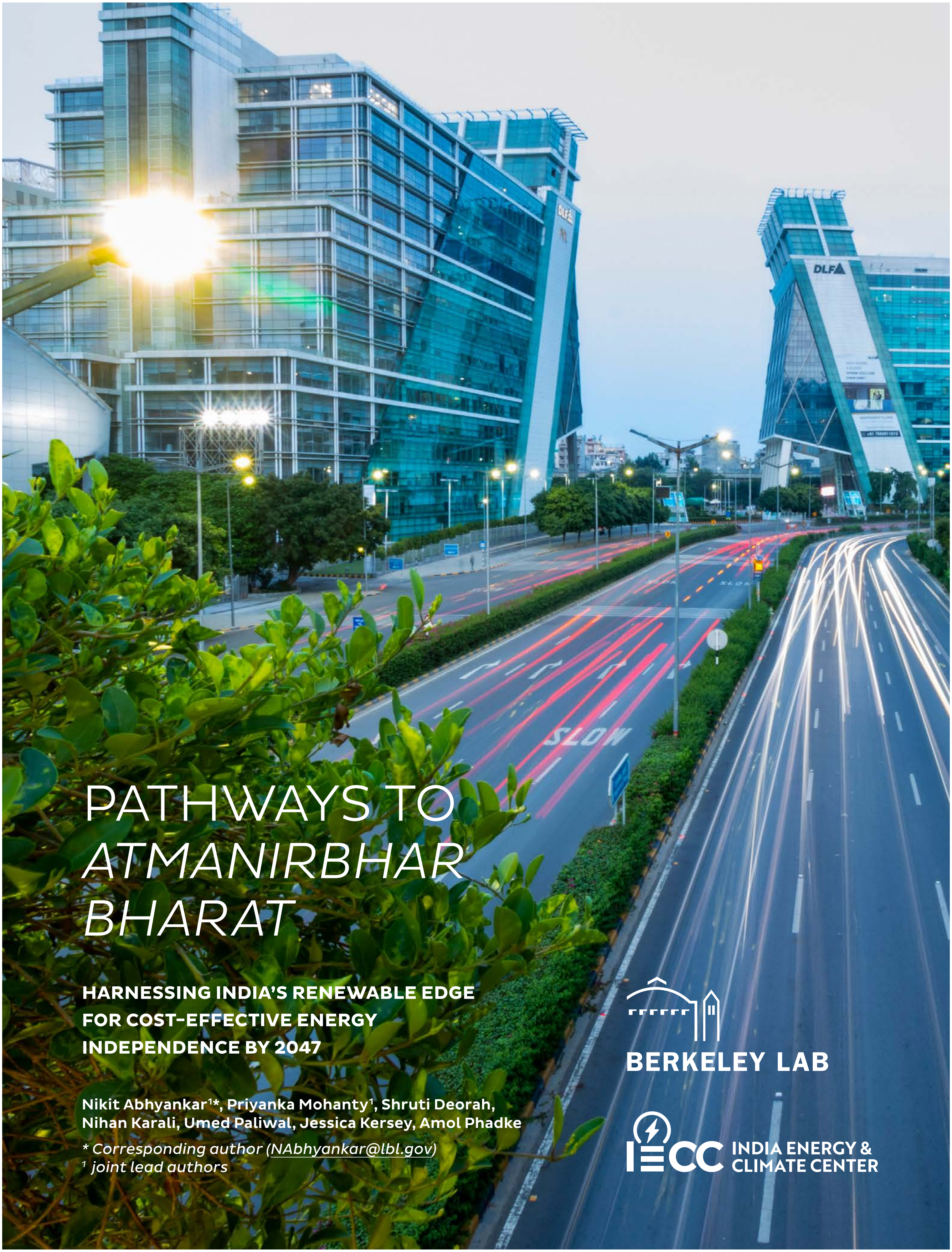

PATHWAYS TO *ATMANIRBHAR BHARAT*

HARNESSING INDIA'S RENEWABLE EDGE FOR COST-EFFECTIVE ENERGY INDEPENDENCE BY 2047

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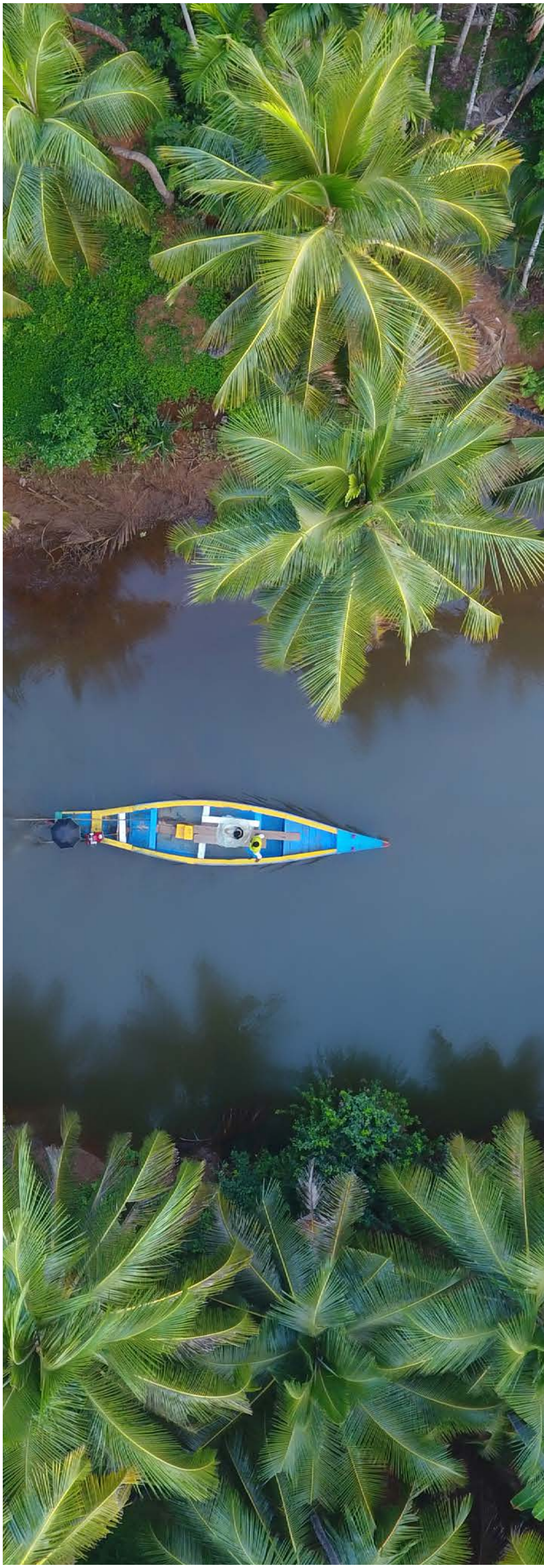

ACKNOWLEDGEMENT

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SUMMARY FOR POLICYMAKERS

Prime Minister Modi's commitment to Atmanirbhar Bharat aims to make India energy independent by 2047. However, India currently imports 90% of its oil and 80% of industrial coal. Price and supply volatility in global energy markets, as witnessed in recent years, strain India's foreign exchange reserves, resulting in economy-wide inflation. Recent dramatic declines in clean energy costs provide India an opportunity to lower energy imports through investment in renewable energy, battery storage, EVs, and green hydrogen.

This study assesses a pathway for India to meet its growing energy needs and achieve near-complete energy independence by 2047, focused on India's three largest energy consuming sectors –power, transport, and industry — which collectively account for more than 80% of energy consumption and energy-related CO_2 emissions. Key findings are as follows:

1. **Energy independence involves investment in renewables, electric vehicles, and green hydrogen.** Since much of India's infrastructure is yet to be built, we find that it is critical to ensure that most of the new energy assets are clean. This would involve installing more than 500 GW of non-fossil electricity generation capacity by 2030, an 80% clean grid by 2040 and 90% by 2047. Nearly 100% of new vehicle sales could be electric by 2035. Heavy industrial production shifts primarily to green hydrogen and electrification: 90% of iron and steel, 90% of cement, and 100% of fertilizers by 2047.

2. **India can achieve energy independence through clean technology by 2047.** The transition to electric vehicles could save crude oil imports by over 90% (or $240 billion) by 2047, while green hydrogen based and electrified industrial production would reduce industrial coal imports by 95%. Lithium needed for manufacturing new electric vehicles and grid-scale battery storage systems (~2 million tons cumulative between 2023 and 2040) could be produced domestically using newly discovered reserves.

3. **Energy independence is economically advantageous.** Clean energy will reduce and inflation-proof India's energy expenditure as renewables, EV batteries, and hydrogen infrastructure are capital assets with rapidly falling costs. A shift to electric transportation will create $2.5 trillion (INR 19 million crores) in net consumer savings by 2047. Indian industry, to remain globally competitive, must also transition to clean technologies like green steel manufacturing, as major export markets (ex. EU) make carbon neutrality commitments.

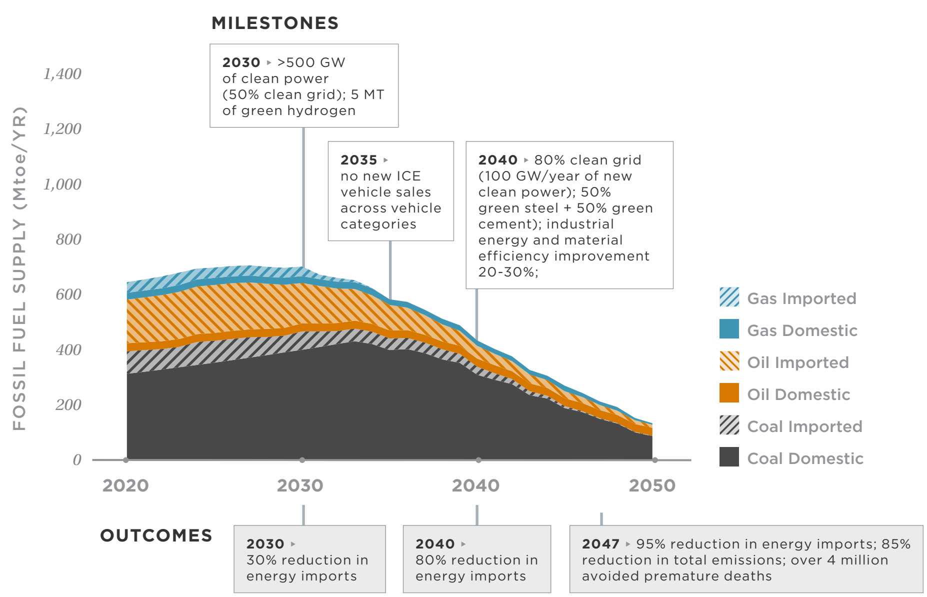
4. **The clean energy transition would have minimal impacts on tax revenues.** Fossil fuel taxes, duties, and royalties contribute ~12% of state and central government revenue. Despite an aggressive clean energy transition, fossil fuel consumption and associated tax revenues will not drop below 2020 levels until the mid-2030s.

5. **A rapid expansion of clean energy infrastructure will be needed.** Because of transport, industrial electrification and green hydrogen production, electricity demand could increase nearly fivefold — from 1300 TWh/yr to over 6600 TWh/yr by 2050. This would require a massive scale-up of renewable energy deployment to 40 GW/year through 2030, ramping up to about 100 GW/year between 2030 and 2050. Clean energy deployment will be more capital-intensive, needing a net additional investment of $1.5-2 trillion (INR 11-15 million crores) between 2023-2047, compared with business-as-usual.

6. **Achieving energy independence could offer environmental and public health benefits without compromising economic growth.** With an aggressive clean energy transition, over 4 million air pollution-related premature deaths could be avoided between 2023-2047. India's CO_2 emissions will peak in the early 2030s, before dropping to ~800 million tons/year by 2047 (85-90% of the way to net-zero emissions).

7. **Managing the clean energy transition would require significant policy support.** The policy ecosystem needs to have five pillars: deployment mandates for commercial / cost-effective clean technologies that provide the economies of scale, financial support for emerging technologies, long-term infrastructure planning, accelerating/scaling domestic manufacturing, and planning for a just transition as summarized in the table below.

SECTOR	MANDATES	INCENTIVES	DOMESTIC MANUFACTURING	INFRASTRUCTURE PLANNING	UPFRONT CONSIDERATION OF A JUST TRANSITION
Power	Renewable Purchase Obligation / Storage Purchase Obligation	Long duration storage, offshore wind	Production Linked Incentive + Strategic Alliances for manufacturing solar panels, batteries, electrolyzers etc	Cross-sectoral least-cost investment planning	Safety Nets Worker Retraining Social Dialogue Economic Diversification
Transport	Zero Emissions Vehicle Sales Mandate	Public EV Procurement (e.g. buses)		Public Fast Charging + Low-Cost Solar Charging	
Industry	Clean Mandate on new Industrial Facilities and Hydrogen Production, energy and material efficiency standards (e.g. expand PAT)	Green hydrogen pilots, RD&D		Hydrogen Infrastructure and Low-Cost Solar PPAs	



EXECUTIVE SUMMARY

Oil, gas, and coal prices have shown significant volatility in the past few years due to geopolitical tensions, supply chain shocks, and a demand rebound following the COVID-19 pandemic. India currently imports 90% of its oil consumption, 40% of its gas consumption, 20% of its coal consumption, making it vulnerable to fluctuations in global energy prices and supply disruptions (MOSPI, 2022). This leads to a strain on the country's balance of payments and economy-wide inflation.

As the fifth largest economy in the world, with rapidly growing incomes, urbanization, and industrialization, India's energy demand is expected to nearly quadruple in the coming decades (IEA, 2021). This study aims to assess a pathway for India to meet its growing energy needs and achieve near-complete energy independence by 2047, a goal set by Prime Minister Narendra Modi. We believe that recent technological advances and deep cost reductions in clean technology, as well as excellent quality renewable resource potential, offer a cost-effective opportunity for India to attain this goal. Since much of the energy infrastructure in the country is yet to be built, we focus primarily on how most of the new investments will be clean in three largest energy consuming sectors in India –power, transport, and industry — which collectively account for more than 80% of the country's energy consumption and energy-related CO_2 emissions. We run detailed energy-emissions models, including hourly grid simulations, for these three sectors, from 2020 through 2050 for the following two scenarios:

(a) Reference: The reference scenario models historical and recent trends in clean energy deployment, assuming that there is progress on existing targets and commitments at the current pace. This pathway includes renewable energy deployment that achieves 37% clean generation by 2030 (>350 GW non-fossil capacity) and 60% by 2047. In the transport sector, the scenario assumes 45% electrified new vehicle sales by 2035 for two-wheelers, 24% for passenger cars and 12% for medium and heavy duty vehicles. . Industrial production continues to be dominated by fossil fuels.

(b) **CLEAN-India (Clean Energy for AtmaNirbhar India):** CLEAN-India scenario incorporates the potential for rapid and cost effective clean energy deployment that is already commercially available today. It models a pathway for renewable energy deployment that achieves the current 2030 targets (>500 GW non-fossil capacity), 80% clean generation by 2040 and 90% by 2047; nearly 100% electrified new vehicle sales by 2035 in all vehicle categories; and a shift to green hydrogen and electrification in industrial production as a replacement for coking coal, natural gas, and oil. It is important to understand that the CLEAN-India pathway is not a projection; rather, it is intended to illustrate a potential pathway for achieving energy independence by accelerating the clean energy transition in India.

KEY FINDINGS

CLEAN ENERGY CAN ENABLE INDIA'S ENERGY INDEPENDENCE BY 2047

The CLEAN-India pathway can achieve energy independence by 2047 by significantly decreasing the amount of oil imported for road transportation and coal imported for industry and power sectors. In the Reference scenario, total primary energy consumption is expected to double from 652 mtoe in 2022 to ~1181mtoe by 2047. This would require roughly 39% of primary energy supply in 2047 to be imported, including over 90% of oil consumption (299 mtoe) and 70% of coking coal consumption (175 mtoe), costing $275 billion (INR 2.1 million crores). In contrast, the CLEAN-India scenario would reduce fossil fuel imports to $15 billion (INR 112,500 crores) by 2047, with oil imports decreasing to 27 mtoe and industrial coking coal imports decreasing to below 5 mtoe (Figure ES-1-2).

CLEAN-India pathway avoids fossil fuel imports, but it also involves a multi-fold increase in the deployment of solar panels, wind turbines, electrolyzers for producing green hydrogen, and lithium-ion batteries for grid-scale storage and electric vehicles. While India has made significant progress in domestic manufacturing of clean technologies, there are concerns about the availability and supply security of lithium and other critical minerals used in them, especially in batteries. Our analysis finds that total cumulative lithium requirements between 2022 and 2040 would be roughly 1.9 million tons;1.7 million tons of that lithium will be used for electric vehicles. India's recent lithium discovery is estimated to be 5.9 million tons, substantially larger than the cumulative lithium requirement over the next 20 or so years (Figure ES-3). Studies have shown that large portions of lithium in spent car batteries can be recycled and reused in new batteries. We estimate that if the lithium in retiring EV batteries is recycled (up to 95%), it could meet between a quarter and a half of the annual lithium demand in the 2040s in the CLEAN-India case (Figure ES-4).

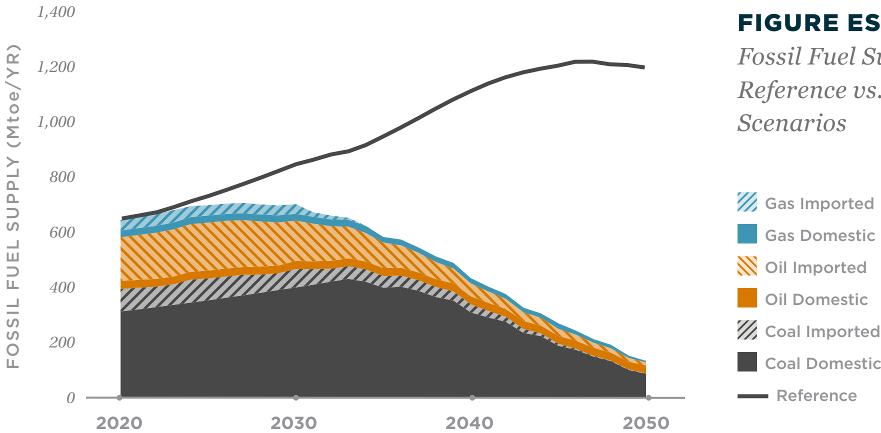


FIGURE ES-1.
Fossil Fuel Supply, Reference vs. CLEAN-India Scenarios

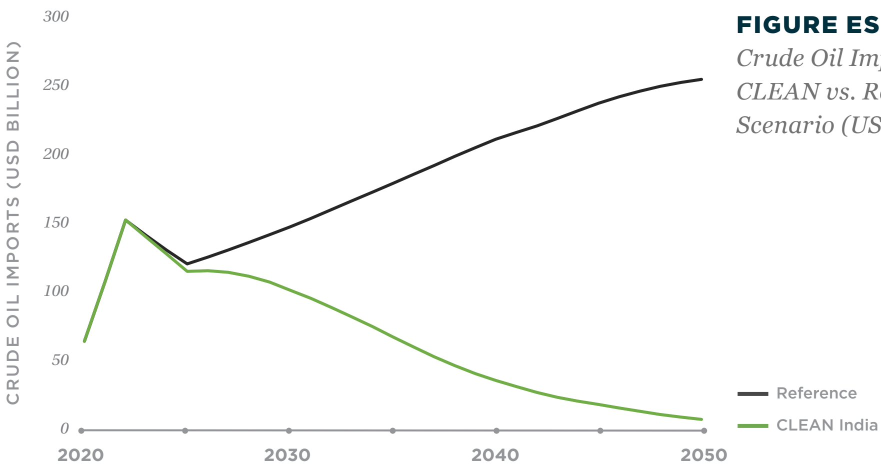


FIGURE ES-2.
Crude Oil Import Costs, CLEAN vs. Reference Scenario (USD billions)

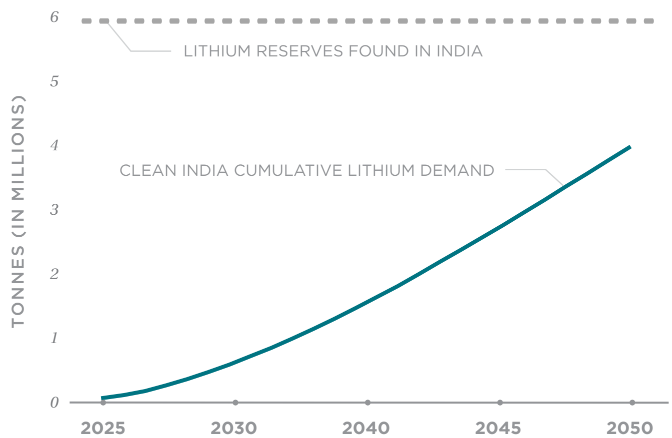


FIGURE ES-3.
Cumulative Lithium Demand vs. Estimated Lithium Reserves in India

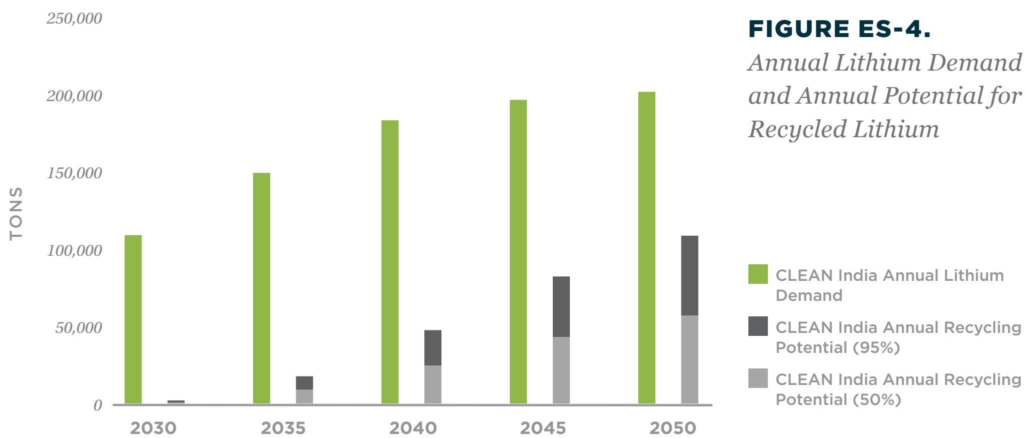


FIGURE ES-4.
Annual Lithium Demand and Annual Potential for Recycled Lithium

While the CLEAN-India pathway can avoid expensive fossil fuel imports in the transport and industrial sectors, one could envision a domestic coal dominant energy independence pathway for the power sector. However, such a pathway may not be cost-effective due to the declining costs of RE and energy storage. For example, the levelized cost of solar energy co-located with energy storage, which would provide a combined capacity factor of around 60%, is expected to be around INR 3.5/kWh by 2030, which is cheaper than building new coal power plants (Abhyankar et.al, 2021).

SWITCHING TO CLEAN ENERGY WOULD ENHANCE INDUSTRIAL COMPETITIVENESS

India's heavy reliance on imported fuels makes the industrial energy and freight movement costs vulnerable to global energy price fluctuations and supply disruptions, leading to economy-wide inflation as well as straining the country's balance of payments. For example, just in the financial year 2021-22, average crude oil import price in India fluctuated from $40 to $120 per barrel. It is estimated that every $10 increase in crude oil prices adds $12.5 billion to India's current account deficit, leading to rising inflation (Ghosh and Tomar, 2019).

The CLEAN-India scenario offers an opportunity to reduce and inflation-proof India's energy costs because renewables, storage, EV batteries, electrolyzers, and hydrogen infrastructure are capital assets. Additionally, Indian industry, to remain globally competitive, must transition to clean technologies such as EV manufacturing and green steel manufacturing. For instance, the Indian auto industry is the fourth largest producer of passenger vehicles in the world and exports nearly a quarter of its production. Some of their largest export markets are EU countries including Italy, Germany, and the Netherlands, all of which have committed to phasing out internal combustion engine vehicles by the 2030s. Similarly, India is one of the largest steel exporters, with its largest markets in EU countries that have committed to carbon neutrality by 2050, including imported goods.

ELECTRIC VEHICLES AND A CLEAN GRID WOULD SAVE CONSUMERS TRILLIONS, WITH MANAGEABLE IMPACTS ON TAX REVENUES

This study finds that transitioning from a coal-dominated power grid to a 90% clean grid in the CLEAN-India scenario is technically feasible and economically viable. As clean technology prices continue to fall, the average cost of electricity generation is expected to drop by about 10% in real terms between 2020 and 2050. Similarly, in the transportation sector, for most vehicle classes, EVs are already on par with internal combustion engine (ICE) vehicles in terms of the total cost of ownership (TCO). With a steep reduction in upfront prices expected in the coming years, EVs will have a 34-53% lower TCO than ICE vehicles by 2030. As a result, a shift to electric transportation is estimated to create $2.5 trillion (INR 19 million crores) in net consumer savings by 2050 from reduced fuel and maintenance costs, even after accounting for the high upfront costs of EVs. In the industrial sector, the cost-effectiveness of clean energy transition, in particular green hydrogen based steel manufacturing or electrified cement production etc, is still a decade away.

Fossil fuel taxes, duties, and royalties, as well as electricity duties, contribute significantly to state and central government revenues (Figure ES-5), totaling around $80 billion (INR 600,000 crore) per year, or 12% of total government revenue. Under the CLEAN India scenario, despite an aggressive clean energy transition, the fossil fuel consumption and associated tax revenues will not drop below 2020 levels until 2035, assuming the current tax regime continues. By 2047, total energy tax revenue would drop to about half of the 2020 levels, with electricity duties (mostly collected by the state governments) making up for a part of the lost tax revenue from reduced fossil fuel consumption. Because of India's rapid economic growth and expanding tax base, we believe that there will be several opportunities to offset this modest loss (i.e. 2-3% of the total government tax and non-tax revenue by 2047) in the coming decades. Note that a more nuanced analysis will be needed to assess this issue in more detail. For instance, our analysis aggregates the total tax revenue irrespective of where the tax is collected and how it is shared between the state and the central governments.

Indian Railways (IR) transport most of the coal consumed in the country and there will be a major revenue loss for them due to decreased coal consumption, but this will potentially open up the rail network for industrial freight that currently relies on road transport, making up for the lost coal revenue.

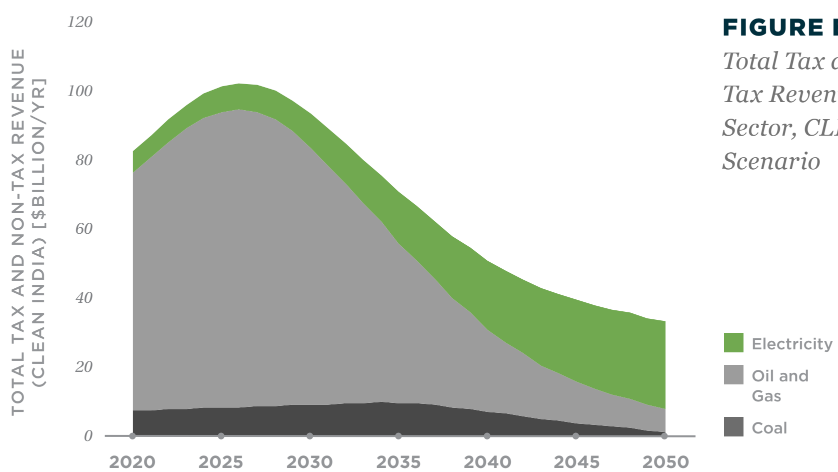


FIGURE ES-5.
Total Tax and Non-Tax Revenue by Sector, CLEAN India Scenario

A RAPID EXPANSION OF CLEAN ENERGY INFRASTRUCTURE WILL BE CRITICAL IN THE COMING DECADES

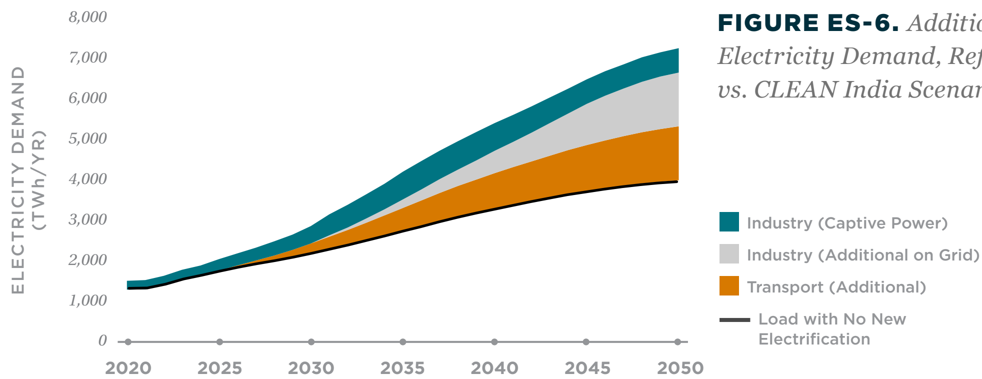


FIGURE ES-6. *Additional Electricity Demand, Reference vs. CLEAN India Scenarios*

Because of the transport and industrial electrification and green hydrogen production, the electricity demand increases drastically in the CLEAN-India scenario — from 1300 TWh/yr (bus-bar) to over 6600 TWh/yr by 2050 (Figure ES-6). This demand is 70% higher than a scenario with no new electrification policies and 50% higher than the Reference case, which also includes significant transport sector electrification. Note that this is only utility-supplied electricity. If industrial captive power is included (as seen in the graph), electricity demand jumps to roughly 7200 TWh/year by 2050. The CLEAN-India scenario includes several energy, process, and material efficiency policies resulting in a significant reduction in the overall load. In absence of such policies, the additional electricity demand from the industrial sector could be 40% higher.

In the CLEAN-India scenario, the power sector achieves carbon free electricity generation of 90% by 2047. This entails 1236 GW of solar capacity, 909 GW of onshore wind and 375 GW of offshore wind capacity, and 452 GW / 2500 GWh of energy storage. The pace of required renewable capacity additions is around 40 GW/year through 2030, ramping up to about 100 GW/year between 2030 and 2050.

In the transport sector, over 22.5 million electric 2-W, 7.5 million electric cars and 330,000 heavy duty electric trucks will be sold each year by 2035. By 2047, over 95% of all on-road vehicles will be electric.

In industry, the pathway primarily focuses on electrification and green hydrogen across the iron and steel, cement, and fertilizer, chemical and petrochemical sectors. 255 MT/yr of steel (60%) will be manufactured using green hydrogen and 42 MT/yr (10%) with electrification by 2050. In the cement sector, 480 MT of cement production (65%) will be manufactured using electrification and 184 MT (25%) will be manufactured using green hydrogen by 2050. 67 MT (100%) of fertilizer production will be green hydrogen based by 2050, and 82 MT (100%) of chemical and petrochemical production will be green hydrogen based by 2050.

The CLEAN-India pathway will be more capital-intensive and will change the cost structure of the energy sector to one dominated by capital assets/fixed costs. We find that the total investment required for building new clean energy infrastructure between 2020 and 2047 will be $3.5-4 trillion (INR 26-33 million crores), including $2.6 trillion for power generation, $60 billion for charging infrastructure, and over $1-1.5 trillion for the heavy industry. It should be noted that even in the Reference case scenario, India will need to invest over $2 trillion from 2020-2050, including approximately $1.5 trillion in power generation, $20 billion in charging infrastructure for electric vehicles, and $500 billion in heavy industry. The net additional investment required for the CLEAN pathway would be $1.5-2 trillion (INR 11-15 million crores). These estimates are high-level and require further analysis, but they are also consistent with other recent studies (McKinsey, 2022). While the scale of the additional investments is significant, they are manageable given the rapid growth of the Indian economy (annual GDP increasing from approximately $3 trillion in 2020 to $15-20 trillion/year by 2050) and the availability of global capital (PwC, 2017).

CLEAN ENERGY OFFERS ENVIRONMENTAL AND PUBLIC HEALTH BENEFITS WITHOUT COMPROMISING ECONOMIC GROWTH

In the Reference case scenario, energy-related carbon dioxide (CO_2) emissions from power, transport, and industry sectors will continue to grow until the late 2040s, peaking a little above 4 gigatons/year (nearly double current levels). In the CLEAN India scenario, emissions will peak in the early 2030s, before dropping to under 500 million tons/year by 2047 and near-zero by 2050 (Figure ES-7). The majority of emission reductions (41%) will be achieved through clean electricity generation, followed by electrified industrial processes and hydrogen-based iron/steel and fertilizer production (29%), and electrified transport, particularly electric heavy-duty vehicles(16%). Additionally, due to the significant reduction in fossil fuel consumption, over 4 million premature deaths related to air pollution could be avoided between 2022 and 2047.

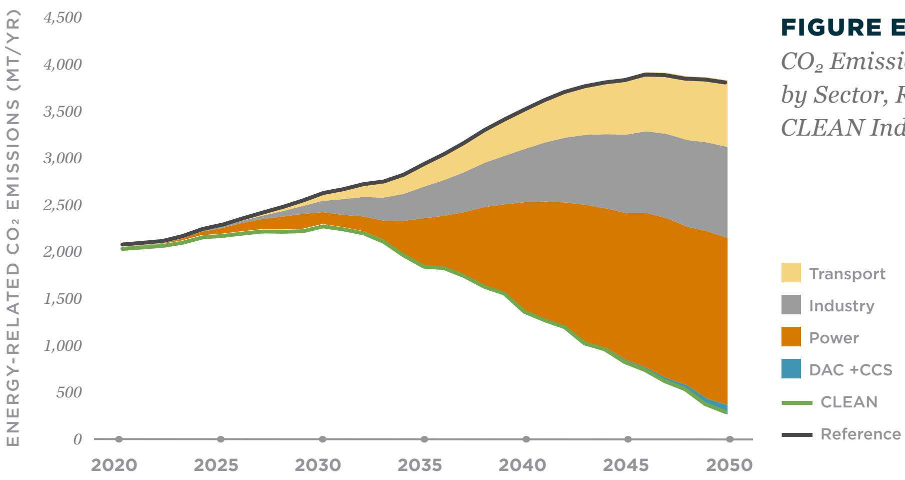


FIGURE ES-7.

CO_2 Emissions Reductions by Sector, Reference vs. CLEAN India Scenarios

MANAGING THE CLEAN ENERGY TRANSITION WOULD REQUIRE SIGNIFICANT POLICY SUPPORT

Given the scale and pace of the clean energy transition needed to attain energy independence by 2047, creating an enabling policy and regulatory ecosystem will be critical.. This will be also essential to manage this transition in an equitable and just manner. Due to India's rapidly growing energy demand , we find that there is a lead time of 10-15 years to make this transition and it will be important to do so in concert with the most affected communities.

The policy ecosystem needs to have five pillars: deployment mandates for commercial / cost-effective clean technologies that creates a virtuous cycle of economies of scale and cost reduction, financial support for emerging technologies, long-term infrastructure planning, accelerating and scaling domestic manufacturing, and planning for a just transition as summarized in Table ES-1.

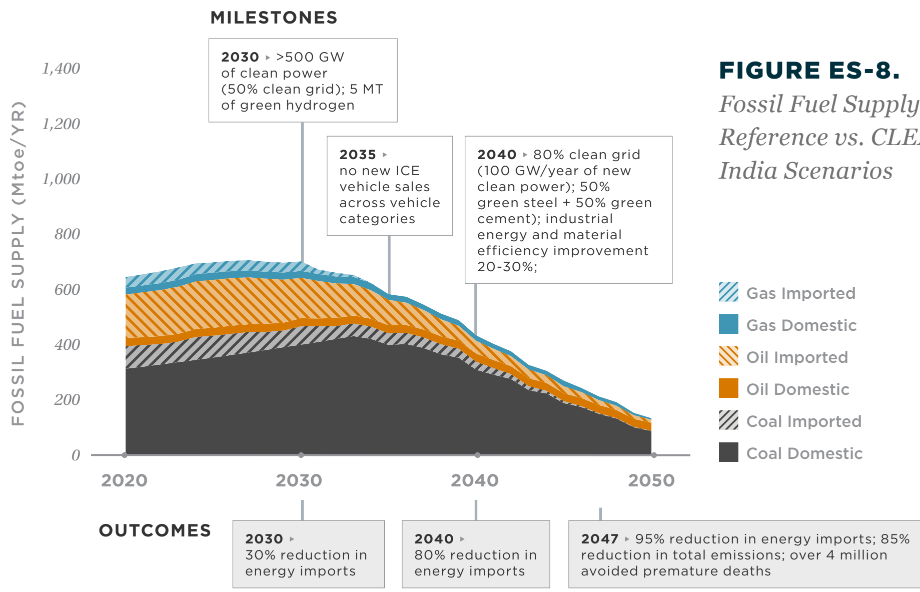


FIGURE ES-8. *Fossil Fuel Supply, Reference vs. CLEAN India Scenarios*

TABLE ES-1. *Policy Ecosystem Needed for Achieving Energy Independence*

SECTOR	MANDATES	INCENTIVES	DOMESTIC MANUFACTURING	INFRASTRUCTURE PLANNING	UPFRONT CONSIDERATION OF A JUST TRANSITION
Power	Renewable Purchase Obligation / Storage Purchase Obligation	Long duration storage, offshore wind	Production Linked Incentive + Strategic Alliances for manufacturing solar panels, batteries, electrolyzers etc	Cross-sectoral least-cost investment planning	Safety Nets Worker Retraining Social Dialogue Economic Diversification
Transport	Zero Emissions Vehicle Sales Mandate	Public EV Procurement (e.g. buses)		Public Fast Charging + Low-Cost Solar Charging	
Industry	Clean Mandate on new Industrial Facilities and Hydrogen Production, energy and material efficiency standards (e.g. expand PAT)	Green hydrogen pilots, RD&D		Hydrogen Infrastructure and Low-Cost Solar PPAs	

1
INTRODUCTION

India is the world's fifth-largest economy in nominal terms, behind the United States, China, Japan, and Germany (Myers, 2020), and one of the largest energy consumers. Due to growing industrialization, urbanization, and rising incomes, India's energy consumption is expected to increase three to four-fold in the coming decades (Figure 1). India is projected to be the largest contributor to additional global energy demand between 2020-2040 (IEA, 2021). In comparison to other industrialized economies, India lags behind by $1-2 trillion in its energy infrastructure investment, which is likely to take place in the next 2-3 decades (IEA, 2021).

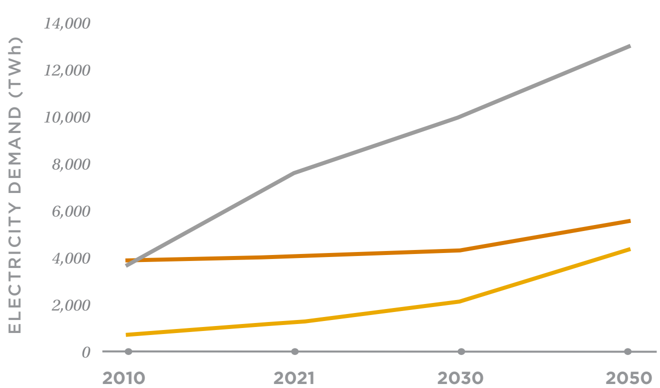


FIGURE 1. *Electricity Demand In India Relative To Other Countries (Source: IEA, 2022)*

Imports account for a significant share of India's overall energy consumption, particularly fossil fuels, making India one of the largest net-importers in the world. For instance, India imports more than 88% of its oil, and this dependence is expected to increase due to the expected energy demand growth in the transportation and industrial sectors. In 2021 alone, India's oil import cost was over $100 billion (INR 750,000 crores) per year — about 3% of its GDP that year (The Economic Times, 2022). Additionally, over 80% of the industrial coking coal used for iron and steel production and about 20% of the coal used in the power sector for electricity generation is imported. Therefore, fluctuations in the international fuel market, especially oil, have a major impact on India's consumer inflation, industrial energy costs, and the country's foreign trade balance/currency. In light of such high fuel imports, Prime Minister Modi has announced an aspirational goal for an Energy Independent India, or "Atmanirbhar Bharat," by 2047 — the 100th year of India's independence (Times of India, 2021).

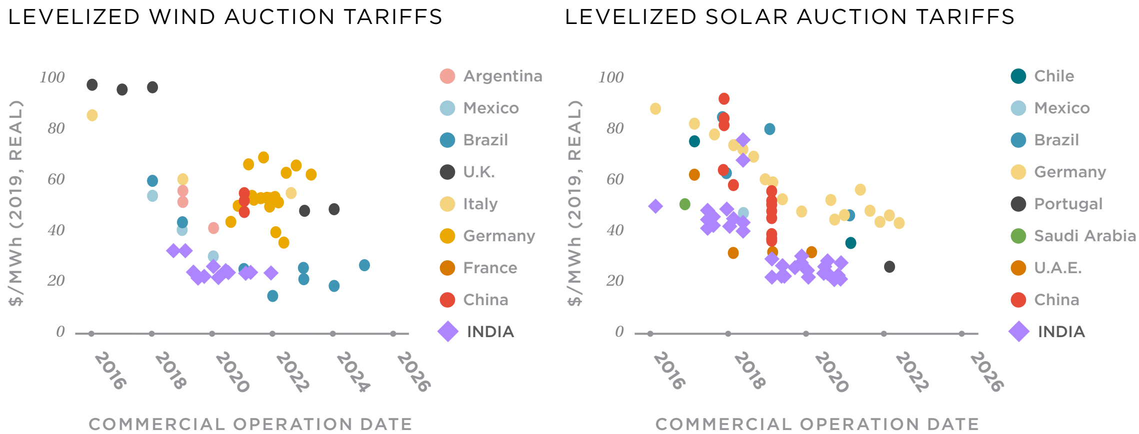
Fossil fuel use in the energy sector is also a primary contributor to outdoor air pollution in India. 22 of the world's 30 most heavily polluted cities are located in India (IQAir, 2021). Poor air quality is estimated to contribute to over one million premature deaths each year in India (Pandey et. al., 2021). India's growing energy needs for development and economic growth have also led to increasing greenhouse gas (GHG) emissions in the country. Currently, India is the third largest emitter of CO_2 after China and the United States. India, and more broadly South Asia, have already experienced a series of natural disasters and extreme weather events such as flooding and heatwaves due to climate change. In November 2021, at the Glasgow COP, India made a commitment to achieve net-zero GHG emissions by 2070.

India's anticipated energy demand growth has been accompanied by a deep reduction in clean energy technology costs, especially for wind turbines, solar PV cells, lithium-ion (Li-ion) batteries, and hydrogen electrolyzers. Between 2010 and 2020, the global levelized cost of energy (LCOE) for solar and wind dropped over 80%. India saw the largest reduction in country-level solar LCOE, at 85%, and the average solar tariff in 2020 was 34% lower than the global weighted average due to innovative reverse auction design and other policies (Figure 2, BNEF, 2021). Renewables are now cost-competitive with thermal power generation throughout India, even in regions previously considered resource poor for renewable generation. The cost of co-located solar and storage projects with approximately 2-4 hours of energy storage to meet evening peak demand is projected to be Rs. 3-4/kWh by 2030 — lower than the variable cost of nearly half (80-100 GW) of India's existing coal capacity (Abhyankar et al. 2021). Recent large-scale Round-The-Clock power and storage auctions by the Solar Energy Corporation of India (SECI) and National Thermal Power Corporation (NTPC) have demonstrated the cost effectiveness of energy storage in India.

Globally, Li-ion battery pack prices have seen a 90% reduction between 2010 and 2020, and another 40-50% reduction is expected by 2030 (Figure 3, BNEF, 2021). In the transport sector, the increasing commercial viability of EVs has led to 13% of new passenger vehicle sales and 40% of global bus sales being electric (Paoli and Gul, 2022). The International Energy Agency (IEA) estimates that over 300 million electric vehicles will be on the road globally by 2030 (IEA, 2022). In India, EV sales, including private passenger vehicles such as two-wheelers and cars as well as public buses, have seen a significant increase in recent years.

The global policy and investment landscape in the energy sector is also changing rapidly. For example, the United States has passed the Inflation Reduction Act, the largest clean energy investment package in the country's history, which includes incentives for clean technology across sectors. The European Union has banned the sale of new petrol and diesel cars by 2035, and states such as California and Washington in the United States have set targets for 100% zero-emission vehicle sales by 2035. Many countries are also committing to transitioning to greener industrial practices in sectors such as iron and steel, cement, and fertilizers. China and Indonesia, two of the largest emerging economies, have made commitments to achieve net zero emissions by 2060.

FIGURE 2. *Solar and Wind Energy Prices in India and other Countries (BNEF, 2021)*



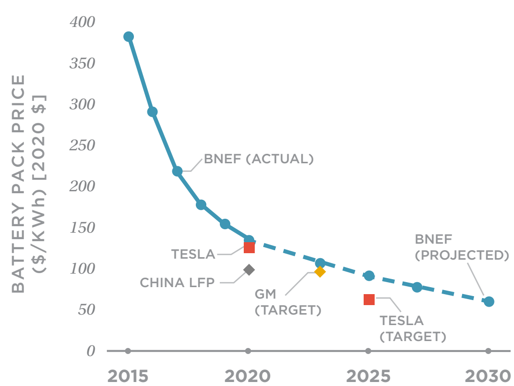


FIGURE 3.
Global Average Battery Pack Price over Time (BNEF, 2021)

Given the significant reductions in clean technology costs and the anticipated growth in India's energy demand in the coming decades, the objective of this paper is to assess a pathway for India to achieve Prime Minister Modi's goal of energy independence by 2047. We focus primarily on the three sectors that consume the most energy in India — power, transport, and industry — which together account for more than 80% of the country's energy consumption and energy-related CO_2 emissions (IEA, 2021). This transition to a clean energy economy is likely to face several challenges, including the technical feasibility of new technologies like hydrogen and high-heat electrification, grid reliability with a high renewable energy penetration, tax impacts from the loss of fossil fuel revenue, a fair and equitable transition, and robust supply chains to support the rapid expansion of clean technology. This paper aims to address these issues.

2

LITERATURE REVIEW

This topic has been analyzed in the literature by several researchers and organizations. Below is a summary of the most recent and significant assessments:

The International Energy Agency's India Energy Outlook 2021 report (IEA, 2021) explores the opportunities and challenges for India as it seeks to ensure reliable, affordable, and sustainable energy to a growing population. The report examines pathways for India's energy sector up until 2040, as well as longer-term trends, exploring how the energy sector might evolve under a range of scenarios. These include the Stated Policy Scenario, which provides projections for emissions reductions based on today's policy settings and constraints; the IndiaVision Case, which is based on a realization of India's stated energy policy objectives as well as faster assumed economic growth; the Delayed Recovery Scenario, which analyzes a scenario in which the COVID-19 pandemic recovery is delayed; and the Sustainable Development Scenario, which explores how India could mobilize an additional surge in clean energy investment to produce an early peak and rapid subsequent decline in emissions.

The McKinsey report "Decarbonizing India: Charting a pathway for sustainable growth" (McKinsey, 2022) proposes more than 100 decarbonization levers to achieve India's 2070 net zero commitment across key sectors such as power, steel, automotive, aviation, cement, and agriculture. The report looks at four cross-cutting decarbonization opportunities: green hydrogen, carbon capture, usage, and storage (CCUS), natural climate solutions, and material circularity. It utilizes two scenarios: one in which only current/announced and foreseeable technology adoption is applied, and the second in which far-reaching policies like carbon pricing and accelerated technology adoption are implemented.

The TERI/Shell report "Transforming to a Net-Zero Emissions Energy System" (TERI, 2021) relies heavily on biofuels, hydrogen, nuclear, and CCUS, with less consideration of electrification and batteries. By 2050, the TERI study finds that most emissions will come from the mining sector, with massive reductions across the power, transport, residential, agricultural, commercial, and industrial sectors.

The World Economic Forum's report "Mission 2070: A Green New Deal for a Net-Zero India" (World Economic Forum, 2021) outlines a 2070 scenario through decarbonizing the power sector with renewables, energy efficiency, and CCUS; decarbonizing the transportation sector via CNG and LNG in the short term and electrification and hydrogen-based mobility in the medium and long term; decarbonizing industry through electrification, energy efficiency, circular economy acceleration, and hydrogen; and green buildings and sustainable agriculture.

The Council on Energy, Environment and Water (CEEW) net-zero study "Peaking and Net-Zero for India's Energy Sector CO_2 Emissions" (Malyan and Chaturvedi, 2021) focuses on four scenarios: 2030 peak/2050 net zero, 2030 peak/2060 net zero, 2040 peak/2070 net zero, and 2050 peak/2080 net zero. The paper finds that reaching net zero by 2050 will require the share of fossil energy in India's primary energy mix to fall from 73% (2015) to 5% in 2050; for 83% of electricity to be generated by renewable energy by 2050; for biofuels to replace 98% of India's oil use in 2050; and for more than two-thirds of India's industrial energy use and new vehicle sales to be electrified. The selection of peaking and net-zero years is based on average per capita income, economic growth rate, costs of stranded assets, and cumulative emissions.

The World Resources Institute India and Energy Innovation paper, *Pathways for Decarbonizing India's Energy Future: Scenario Analysis Using the India Energy Policy Simulator* (Swamy et al., 2021), explores two climate policy scenarios for India through 2050 using the India Energy Policy Simulator, an open-source systems dynamics model. Its analysis considers the NDC-SDG Linkages scenario, which connects India's climate actions and the Sustainable Development Goals (SDG) for 2030; as well as the Long-Term Decarbonization (LTD) scenario, which outlines policies with high emissions reduction potential. In the NDC-SDG scenario, emissions are reduced by 27% in 2050 while in the LTD scenario, emissions are reduced by 65% in 2050, relying on renewables, carbon taxes, energy efficiency standards, and hydrogen.

3 METHODS

In this paper, we use detailed power, transport, and industrial energy models to assess a pathway towards energy independence by 2047. We evaluate two scenarios:

(a) Reference: The reference scenario projects historical and recent trends in clean energy deployment, assuming that there is progress on existing targets and commitments at the current pace of deployment. This pathway includes renewable energy deployment that achieves 37% clean generation by 2030 (>350GW non-fossil capacity) and 60% by 2047 as well as 45% electrified new vehicle sales by 2035 for two-wheelers, 24% for passenger cars and 12% for medium and heavy duty vehicles as well as renewable energy deployment that achieves 37% clean generation by 2030 and 60% by 2047. Industrial production continues to be dominated by fossil fuels.

(b) CLEAN-India (Clean Energy for AtmaNirbhar) India: CLEAN-India scenario incorporates the potential for rapid and cost effective clean energy deployment that is already commercially available today. It models a pathway for renewable energy deployment that achieves the current 2030 targets (>500 GW non-fossil capacity), 80% clean generation by 2040 and 90% by 2047; nearly 100% electrified new vehicle sales by 2035 in all vehicle categories;, renewable energy deployment that achieves the current 2030 targets (>500 GW non-fossil capacity), 80% clean generation by 2040 and 90% by 2047 as well as and a shift to green hydrogen and electrification in industrial production as a replacement for coking coal, natural gas, and oil. It is important to understand that the CLEAN-India pathway is not a projection; rather, it is intended to illustrate a potential pathway for achieving energy independence by accelerating the clean energy transition in India.

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It is important to understand that the CLEAN-India pathway is not a projection; rather, it is intended to illustrate a potential pathway for achieving energy independence by accelerating the clean energy transition in India.

Table 1 shows each scenario in detail.

TABLE 1. *Details of the modeled scenarios*

SECTOR	POLICY LEVER	REFERENCE SCENARIO	CLEAN-INDIA
Power	% of carbon free electricity generation	• 23% in 2020 • 37% by 2030 (39% of native power demand; 350 GW of clean power) • 50% by 2040 • 60% by 2047	• 23% in 2020 • 46% by 2030 (50% of native power demand; 500 GW of clean power) • 80% by 2040 • 90% by 2047
	Appliance Energy Efficiency	• ~2-3% improvement per year 2020-2030 • ~1-2% improvement per year 2030-2040 • ~0.5-1% improvement per year 2040-2050	• ~4-6% improvement per year 2020-2030 • ~2-4% improvement per year 2030-2040 • ~1-2% improvement per year 2040-2050

SECTOR	POLICY LEVER	REFERENCE SCENARIO	CLEAN-INDIA
Transport	EV Sales Mandate (% of new vehicle sales)	• 2W/3W: 23% by 2030, 60% by 2040, 70% by 2050 • Cars: 15% by 2030, 30% by 2040, 60% by 2050 • MDV/HDV: 7% by 2030, 15% by 2040, 35% by 2050	• 2W/3W: 100% by 2035 • Cars: 100% by 2035 • MDV/HDV: 80% by 2030, 100% by 2035
Industry	Electrified Production (% of total)	• Iron & Steel: 15% by 2050 • Cement: 0% by 2030, 15% by 2050	• Iron & Steel: 35% by 2050 • Cement:65% by 2050
	Green Hydrogen Based Production	• Iron & Steel: 0% by 2030, 5% by 2050 • Cement: 0% by 2030, 5% by 2050 • Fertilizers & Chemicals & Petrochemicals: 25% by 2050	• Iron & Steel: 10% by 2030, ~40% by 2040, 60% by 2050 • Cement: 15% by 2040, 25% by 2050 • Fertilizers, Petrochemicals & Chemicals: 50% by 2030, 100% by 2050
	Process and Material Efficiency	• Energy efficiency improvement: Steel (10% between 2020-2050), Cement (5% between 2020-2050), • Steel: Scrap ratio in recycling, i.e., secondary steel production, (~0.5by 2040-2050) • Improve Clinker to Cement ratio by 2% per decade	• Energy efficiency improvement: Steel (25% between 2020-2050), Cement (15% between 2020-2050), Fertilizers, Chemicals & Petrochemical (15% between 2020-2050) • Steel: Scrap ratio in recycling (0.65% by 2040,0.9 by 2050) • Improve Clinker to Cement ratio by 5% per decade • Demand Reduction/ Material Efficiency: Cement 10%, Petrochemicals 50% • Captive Heat (Cement) by 2.5% by 2050
Carbon Capture, Utilization and Storage (CCUS) + Direct Air Capture (DAC)	Share of sectoral emissions	• Power: 0.5% CCUS by 2050 • Industry: 2.5% CCUS by 2050 • No DAC	• Power: 2% CCUS by 2050 • Industry: 5% CCUS by 2050 • Economy: 1% DAC by 2050

3.1 POWER

As seen in the Table above, the Reference scenario models a pathway achieving 60% of carbon free electricity generation by 2047. In the CLEAN-India scenario, carbon free electricity generation reaches 90% by 2047. We model 90% clean grid (vs 100% clean) because studies have shown that the transition from 90% to 100% clean grid requires steep additional costs and technologies that are not currently commercially viable. We use PLEXOS,[1] an industry standard power system simulation software that conducts optimal capacity expansion and hourly system dispatch to assess a resource mix and hourly dispatch for each year between 2020 and 2050.[2] The model minimizes total generation cost (i.e., fixed plus variable costs) for the entire system, including existing and new generation capacity. We represent the Indian electricity grid using a single-node model, and do not model transmission.

For projecting the native (i.e., without any new transport or industrial electrification or green hydrogen production) electricity demand until 2037, we use state-level demand projections from Central Electricity Authority's (CEA) 19th and 20th Electric Power Surveys (EPS) (CEA, 2017 and 2022). Beyond 2037, we project the native electricity demand using historical growth rates. Additional electricity demand from transport and industrial electrification/hydrogen production is then added to the native electricity demand to estimate the aggregate national electricity demand for each year between 2020 and 2050. Hourly load pattern for the native electricity demand is estimated using actual load data for 2018 and our previous work on changing appliance and equipment penetration in India (Abhyankar et al, 2017). Hourly load patterns for electric vehicle charging are taken from Phadke et al (2016), Karali et al (2020), and Abhyankar et al (2022). Hourly load pattern for industrial electrification and green hydrogen production is taken as the average hourly heavy industrial load profile (largely flat throughout the day) based on our previous work (Karali et al, 2020).

Hourly wind generation profiles and hydro dispatch constraints are assessed using historical generation data (for the load-synchronized 2018 weather year). For solar, hourly generation profiles are developed using Global Horizontal Irradiance (GHI) or Direct Normal Irradiance (DNI) data for key sites within each state (Abhyankar et al., 2016). The scenario also incorporates coal capacity already under construction per CEA annual progress reports: about 38 GW between 2021 and 2025, 23 GW until 2022, and 15 GW between 2023 and 2025 (CEA, 2021). The National Electricity

1 For more information on PLEXOS, see energyexemplar.com. PLEXOS uses deterministic or stochastic, mixed-integer optimization to minimize the cost of meeting load given physical (e.g., generator capacities, ramp rates, transmission limits) and economic (e.g., fuel prices, start-up costs, import/export limits) grid parameters.

2 The fiscal year in India runs from April 1 through March 31. For example, FY 2030 runs from April 1, 2029 to March 31, 2030. In this report, we use the terms "fiscal year" and "year" interchangeably. Any reference to a year implies fiscal year unless specified otherwise.

Policy (NEP) stipulates that about 8 GW of existing coal capacity would retire by 2022, and about 25 GW by 2027; this includes plants that have surpassed their useful life and plants that are unable to meet required emission standards (CEA, 2018). For projecting clean technology costs, the scenario assumes cost reductions for solar and wind technologies over the next decade are half the observed historical rate, while Li-ion battery levelized cost of storage (LCOS) projections are based on previous bottom-up cost analysis (Deorah et al., 2020).[3] Between 2030 and 2040, clean technology cost reductions are assumed to continue at a 50% lower reduction rate (i.e. 25% of historical rate) and no cost reductions are assumed beyond 2040. Conventional fixed costs, fuel costs, plant-level variable costs, operational parameters, and cost of capital are based on Central Electricity Regulatory Commission (CERC) norms, and other Government of India (GoI) sources (e.g., MERIT website, reports under the RRAS mechanism, or state tariff orders).

3.2 TRANSPORT

This paper uses the latest data to examine the economic feasibility and impact of achieving 100% electric vehicle (EV) sales for all ground transportation in India by 2035 for medium- and heavy-duty vehicles. As explained in the previous section, our power sector module also looks at the impact of these goals on the reliability and functionality of the electric grid. As shown in table 1, we evaluate two scenarios: Reference scenario in which fleet electrification occurs according to market forces without new policy intervention, and a "CLEAN-India" scenario in which new policies are implemented and market forces shift to overcome barriers to EV adoption. Under the Reference scenario, by 2030, EVs make up about 23% of two-wheeler and three-wheeler sales, 15% of passenger car sales, and 7% of medium-duty and heavy-duty vehicle sales. By 2040, these numbers nearly double and increase to 60%, 30%, and 15%, respectively. Under the CLEAN-India scenario, EV sales increase logarithmically to 100% between 2020 and 2035, and by 2050, EVs make up 97% of all on-road vehicles.

3.3 INDUSTRY

Our industrial energy model is a bottom-up energy-emissions model and consists of four main components: demand module, production module, capacity module, and energy and emissions module. It focuses on key heavy industries, including iron and steel, cement, fertilizers, and petrochemicals, which make up 80% of industrial energy consumption. We assume that the Reference Scenario continues to rely

3 Battery pack life is assumed to be 3,000 cycles, or 10 years. Project life is assumed to be 20 years, meaning that there will be one battery pack replacement in Year 11.

on coking coal and oil as fuel sources, while incorporating some green hydrogen and electrification into the energy processes associated with each sub-sector. In the reference scenario, electrified production is already very efficient, so efficiency measures are focused on BF-BOF and DRI processes. In the CLEAN-India Scenario, we assume that most of the hydrogen is used as a feedstock in fertilizers or other petrochemicals, and in hydrogen-based direct reduction processes in iron and steel production. Hydrogen is also assumed to be used in cement production to create high temperature heat, although some cement production is also assumed to be electrified. Most of the other low and medium heat applications are assumed to be electrified. Please refer to table 1 for details on scenario definitions and Appendix C for more detailed information about how the three sub-sectors were modeled.

The demand module forecasts the demand for various industrial products in India based on various sources, including the International Energy Agency (IEA) for steel, Bloomberg New Energy Finance (BNEF) for cement, and the Chemicals Petrochemicals Manufacturers Association (CPMA) for fertilizers, chemicals, and petrochemicals. The production module covers all existing and future production processes used in the production of industrial outputs, and models that total production must meet the demand (including exports) while conforming to scenario-specific constraints. The capacity module is a stock turnover model that models the existing capacity of production facilities, along with a forecast of their phase-out rate over time. New capacity needs are estimated based on annual demand, utilization of production capacity, production, and the retirement of existing production capacity, considering the median plant lifetime and a growth parameter. Finally, the energy and emissions module uses the energy/fuel and emissions intensity for each production process to estimate the total energy / fuel use and CO_2 emissions. We detail the energy needed per ton of production output according to fuel type and track the use of each fuel in each production process within each sub-sector.

4

KEY FINDINGS

4.1 ENERGY INDEPENDENCE

The CLEAN-India pathway can achieve energy independence by 2047 by significantly decreasing the amount of oil imported for road transportation and coal imported for industry and power sectors. In the Reference scenario, total primary energy consumption is expected to double from 652 mtoe in 2022 to ~1181 mtoe by 2047. This would require roughly 39% of primary energy supply in 2047 to be imported, including over 90% of oil consumption (312 mtoe) and 70% of coking coal consumption (123 mtoe), costing $245 billion (INR 1.9 million crores). In contrast, the CLEAN-India scenario would reduce crude oil imports by over 90% to $15 billion (INR 112,500 crores) by 2047. Overall fossil fuel imports reduce from $275 billion (INR 2.1 million crores) to $15 billion (INR 112,500 crores) by 2047, with oil imports decreasing to 27 mtoe and industrial coking coal imports decreasing to below 5 mtoe (Figure 4-5).

CLEAN-India pathway avoids fossil fuel imports, but it also involves a multi-fold increase in the deployment of solar panels, wind turbines, electrolyzers for producing green hydrogen, and lithium-ion batteries for grid-scale storage and electric vehicles. While India has made significant progress in domestic manufacturing of clean technologies, there are concerns about the availability and supply security of lithium and other critical minerals used in them, especially in batteries. Our analysis finds that total cumulative lithium requirements between now and 2040 is roughly 1.9 million tons, and 1.7 million of that lithium will be used for electric vehicles in the transport sector. India's recent lithium discovery is estimated to be 5.9 million tons, substantially larger than the cumulative lithium requirement over the next 20+ years (Figure 6). Studies have shown that large portions of lithium in spent car batteries can be recycled and reused. . We estimate that if the lithium in retiring EV batteries is recycled (up to 95%), it could meet between a quarter and a half of the annual lithium demand in the 2040s in the CLEAN-India case. The share of recycled lithium could increase substantially in the 2040s as more EVs get retired and could provide a large portion of estimated lithium demand (Figure 7). Thus, all future demand for batteries could be met with domestic lithium supply.

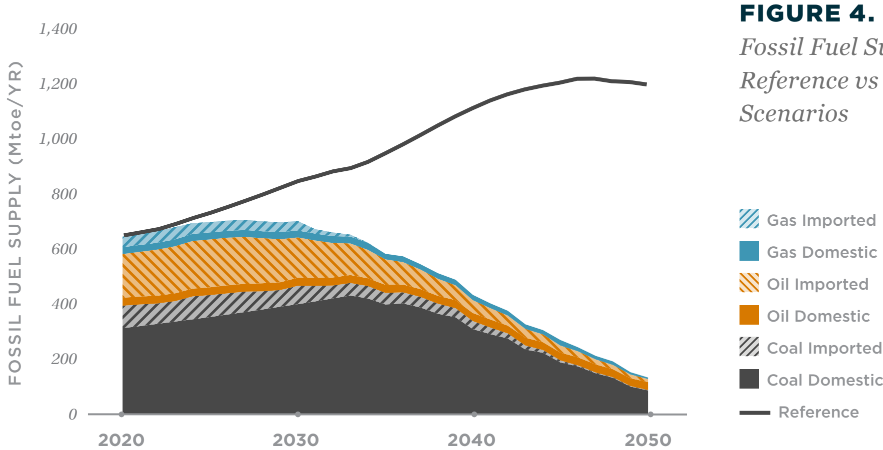


FIGURE 4.
Fossil Fuel Supply, Reference vs CLEAN-India Scenarios

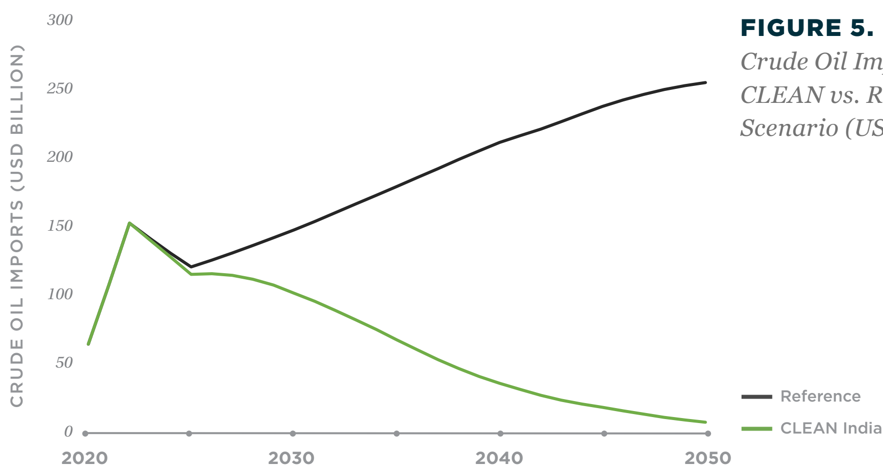


FIGURE 5.
Crude Oil Import Costs, CLEAN vs. Reference Scenario (USD billions)

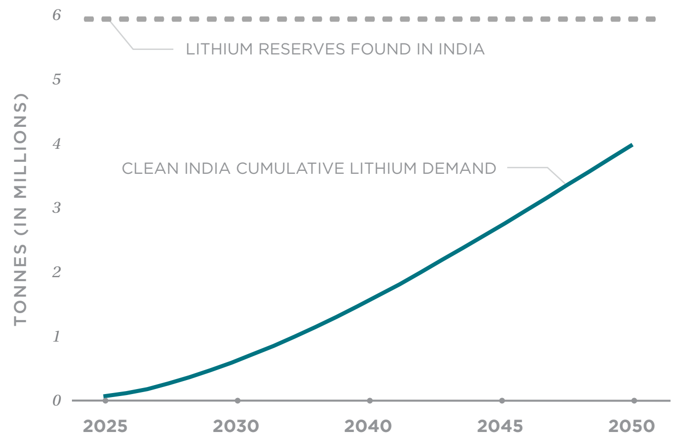


FIGURE 6.
Cumulative Lithium Demand vs. Estimated Lithium Reserves in India

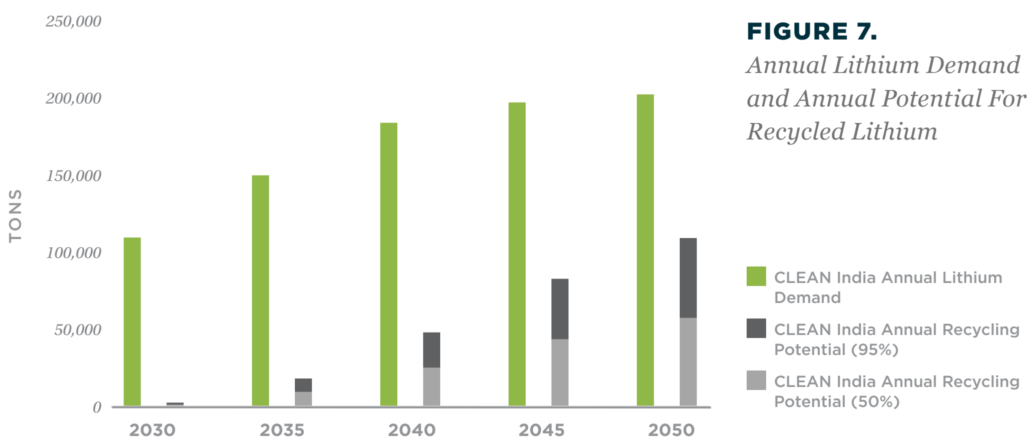


FIGURE 7.
Annual Lithium Demand and Annual Potential For Recycled Lithium

While the CLEAN-India pathway can avoid expensive fossil fuel imports in the transport and industrial sectors, one could envision a domestic coal dominant energy independence pathway for the power sector. However, such a pathway may not be cost-effective due to the declining costs of RE and energy storage. For example, the levelized cost of solar energy co-located with energy storage, which would provide a combined capacity factor of around 60%, is expected to be around INR 3.5/kWh by 2030, which is cheaper than building new coal power plants (Abhyankar et.al, 2021).

4.2 ECONOMIC BENEFITS

India's heavy reliance on imported fuels makes the industrial energy and freight movement costs vulnerable to global energy price fluctuations and supply

disruptions, leading to economy-wide inflation as well as straining the country's balance of payments. For example, just in the financial year 2021-22, average crude oil import price in India fluctuated from $40 to $120 per barrel. It is estimated that every $10 increase in crude oil prices adds $12.5 billion to India's current account deficit, leading to rising inflation (Ghosh and Tomar, 2019).

The CLEAN-India scenario offers an opportunity to reduce and inflation-proof India's energy costs because renewables, storage, EV batteries, electrolyzers, and hydrogen infrastructure are capital assets. Additionally, Indian industry, to remain globally competitive, must transition to clean technologies such as EV manufacturing and green steel manufacturing. For instance, the Indian auto industry is the fourth largest producer of passenger vehicles in the world and exports nearly a quarter of its production. Some of their largest export markets are EU countries including Italy, Germany, and the Netherlands, all of which have committed to phasing out internal combustion engine vehicles by the 2030s. Similarly, India is one of the largest steel exporters, with its largest markets in EU countries that have committed to carbon neutrality by 2050, including imported goods.

4.3 CONSUMER SAVINGS AND TAX REVENUES

This study finds that transitioning from a coal-dominated power grid to a 90% clean grid in the CLEAN-India scenario is technically feasible and economically viable. As clean technology prices continue to fall, the average cost of electricity generation is expected to drop by about 10% in real terms between 2020 and 2050. Similarly, in the transportation sector, for most vehicle classes, EVs are already on par with internal combustion engine (ICE) vehicles in terms of the total cost of ownership (TCO). With a steep reduction in upfront prices expected in the coming years, EVs will have a 34-53% lower TCO than ICE vehicles by 2030. As a result, a shift to electric transportation is estimated to create $2.5 trillion (INR 19 million crores) in consumer savings by 2050 from reduced fuel and maintenance costs. In the industrial sector, the cost-effectiveness of clean energy transition, in particular green hydrogen based steel manufacturing or electrified cement production etc, is still a decade away.

Fossil fuel taxes, duties, and royalties, as well as electricity duties, contribute significantly to state and central government revenues (Figure 8), totaling around $80 billion (INR 600,000 crore) per year, or 12% of total government revenue. Under the CLEAN India scenario, despite an aggressive clean energy transition, the fossil fuel consumption and associated tax revenues will not drop below 2020 levels until 2035, assuming the current tax regime continues. By 2047, total energy tax revenue would drop to about half of the 2020 levels, with electricity duties (mostly collected by the state governments) making up for a part of the lost tax revenue from reduced fossil fuel consumption (Figure 9). Because of India's rapid economic growth and expanding tax base, we believe that there will be several opportunities to offset this modest loss (i.e. 2-3% of the total government tax and non-tax revenue by 2047) in the coming decades. Note that a more nuanced analysis will be needed to assess this issue in more detail. For instance, our analysis aggregates the total tax revenue irrespective of where the tax is collected and how it is shared between the state and the central governments.

Indian Railways (IR) transport most of the coal consumed in the country and there will be a major revenue loss for them due to decreased coal consumption, but this will potentially open up the rail network for industrial freight that currently relies on road transport, making up for the lost coal revenue.

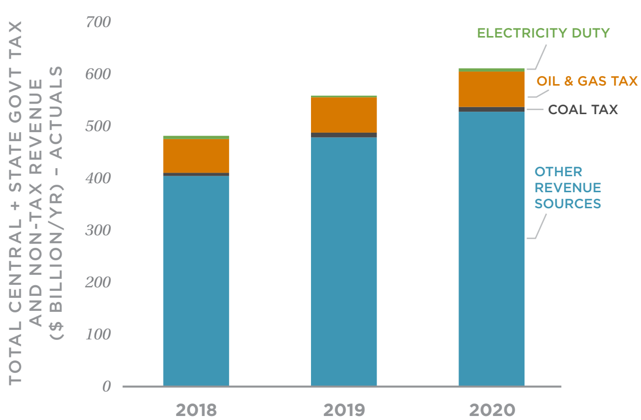


FIGURE 8. *Total Central And State Revenues Associated With Oil, Gas, Coal, And Electricity*

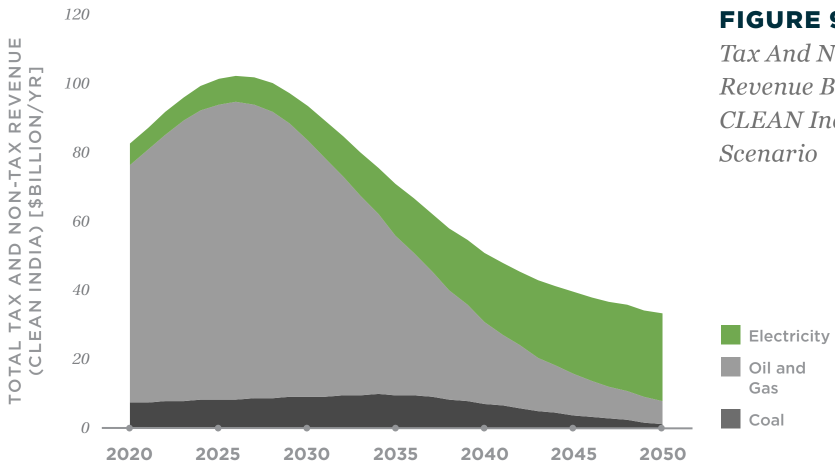


FIGURE 9. *Total Tax And Non-Tax Revenue By Sector, CLEAN India Scenario*

4.4 REQUIRED INVESTMENTS

Because of the transport and industrial electrification and green hydrogen production, the electricity demand increases drastically in the CLEAN-India scenario — from 1300 TWh/yr (bus-bar) to over 6600 TWh/yr by 2050 (Figure 10). This demand is 70% higher than a scenario with no new electrification policies and 50% higher than the Reference case, which also includes significant transport sector electrification Note that this is only utility-supplied electricity. If industrial captive power is included (as seen in the graph), electricity demand jumps to roughly 7200 TWh/year by 2050. The CLEAN-India scenario includes several energy, process, and material efficiency policies resulting in a significant reduction in the overall load. In absence of such policies, the additional electricity demand from the industrial sector could be 40% higher.

In the CLEAN-India scenario, the power sector achieves carbon free electricity generation of 90% by 2047. This entails 1236 GW of solar capacity, 909 GW of onshore wind and 375 GW of offshore wind capacity, and 452 GW / 2500 GWh of energy storage. The pace of required renewable capacity additions is around 40 GW/year through 2030, ramping up to about 100 GW/year between 2030 and 2050.

In the transport sector, over 22.5 million electric 2-W, 7.5 million electric cars and 330,000 heavy duty electric trucks will be sold each year by 2035. By 2047, over 95% of all on-road vehicles will be electric.

In industry, the pathway primarily focuses on electrification and green hydrogen across the iron and steel, cement, and fertilizer, chemical and petrochemical sectors. 255 MT/yr of steel (60%) will be manufactured using green hydrogen and

42 MT/yr (~10%) with electrification by 2050." These numbers are correct in the exec summary. In the cement sector, 480 MT of cement production (65%)will be manufactured using electrification and 184 MT (25%) will be manufactured using green hydrogen based production by 2050. 67 MT (100%) of fertilizer production will be green hydrogen based by 2050, and 82 MT (100%) of chemical and petrochemical production will be green hydrogen based by 2050.

The CLEAN-India pathway will be more capital-intensive and will change the cost structure of the energy sector to one dominated by capital assets/fixed costs. We find that the total investment required for building new clean energy infrastructure between 2020 and 2047 will be $3.5-4 trillion (INR 26-33 million crores), including $2.6 trillion for power generation, $60 billion for charging infrastructure, and over $1-1.5 trillion for the heavy industry. It should be noted that even in the Reference case scenario, India will need to invest over $2 trillion from 2020-2050, including approximately $1.5 trillion in power generation, $20 billion in charging infrastructure for electric vehicles, and $500 billion in heavy industry. The net additional investment required for the CLEAN pathway would be $1.5-2 trillion (INR 11-15 million crores). These estimates are high-level and require further analysis, but they are also consistent with other recent studies (McKinsey, 2022). While the scale of the additional investments is significant, they are manageable given the rapid growth of the Indian economy (annual GDP increasing from approximately $3 trillion in 2020 to $15-20 trillion/year by 2050) and the availability of global capital (PwC, 2017).

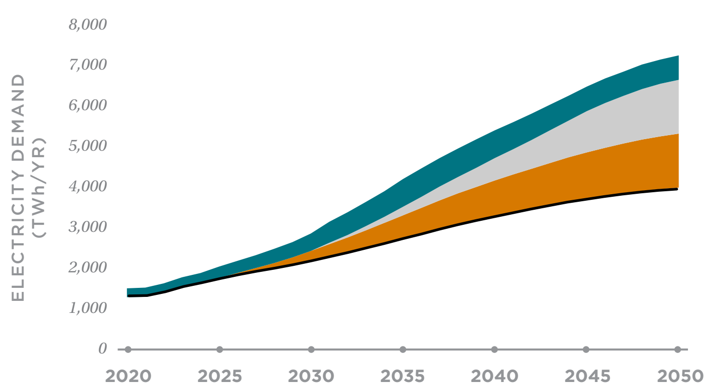


FIGURE 10. *Additional Electricity Demand, Reference vs. CLEAN India Scenarios*

4.5 ENVIRONMENTAL BENEFITS

In the Reference case scenario, energy-related carbon dioxide (CO_2) emissions from the power, transport, and industry sectors will continue to grow until the late 2040s, peaking a little above 4 gigatons/year (nearly double current levels). In the CLEAN India scenario, emissions will peak in the early 2030s, before dropping to under 500 million tons/year by 2047 and near-zero by 2050 (Figure 9). The majority of emission reductions (50%) will be achieved through clean electricity generation, followed by electrified industrial processes and hydrogen-based iron/steel and fertilizer production (23%). Electrified transport, particularly electric heavy-duty vehicles, will result in 21% of emission reductions by 2047. Additionally, due to the significant reduction in fossil fuel consumption, over 4 million premature deaths related to air pollution could be avoided between 2022 and 2047.

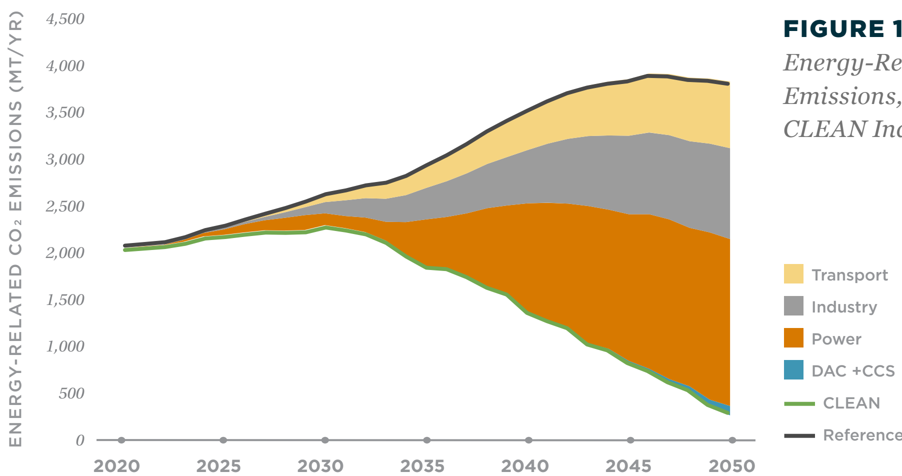


FIGURE 11.
Energy-Related CO_2 Emissions, Reference vs. CLEAN India Scenarios

4.6 POLICY FRAMEWORK

Given the scale and pace of the clean energy transition needed to attain energy independence by 2047, creating the enabling policy and regulatory ecosystem will be critical.. This will be also essential to manage this transition in an equitable and just manner. Due to India's rapid energy demand growth, we find that there is a lead time of 10-15 years to make this transition and it will be important to do so in concert with the most affected communities. The policy ecosystem needs to have five pillars: mandates for commercial / cost-effective clean technologies, long-term infrastructure planning, financial support for emerging technologies, accelerating and scaling domestic manufacturing, and planning for a just transition.

5

SECTORAL PATHWAYS

5.1 POWER

Deep reduction in renewable energy costs, particularly solar and wind and existing policy support in India, have made renewables the most economical choice for new power generation investments in India (Abhyankar et al., 2021). In the past five years, India has added 55 GW of renewable capacity, 18 GW higher than coal based power plants (27 GW) during the same duration. In 2020, investment in renewables surpassed investment in fossil fuels for the fifth consecutive year, albeit there are concerns about the capacity value of RE generation i.e. whether RE can generate electricity during peak load periods (IEA, 2021 and Abhyankar et al., 2021). However, coal still accounts for over 70% of electricity generation in India in 2020 (IEA, 2021). The CLEAN-India scenario examines the potential for low-cost renewables to make up over 90% of the power sector's energy mix by 2050, building on India's commitment to install 500 GW of non-fossil capacity by 2030, nearly equivalent to a 50% clean grid by energy (Figure 12-13).

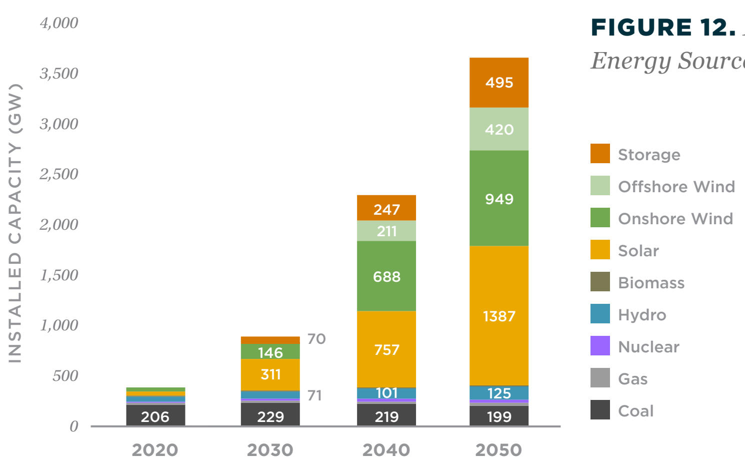


FIGURE 12. *Installed Capacity by Energy Source, CLEAN-India Scenario*

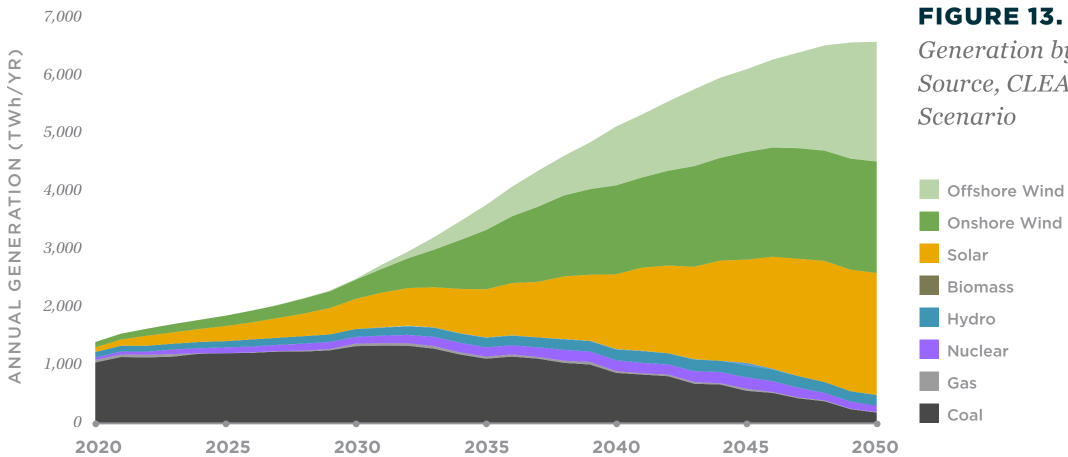
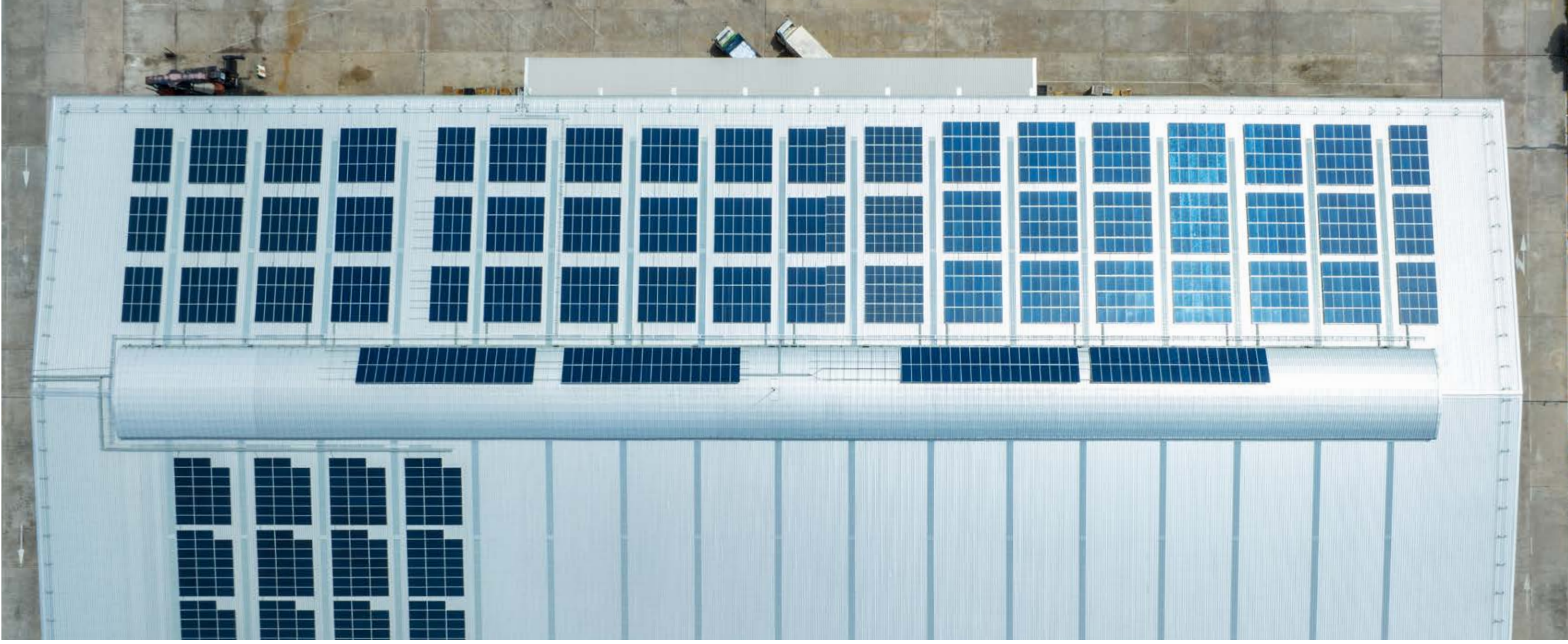


FIGURE 13. *Annual Generation by Energy Source, CLEAN-India Scenario*

In the CLEAN-India scenario, annual electricity demand grows from 1,300 TWh in 2020 to ~4700 TWh by 2040, and ~6600 TWh by 2050, owing to transport and industrial electrification and hydrogen production. This is a 70% increase relative to a No-New-Electrification scenario and over 40% relative to the Reference case by 2050. Our modeling finds the cost-optimal solution for meeting most of this load growth is primarily building new clean power assets combined with energy storage. This is due to the deep cost declines for renewables and storage technologies that make them competitive with thermal power throughout the country – even in regions previously considered resource poor for renewable energy generation.

This implies a significant scaling-up of RE capacity addition. For example, the total installed RE capacity will need to increase to 470 GW by 2030, 1650 GW by 2040 and 2750 GW by 2050 (Table 3). Note that owing India's excellent offshore wind potential (over 400GW at capacity factors greater than 40-50%), we have included 200 GW of offshore wind capacity deployment by 2040, and 420 GW deployment by 2050. Offshore wind turbines have much higher capacity factors (>50%) than land based RE and therefore will be critical in lowering the deployment pressure / bottlenecks on land-based RE. They would also increase the electricity resource diversity, which would lower the RE integration cost and enhance its capacity value. Most of the offshore wind potential in India is concentrated off the coasts of Gujarat, Tamil Nadu, Andhra Pradesh, and Odisha. There is also excellent offshore wind potential (capacity factors upwards of 50-60%) between India and Sri Lanka and a strategic cooperation between the two countries will be critical to develop these resources.

The pace of required renewable capacity additions is around 40 GW/year through 2030, ramping up to over 100 GW/year between 2030 and 2050. This would require new policy and regulatory interventions such as more ambitious state /



national Renewable Purchase Obligations (RPOs), expanding electricity markets, and scaling up domestic clean technology manufacturing. These are discussed in greater detail in section 7 of this report. In addition to solar and wind, the scenario includes expansion in nuclear and hydro capacity based on announced government policies (Table 2).

The CLEAN-India scenario includes coal power capacity under construction, with total coal capacity reaching 229 GW by 2030. This result is like our previous studies as well as CEA's National Electricity Plan 2022 (Abhyankar et al., 2021 and CEA, 2022). However, beyond 2030, we do not find any new coal capacity cost-effective in the CLEAN-India scenario, as alternative technologies are much cheaper, even after including the costs of energy storage (Abhyankar et al., 2021). Because of the rapid electricity demand growth, despite building mostly new clean assets, coal-based power generation keeps increasing, albeit slightly, between 2020 and early-2030s and drops thereafter (Figure 13). This gives the Indian power sector more than a decade to plan a transition away from coal and ensure a just transition for coal-dependent communities. The system would still need to maintain nearly 200 GW of firm thermal capacity by 2050 for system reserves and reliability, although it would be operated at very low-capacity factors.

In the CLEAN-India scenario, energy storage capacity of 70 GW / 340 GWh will be required by 2030, and 495 GW / 3100 GWh by 2050. We also include 145 GW of industrial and agricultural demand response, that would be critical to provide diurnal balancing for a solar-heavy grid. Energy storage (mostly diurnal balancing), demand response (diurnal balancing), and existing coal units (seasonal balancing) work in tandem to maintain the grid reliability and ramping requirements. Dispatchable hydro resources also contribute in providing the ramping support, albeit their availability is highly seasonal.

TABLE 2.

CLEAN-India Scenario Installed Power Generation Capacity by Resource Type

Capacity by Resource Type (GW), CLEAN-India Power Scenario	2020	2030	2040	2050
Coal	206	229	219	199
Gas	25	25	25	25
Nuclear	7	19	29	39
Hydro	51	71	101	125
Biomass	10	10	10	10
Onshore Wind	42	146	688	949
Offshore Wind	0	4	211	420
Solar	45	311	757	1387
Demand Response	5	60	94	145
Energy Storage	0	70	247	495
Total (GW)	391	945	2381	3794

In terms of land use requirements, we estimate that less than 30,000 sq. kms would be needed to install ~1400 GW of solar and ~950 GW of wind capacity (Roy et. al., 2015). This assumes current land efficiency of solar and wind technology and would constitute ~1% of the country's total land area, and 5% of fallow, barren, and waste land. Note that these estimates are based on satellite land use data (Roy et.al., 2015) and would need on-ground validation. The availability of barren and waste land varies from state to state, and their overlap with renewable resources needs to be assessed in greater detail.

Because of the falling costs of RE and storage technologies, we find that the average cost of electricity generation in the CLEAN-India scenario does not increase beyond 2020 levels (Rs 3.6/kWh) until 2030. The average cost starts to fall beyond 2030 and reaches Rs 3/kWh by 2050, owing to the continued reduction in clean technology costs.[4]

The transition to a renewable energy grid in the CLEAN-India scenario will have significant environmental benefits, without increasing wholesale electricity costs. Annual CO_2 emissions from the grid drop by over 90% by 2050, compared to the reference case, to approximately 176 million tons per year. In the reference

4 Average cost of electricity generation includes the fixed costs of all existing and new power plants, battery assets (including battery pack replacement costs), fuel costs of thermal, biomass, and nuclear generators, and any startup/shutdown costs.

scenario, power sector emissions peak by early 2040s, while in the CLEAN-India scenario, they peak a decade earlier, in early-2030s. The transition to a renewable energy grid will also have local environmental and health co-benefits, which will be discussed in Section 6.3.

5.2 TRANSPORT

India's transport sector is the fastest-growing source of CO_2 emissions and a significant portion of national energy expenditure (IEA, 2021). Transport currently accounts for 13.5% of India's energy-related CO_2 emissions, with road transport accounting for 90% of the sector's total final energy consumption, followed by rail and domestic aviation (IEA, 2021). The past two decades have seen a significant increase in energy demand in the transport sector due to a rise in freight activity and an increase in the number of light and heavy freight trucks. Energy use in India's transport sector has increased fivefold over the past 30 years, reaching more than 100 mtoe in 2019 (IEA, 2021).

While other sectors are fueled by diverse energy sources, transport in India relies almost entirely on oil, which meets nearly 90% of demand. India's limited domestic oil resources create significant dependence on crude oil imports. If demand continues to grow rapidly, expenditure on oil imports will also increase. Reliance on oil imports makes India vulnerable to global crude oil price shocks, which reverberate throughout the economy. Moreover, air pollution from the transport sector results in adverse health effects and premature deaths.

The CLEAN-India scenario assesses how the adoption of EVs in India would reduce the oil import expenditure and greenhouse gas emissions and impact the electricity grid. CLEAN-India models 100% of new vehicles being electric by 2035, across all vehicle categories. This scenario also includes the deployment of EV charging infrastructure. In contrast, the Reference scenario assumes that EVs will make up 45% of new 2-wheeler sales by 2035 and 67% by 2050, 24% of new LDV sales by 2035 and 60% by 2050, and 12% of new MDV and HDV sales by 2035 and 35% by 2050.

We find that EV's total cost of ownership (TCO) is already lower than that of internal combustion engine (ICE) vehicles for all vehicle segments. In addition, we project that light-duty EVs will likely reach upfront price parity with ICE counterparts in the late-2020s, while electric trucks will approach upfront price parity with diesel trucks by mid to late 2030s — eliminating the most significant consumer barrier to EV adoption. Figures 14-16 compare the TCO for EVs and ICE vehicles between 2020 and 2050. In 2020, EV and ICE counterparts are nearly on par with each other in terms of overall TCO, albeit EVs have much higher upfront price. However, by 2030, this changes drastically. The per km TCO of an electric 2-wheeler would be 40% lower than the ICE counterpart. TCO of electric cars would be 35% lower than the ICE counterpart, and TCO of heavy-duty electric trucks would be 37% lower than their diesel counterparts. In absolute terms, this translates into overall TCO savings of ~$1450 by 2030 and ~$1700 by 2035 for two-wheelers, nearly $11,500 in 2050 to over $13,000 by 2035 for passenger cars, and over $100,000 in 2030 to over $130,000 in 2035 for heavy duty trucks (Figures 14-16). These TCO savings are due to a combination of declining upfront vehicle prices, declining battery prices, and increasing fuel cost savings. Between 2020 and 2050, the CLEAN-India scenario results in cumulative consumer savings of approximately $2.5 Trillion (INR 19 million crores) compared to the Reference case scenario (Figure 17).[5]

FIGURE 14. *Two-Wheeler TCO: EV vs. ICE Vehicle*

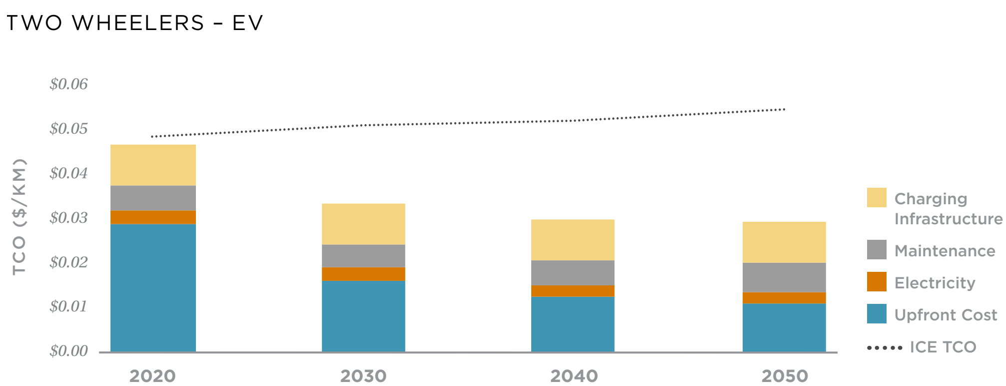
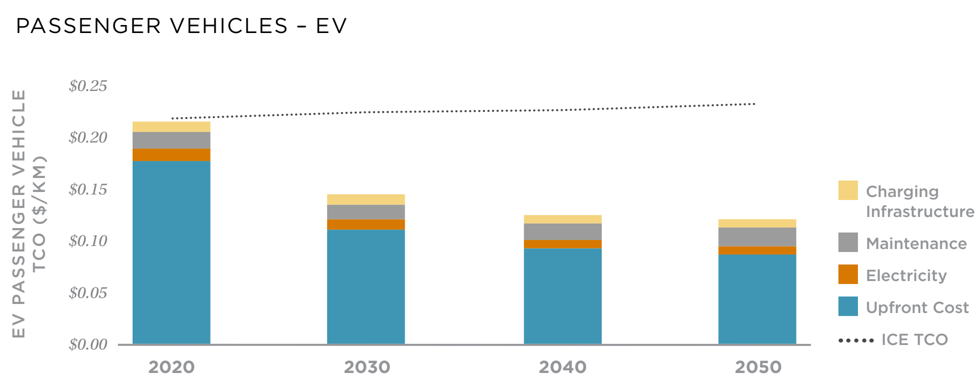
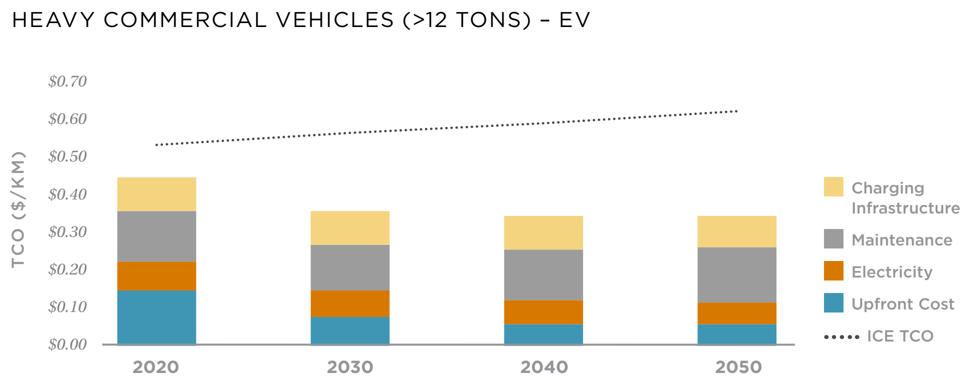


FIGURE 15. *Passenger Vehicle TCO: EV vs. ICE Vehicle*



5 These values have been discounted at a real discount rate of 3% and are presented as the net present value of cumulative savings through 2050.

FIGURE 16. *Heavy-Duty Vehicle (>12 tons) TCO: EV vs. ICE Vehicle*



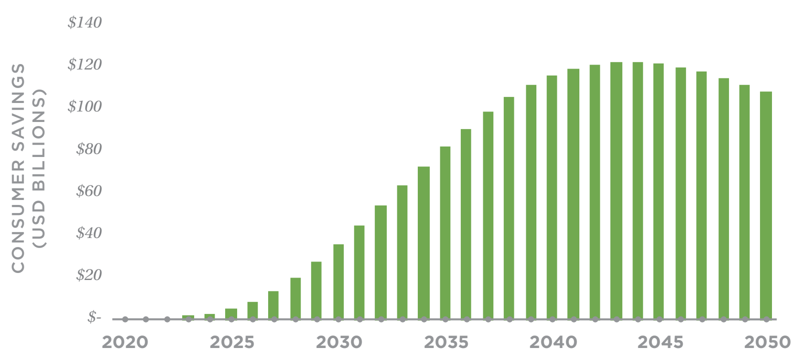


FIGURE 17. *Annual Consumer Saving ($ Billions per year) in the CLEAN-India Scenario*

Note that these TCO estimates assume that electric vehicle manufacturing and supply chains have achieved a minimum scale across all aspects of the value chain globally as well as in India. If such a scale of production is not achieved, electric vehicles, particularly in the HDV segment, will likely be costlier and unprofitable relative to ICE vehicles. Realizing their commercial viability and achieving the potential savings would require sustained public policy support that is detailed in section 7.

Accelerating the adoption of electric vehicles (EVs) in India can have significant benefits for human health and the environment. In the CLEAN-India scenario, EVs can help reduce transportation sector greenhouse emissions by 95% in 2050 compared to the Reference scenario (Figure 18). This is due to the elimination of emissions from gasoline and diesel-powered vehicles, which are a major source of fine particulate matter, nitrogen oxides, sulfur oxides, and greenhouse gasses. In the reference case, CO_2 emissions from the transportation sector will continue to grow until the late 2040s, while in the CLEAN-India scenario, emissions would peak around 2030 and fall to nearly zero by 2050. Most of these avoided emissions will come from the electrification of heavy-duty vehicles. Note that HDVs show an outsized share (about 75%) in emissions reduction because even in the Reference scenario, there are high levels of passenger vehicle electrification (2-wheelers and cars). In contrast, HDV electrification in the CLEAN scenario is significantly more ambitious than the Reference case.

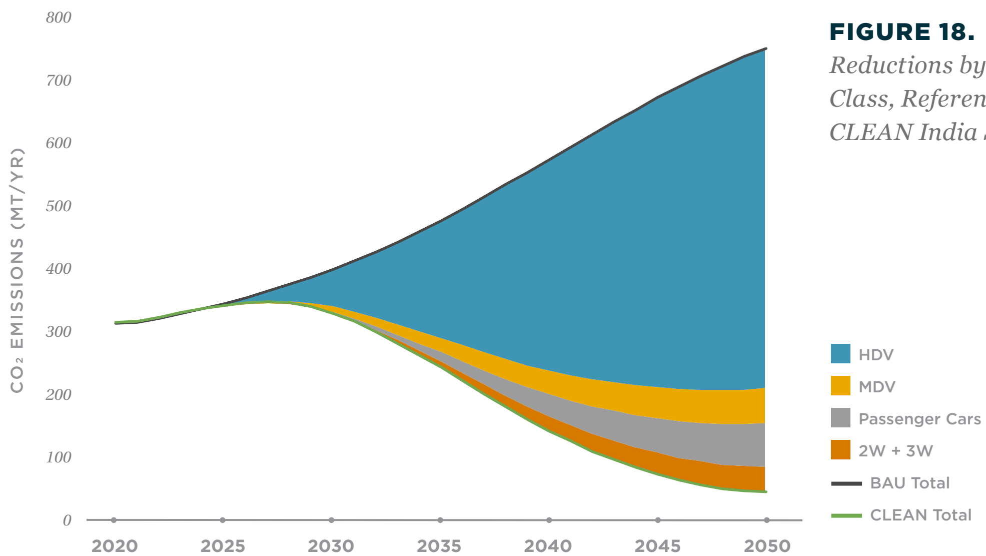


FIGURE 18. *Emissions Reductions by Vehicle Class, Reference vs. CLEAN India Scenarios*

Because India imports nearly 85-90% of its oil consumption, with aggressive penetration of EVs in the CLEAN-India scenario, the Indian economy could accrue massive foreign exchange savings, over $200 billion/year by 2047, from avoided oil imports, as explained in section 4.1. While reduced oil consumption and imports will result in potential loss of tax revenue for the central and state governments, we show in section 4.3 that the tax revenue does not drop below the 2020 levels until the mid-2030s, which offers the government an opportunity to adjust tax regimes as necessary.

Under the CLEAN-India scenario, in order to meet the EV demand, we find that >1000 GWh/yr of battery capacity would be required from 2035 onward. As shown in section 4.1, even if India were to import all the lithium required to manufacture those batteries, the import expenditure would be about 2% of the avoided oil imports.

5.3 INDUSTRY

India's industry sector has been the main driver of energy demand growth since 2000 (IEA, 2021). In the past three decades, industrial energy demand has tripled and now accounts for 36% of final energy consumption, which is higher than its share of GDP (nearly 30%). Due to rapid industrialization and urbanization, this growth is expected to continue, with India accounting for nearly one-third of global industrial energy demand growth by 2040 (IEA, 2021).

India is the second-largest steel producer in the world, accounting for about 6% of global steel production (World Steel Association, 2021). The iron and steel industry is the largest energy consumer among industrial subsectors, accounting for more than 35% of industrial energy consumption (MOSPI, 2021; CEA, 2021). The majority of the energy used in this sector comes from coal, out of which nearly 75% is imported.

India produces 8% of global cement supply (IEA, 2021). Cement is the second-largest energy consumer among industrial subsectors, accounting for more than 20% of energy consumption (MOSPI, 2021; CEA, 2021) and is also primarily powered by coal. The third major industrial sector in India is fertilizers, chemicals, and petrochemicals (F, C&PC), which accounts for about 15% of industrial energy consumption (MOSPI, 2021; CEA, 2021). Most of this energy comes from oil and gas (for feedstock as well as energy) and coal (for heat and captive power).

However, it is now possible to decarbonize heavy industries due to the availability of new technologies and other opportunities. Electrification is more energy efficient for most industrial processes, often has lower maintenance and investment costs, and can reduce India's dependence on fossil fuel imports. Decarbonization of heavy industrial high-heat applications is also technically feasible, although it is not yet commercially available for all applications. Although we find that economic and commercial viability of green hydrogen based heavy industrial decarbonization is about a decade away, there are promising signs, including the announcement and allocation of investment in India's National Green Hydrogen Mission.

The CLEAN-India scenario models an industrial sector that reduces fossil fuel consumption and energy-related emissions, with a focus on the iron and steel, cement, and F, C&PC industries. Measures such as process and material efficiency, electrification, use of green hydrogen, and carbon capture, utilization, and storage (CCUS) can peak industrial energy consumption by 2035 and significantly reduce India's dependence on imported coal and crude oil by 2050.

Total energy consumption is expected to decrease by almost 50% by 2050 due to the use of more energy-efficient technologies, such as electrification and hydrogen, and increased material efficiency, compared to a reference scenario in which coal, natural gas, and oil are heavily relied upon (Figure 19). As a result, energy-related emissions would reduce by ~90% in 2050 (Figure 20). In the CLEAN case, hydrogen demand for industrial activity reaches 5 MT by 2030, increasing to 23 MT by 2040, and reaching 37 MT by 2050. Process-related emissions, particularly in the cement sector, will persist and will require investments in alternative materials, such as green cement and bamboo, as well as the implementation of circular economy industrial processes. (See Appendix C for more information.)

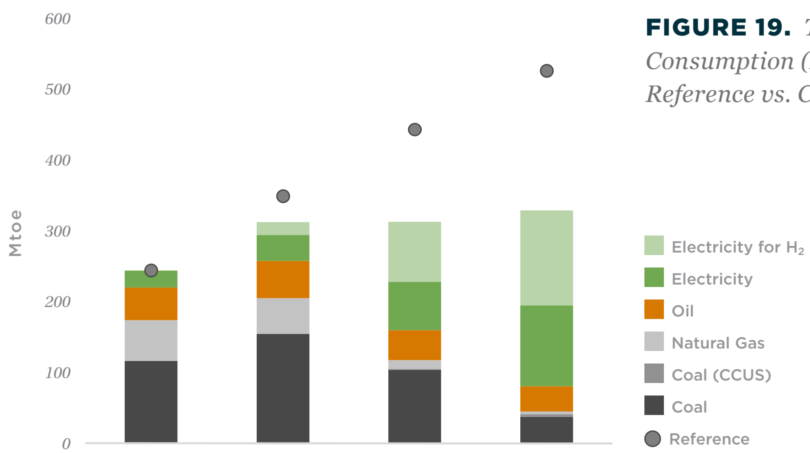


FIGURE 19. *Total Energy Consumption (Including Feedstock), Reference vs. CLEAN India Scenarios*

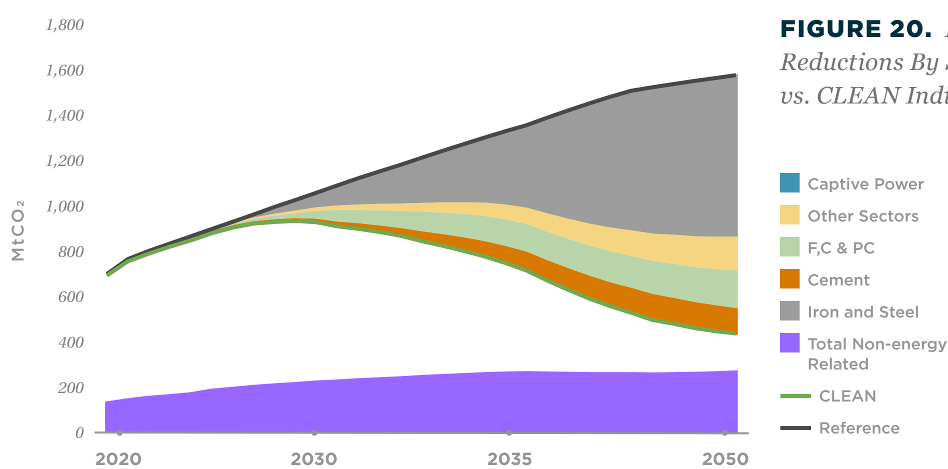


FIGURE 20. *Emissions Reductions By Sector, Reference vs. CLEAN India Scenarios*

5.3.1 Iron and Steel

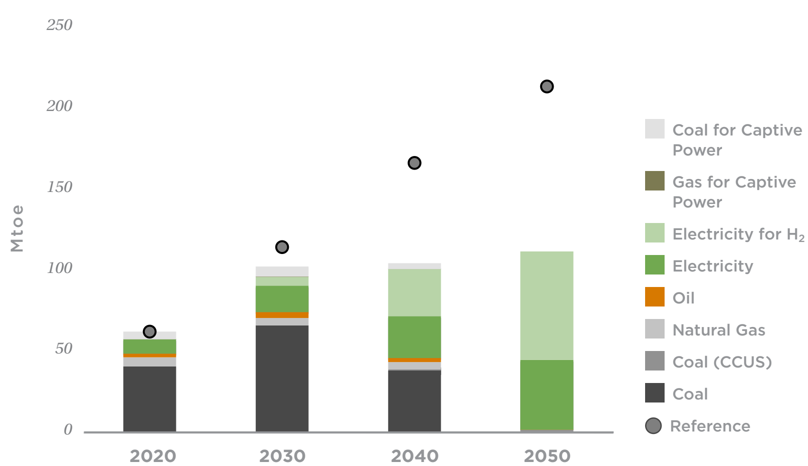
India is the second-largest steel-producing country in the world, with 118.2 million tons (Mt) of steel produced in 2021 — a ~70% increase from the 68.9 Mt produced in 2010 (World Steel Association, 2021). It is expected that India's steel demand will double by 2030 and quadruple by 2050 (IEA, 2020). There are three main methods for producing steel: blast furnaces (BF), basic oxygen furnaces (BOF), and electric furnaces (EF). The BF BOF method involves reducing iron ore in a BF to create molten iron (also known as pig iron), which is then refined to create crude steel in a BOF. Currently, about 45% of steel production in India is done through the BF BOF method, which is highly energy intensive (IEA, 2020). The remaining 55% of steel production is done through EFs, with induction furnaces and electric arc furnaces (EAFs) being the most common types. Induction furnaces reduce iron ore without melting it, using a reducing gas to create direct reduced iron (DRI), or sponge iron, which is then melted in an EAF to produce steel. EAFs also melt and recycle old scrap metal, which constitutes a smaller share (23%) of the sector's total metallic inputs compared to the global average of 32% (IEA, 2020).

In 2019, the steel industry in India consumed around 90 million tons of oil equivalent (Mtoe) for energy, including captive power generation within the sector. Approximately 85% of this energy came from coal. There are several factors that make the steel industry in India more energy-intensive than in other countries, including the heavy reliance on coal in BF BOF and DRI EAF production methods, the low quality of domestic coal and iron ore, the smaller share of scrap input, and the relatively old stock of BF BOFs (which have been in use for about 25 years and have not undergone major refurbishment for about 15 years) (The Energy and Resources Institute, 2020).

The CLEAN-India scenario models the continuous improvement of process efficiency and a transition to a scrap-based EAF production method, assuming that domestic scrap will constitute about 25% of the sector's metallic inputs by 2050. Scrap-based production requires about a tenth of the energy needed for BF BOF production, and projections indicate that more domestic steel-based scrap will be available in the coming decades as infrastructure such as vehicles and buildings reach the end of their life cycles (International Energy Agency, 2020). Although scrap-based EAF production is currently the most expensive method due to high scrap prices in India, it is expected to become cost-competitive and potentially cheaper than traditional production methods as the availability of domestic scrap increases. The scenario finds that primary energy consumption in the clean scenario experiences a nearly 60% reduction (Figure 21).

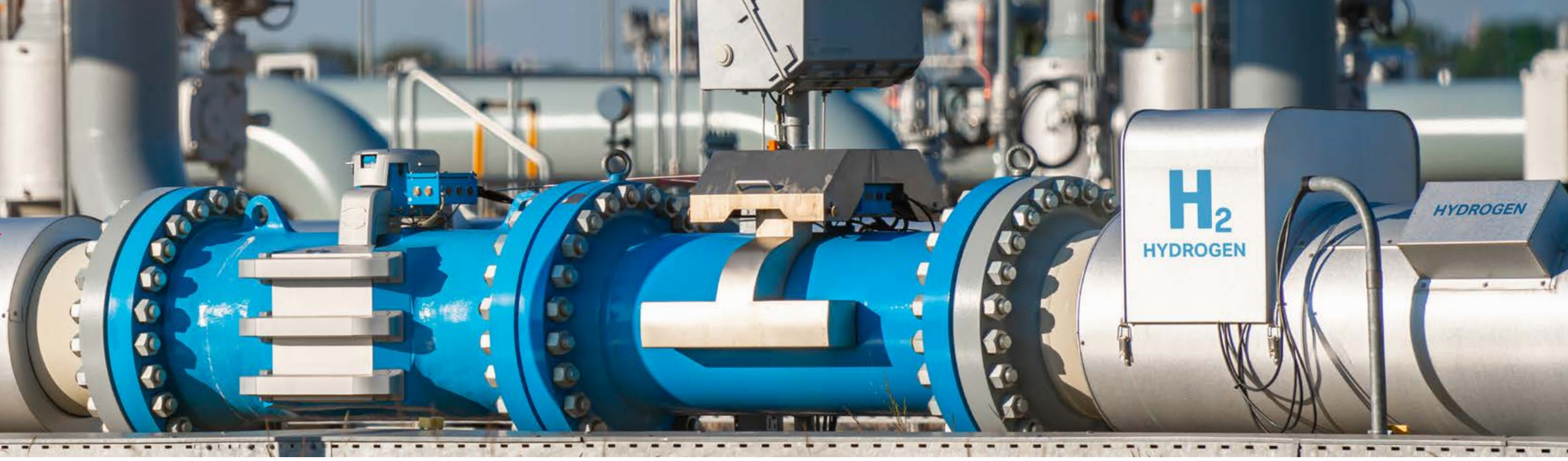
The CLEAN-India scenario also assumes the use of green hydrogen-based DRI EAFs (60% share by 2050) and molten oxide electrolysis (MOE) (10% share by 2050) in steel production. This will require new DRI plants to be built with the potential for retrofitting for hydrogen in the short term and hydrogen-only production in the long term. Electrolysis is an entirely electrified process that allows for the direct production of steel from iron ore feedstock. In contrast to hydrogen, steel electrolysis is a new process that shares almost no infrastructure with existing production technologies, requiring the construction of new dedicated plants. Although the cost of this technology is currently prohibited for commercial adoption, the scenario assumes that costs will drop after 2040 due to technological improvements and the establishment of more demonstration plants. A pilot plant in India is currently using carbon capture, utilization, and storage CCUS with smelting reduction (SR), an alternative process that facilitates the use of iron ore directly and avoids the use of a coke oven or coking coal. We assume that this plant will still be functioning with a small capacity by 2050 (~5% share).

FIGURE 21. *Iron And Steel Sector Primary Energy Consumption (Mtoe), Reference vs. CLEAN India Scenarios*



5.3.2 Cement

India produced approximately 329 million tons (Mt) of cement in 2020 – a ~60% increase from the 207 Mt produced in 2010 – and is expected to become the world's third-largest construction market in 2022 (India Brand Equity Foundation, 2021). Market growth, along with the Indian government's policies to invest in new commercial and housing infrastructure and highway construction, will increase demand for cement (IBEF, 2021). Cement is made by chemically combining calcium, silicon, aluminum, iron, limestone, and other ingredients and heating them at high temperatures to form a rock-like substance called clinker, which is then ground into

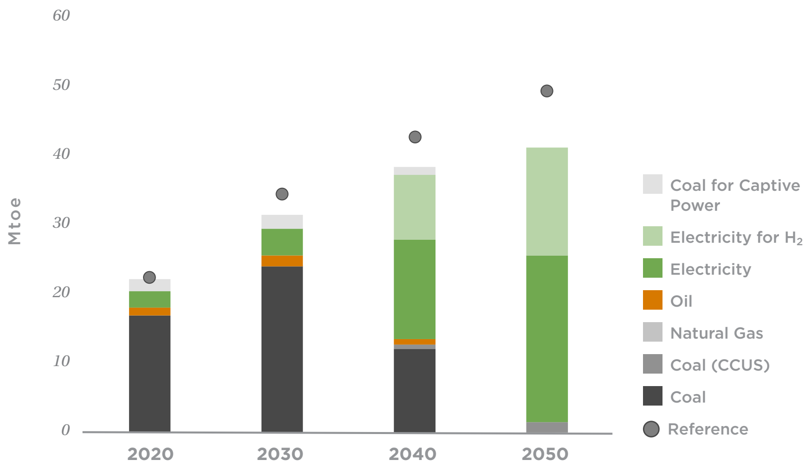


a fine powder to create the final cement product used to make concrete. Cement production in India is primarily powered by bituminous coal, and the sector's emissions come from both its chemical processes and energy consumption. Indirect emissions from burning coal to heat cement kilns account for about 45% of sector emissions (IEA, 2021). Changes already underway in India's cement industry, such as the increased use of alternative fuels for kiln heating, blended cement production, improved energy efficiency, and reducing the clinker-to-cement ratio, align with the CLEAN-India scenario. In addition, Indian cement companies topped the Carbon Disclosure Project's assessments of industrial decarbonization, and the industry has continued to reduce its direct emissions by participating in India's Perform, Achieve, Trade (PAT) scheme for energy efficiency (Ministry of Power, 2022).

The CLEAN-India scenario models many of the processes mentioned above. There are opportunities for improving clinker ratios, energy efficiency, electrification of rotary kilns, and the use of green hydrogen to reduce the energy and emissions intensity of the cement sector. It should be noted that some of these technologies have not been commercialized at scale but we project that they will be by 2050.

The production of clinker is the most energy- and emissions-intensive part of cement production. The scenario models a reduction in the clinker-to-cement ratio of 5% per decade (2020s, 2030s, 2040s) using clinker substitutes such as blast furnace slag and fly ash from coal in the short- to medium-term, and natural pozzolan in the long term. Other materials that could be used as clinker substitutes include volcanic ash, ground limestone, and broken glass. The scenario also assumes that green hydrogen will play a role in cement production (over 25% of production by 2050). Green hydrogen can provide the high heat needed for cement kilns, while about 65% of production can be electrified using electric kiln replacements.10% of production is replaced with more efficient materials. The rest of production in the scenario is either fueled by coal with carbon capture, utilization, and storage (CCUS) or captive heat. The energy demand in the cement sector in the CLEAN-India case is much lower than in the reference case (Figure 22). Note that recent advances in microwave heating-based cement production have shown significant promise in lab tests, including an improvement in the cementitious properties.

FIGURE 22. *Cement Sector Primary Energy Consumption (Mtoe), Reference vs. CLEAN India Scenarios*

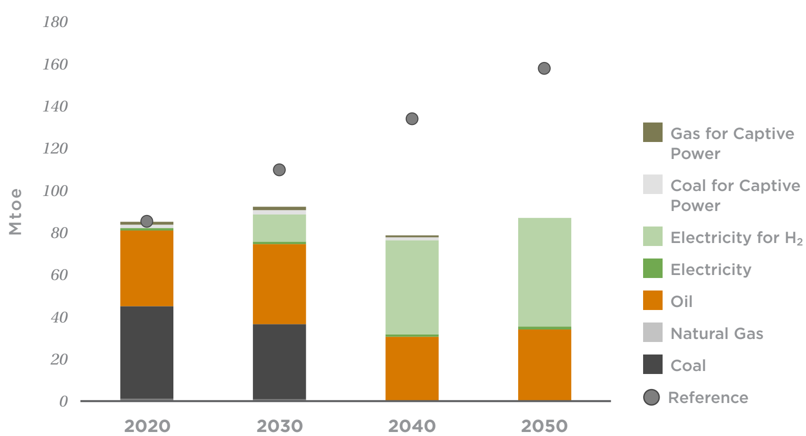


Fertilizers, Chemicals, and Petrochemicals (F, C,&PC)

India's chemical and petrochemical industry is one of the largest in the world and serves as a production hub for over 80,000 commercial products, including olefins and aromatics, which are essential in the production of pharmaceuticals, textiles, construction materials, packaging, automotive parts, and other petrochemical products (PwC India, 2021). The industry is expected to grow by approximately 5-10% by 2030 (PwC India, 2021). India is also the fourth-largest producer of agrochemicals in the world, particularly ammonia for fertilizers (IBEF, 2021). Ammonia production requires a large amount of energy, as well as oil or natural gas for feedstock. Currently, India imports crude oil to refine into products such as naphtha.

The CLEAN-India scenario provides a pathway for reducing energy consumption and emissions in the F, C&PC sector through process electrification, green hydrogen-based production for high heat applications, waste heat recapture for fertilizers and chemicals, and plastics recycling in petrochemicals. However, while electric steam crackers and green hydrogen can potentially decarbonize current chemical F,C&PC production, they are still in the very early stages of research (BNEF, 2021). However, green hydrogen based production is very promising given India's commitment to hydrogen based industrial production by 2050 as outlined in the country's National Hydrogen Mission. The scenario assumes that green hydrogen based production will become the dominant production method, available for small-capacity pilot plants after 2030 and at commercial scale after 2040. By 2050, 1000% of F,C&PC production will come from green hydrogen based production, in line with the National Hydrogen Mission (Figure 23). Additionally, the scenario also assumes that petrochemical demand is reduced by 50% in 2050 due to an elimination of plastic products, material replacement of petrochemical based products with alternative materials, and advances in renewably powered plastic recycling processes. This is based on promising signs from India including bans on single used plastic, as well as active research in bio-based materials to plastic including natural materials and bioplastics, as well as technological investment in many countries to invest in plastic recycling processes.

FIGURE 23. *F, C&PC Sector Primary Energy Consumption (Mtoe) Including Feedstock, Reference vs. CLEAN India Scenarios*



6

TRANSITION

The CLEAN pathway will provide opportunities for India to increase employment, develop expertise in new industries, and become more resilient to fossil fuel-driven macroeconomic shocks. This section outlines the just transition, industrial competitiveness, and environmental benefits.

6.1 JUST TRANSITION

New industries create opportunities for job growth across all sectors, but it is also important to consider the potential job losses associated with a transition away from fossil fuels. Currently, the Indian coal industry employs approximately 3.6 million people directly and indirectly, with two-thirds of these jobs located in Jharkhand, Chhattisgarh, West Bengal, and Odisha (Pai and Zerriffi, 2021). However, due to mechanization and automation, direct coal mining jobs have been declining over the past 15 years (Dash, 2019). Additionally, transitions in the transport sector will affect jobs in the auto sector, which employs 37 million people directly and indirectly, as well as small and medium enterprise (SME) jobs in auto repair, maintenance, and spare parts.

In the CLEAN India scenario, although total coal consumption is reduced by 95% by 2047, domestic coal production increases until the mid-2020s, and does not start to decline below 2020 levels before 2035. This is due to the country's rapid energy demand growth and coal import substitution, particularly in the power sector. Therefore, this offers a lead time of 10-15 years to transition affected communities, with at least 10 years before India ramps down coal production.

Starting in the mid- to late-2030s, coal consumption in the power sector begins to decline, primarily impacting coal mining employment. If India successfully increases its renewable energy, energy storage, and electric vehicle manufacturing capacity, those jobs could potentially offset coal-related job losses. Assessments in other major economies have shown net job gains because of a rapid clean energy transition. For example, in the United States, if 100% of new vehicle sales are electric by 2035 with a 90% clean electricity grid, there would be a net gain of 2 million jobs by 2035 (Phadke et. al, 2021). Similarly, in China, a transition to an 80% clean grid by 2035 translates to a net gain of 1.9 million job-years by 2035 (Abhyankar et. al, 2022).

However, careful policy planning must occur over the next decade to ensure that new jobs are equivalent in terms of region, skillset, and compensation to the jobs that may be lost. Measures would include allocating investment to coal-dependent states for the development of renewable industries and economic diversification strategies. Many coal-dependent states are strategically located between industrial hubs and have natural resources that provide opportunities to develop solar parks, green hydrogen based industrial manufacturing hubs, ecosystem services, eco-tourism, transport and logistic centers, and sustainable agriculture.

These strategies require investment in retraining schemes, educational advancement opportunities, social safety nets and guaranteed compensation for retiring workers, as well as the promotion of social dialogue between governments, utilities, and affected communities. Multi-stakeholder partnerships are the backbone of a successful just transition and will help bring about more informed, locally driven outcomes.

6.2 INDUSTRIAL COMPETITIVENESS

Major global automakers, including Ford, Nissan, and General Motors, have announced plans to transition towards electric vehicles, all of whom have manufacturing operations in India. The Indian auto industry contributes 7% to overall GDP, which is expected to increase to 12% (Confederation of Indian Industry, 2022). Additionally, India's automotive industry is the fourth-largest passenger vehicle producer in the world, with 25% of production exported globally (SIAM, 2022). Its largest export markets include the United Kingdom, Italy, Germany, and the Netherlands (International Organization of Motor Vehicle Manufacturers, 2020), all of which have made commitments to phase out internal combustion engine (ICE) vehicles by the 2030s, either through sales mandates or outright ICE car bans. Given both corporate and government moves towards EVs, India's investments in battery storage and EV manufacturing will be critical to keep its auto industry competitive in global markets. India is also one of the largest steel exporters in the world, with its second- and third-largest markets in EU countries that have made carbon neutrality commitments by 2050. A significant portion of EU emissions reductions will come from industrial standards in iron and steel and cement, including a potential border adjustment emissions tariff. Like the auto industry, the iron and steel and cement sectors in India will need to adopt clean technology to remain globally competitive. However, due to the significant reduction in solar power purchase agreement prices and the excellent solar resource quality, this provides an opportunity for India to become a leader in green manufacturing.

6.3 ENVIRONMENTAL IMPACTS

Fossil fuel use in the energy sector is one of the primary contributors to outdoor air pollution in India. 22 of the world's 30 most heavily polluted cities are in India (IQAir, 2021). Sources of ambient air pollution include thermal power plants, road transport, biomass and waste burning, construction dust, and industrial emissions.

Under the CLEAN-India scenario, premature deaths from coal power plant and road transport emissions in 2050 could be reduced by 90% and 95%, respectively, relative to the Reference case. This assumes that coal plants meet existing emission norms starting in 2030, while vehicle emission standards become more stringent every year (assuming a 20% improvement by 2040 and stable thereafter). The CLEAN-India pathway would avoid ~350,000 premature deaths from energy-related air pollution by 2047. This would equate to avoiding 4.3 million premature deaths between 2021-2050 (Figure 24). These are high level estimates, and as such, the potential premature deaths avoided is undercounted. A more nuanced, in-depth analysis would be needed to quantify reduced mortality and morbidity (not assessed here) impacts from the clean energy transition.

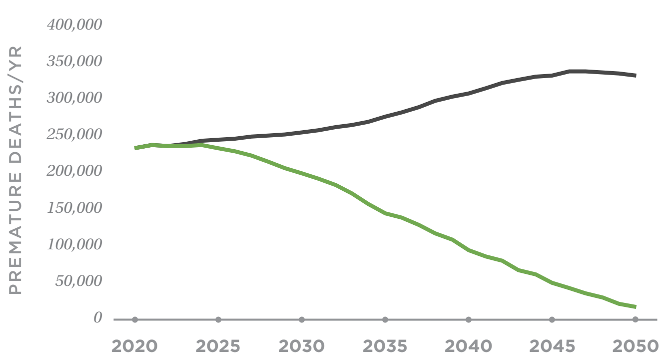


FIGURE 24.
Yearly Premature Deaths Due to Energy-Related Outdoor Air Pollution, Reference vs. CLEAN India Scenarios

7

POLICY FRAMEWORK FOR CLEAN-INDIA

To achieve the CLEAN-India pathway, a robust and innovative policy framework will be necessary to ensure that most new investments are clean and drive an economy-wide transition. These policies could include ambitious sector-specific clean targets, such as Renewable Purchase Obligations (RPO) or zero-emission vehicle (ZEV) sales targets, research, development, and deployment (R&D&D) funding for emerging clean technologies such as offshore wind and green hydrogen and prioritizing domestic manufacturing of clean technologies to ensure global competitiveness. India has already made progress on several of these policy priorities, and this section will outline how the existing policy framework can be scaled up to meet the ambition and pace needed to achieve energy independence by 2047. Enhancing policy ambition could also have global implications given India's leadership in the International Solar Alliance and the recent G20 Presidency.

The policy ecosystem needs to have five pillars: mandates for commercial / cost-effective clean technologies, long-term infrastructure planning, financial support for emerging technologies, mandates for commercial / cost-effective technologies, accelerating and scaling domestic manufacturing, and planning for a just transition as summarized in the following table:

FIGURE 25. *Policy ecosystem roadmap for Atma Nirbhar*

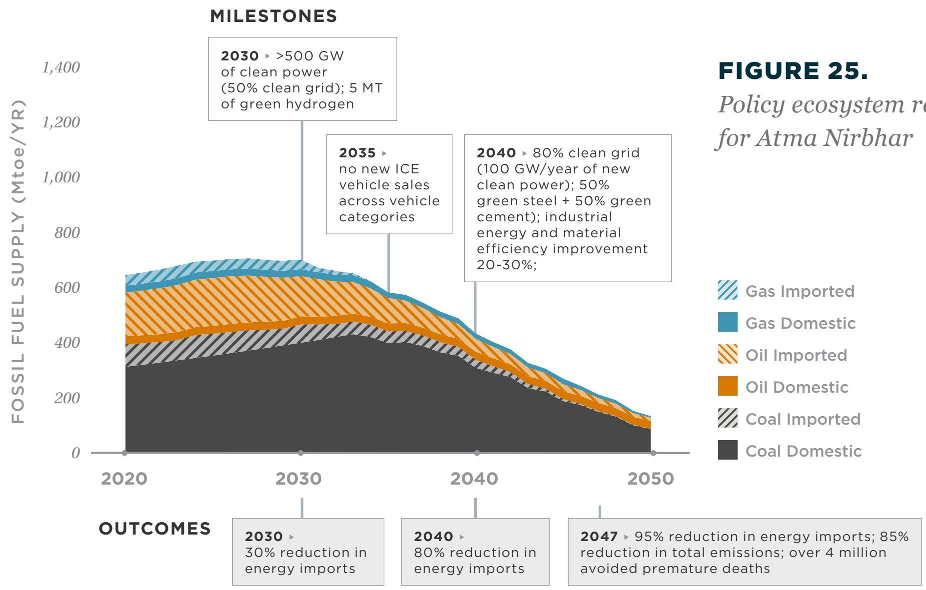


TABLE 3. *Policy Ecosystem Needed for Achieving Energy Independence*

SECTOR	MANDATES	INCENTIVES	DOMESTIC MANUFACTURING	INFRASTRUCTURE PLANNING	UPFRONT CONSIDERATION OF A JUST TRANSITION
Power	Renewable Purchase Obligation / Storage Purchase Obligation	Long duration storage, offshore wind	Production Linked Incentive + Strategic Alliances for manufacturing solar panels, batteries, electrolyzers etc	Cross-sectoral least-cost investment planning	Safety Nets Worker Retraining Social Dialogue Economic Diversification
Transport	Zero Emissions Vehicle Sales Mandate	Public EV Procurement (e.g. buses)		Public Fast Charging + Low-Cost Solar Charging	
Industry	Clean Mandate on new Industrial Facilities and Hydrogen Production, energy and material efficiency standards (e.g. expand PAT)	Green hydrogen pilots, RD&D		Hydrogen Infrastructure and Low-Cost Solar PPAs	

7.1 POWER

India has set national targets of installing at least 500 GW of non-fossil power generation capacity, 44% Renewable Purchase Obligation (50% non-fossil electricity generation including nuclear), and deploying energy storage equivalent to 4% of electricity demand by 2030. While these are promising and ambitious goals, a robust policy and regulatory framework to integrate renewables and energy storage into the national and state level power system planning and operations will be critical in ensuring their success. Beyond 2030, the focus must be on scaling RE and storage deployment as well as commercializing new technologies such as offshore wind and long-duration storage. This will require investments in R,D&D and policies that will develop domestic manufacturing capabilities in solar cells, panels, offshore wind turbines, and battery storage.

1. **Expanding Renewable Purchase Obligation (RPO) and energy storage mandates.** While India's 2030 power sector targets are ambitious, for ensuring economy-side energy independence and a clean grid, India would need to massively scale-up RE and storage deployment beyond 2030. Globally and in India, RPOs have shown to be a central catalyzing policy for RE deployment. We recommend that the non-fossil electricity generation target should be 80% by 2040 and over 90% by 2047 and grid-scale energy storage deployment targets should be over 200 GW by 2040 and over 400 GW by 2047. We have shown these targets to be technically feasible and economically viable. Some technology specific targets for emerging technologies such as offshore wind should be considered for accelerating their deployment. More expansive RPO / storage mandates could be coupled with direct or indirect fiscal incentives and bulk procurement.

2. **Updating state market and regulatory frameworks to facilitate least-cost resource procurement, inter-state power exchange, and power system flexibility.** Expanding Renewable Purchase Obligation (RPO) and energy storage mandates requires state regulatory processes to be reformed in order to account for the contribution of renewables to resource adequacy (RA) and to facilitate least-cost, technology-neutral, all-source procurement within the context of integrated resource planning (IRP). A portfolio approach, which recognizes the interaction between different resources including demand response and flexible resources, is necessary, as well as the removal of barriers to inter-state power exchanges. The regulatory framework should also capture all values of energy storage assets, including capacity, energy, system flexibility, and avoided transmission and distribution investments. The Ministry of Power's guidelines on resource adequacy planning framework and procurement and utilization of battery energy storage systems are steps in the right direction.

3. **Cross-sectoral investment planning is critical.** Transport and industrial electrification and green hydrogen production, which are necessary for achieving energy independence, are expected to increase native electricity demand growth by over 50-60% by the 2047-2050 timeframe. This presents several opportunities for cross-sectoral investment and operational planning. For example, large industries can procure renewable electricity as captive power through open access, allowing them to sign power purchase agreements (PPAs) at lower prices. Electric transport or industrial energy use can also serve as an excellent demand response opportunity, reducing grid balancing costs. For instance, electric vehicle charging or hydrogen production can be scheduled during times of high renewable energy (RE) generation, reducing the need for long-duration energy storage and lowering electricity costs. The location of charging or hydrogen infrastructure will depend on the relative techno-economic factors of charging or hydrogen demand, hydrogen storage and pipeline costs, and energy storage costs. Industrial hydrogen facilities can also provide peaking power through fuel cells or hydrogen turbines to the grid during “super-peak” events, which occur for less than 1% of the year (about 80-90 hours per year).

4. **Scaling up domestic manufacturing of clean technologies along with investment in R&D for new technology innovation.** The transition to clean energy presents an opportunity for Indian industry to develop as a key manufacturing hub and create jobs for the future in order to maintain global competitiveness and ensure energy security. The Government of India (GoI) has already implemented a production-linked incentive (PLI) scheme to incentivize domestic manufacturing of solar cells, panels, and advanced chemistry cell (ACC) batteries. Expanding PLI incentives to include R&D and making strategic investments to secure key supply chains (such as strategic lithium or rare earth reserves with partner countries) would be critical for scaling India’s clean manufacturing industry.

7.2 TRANSPORT

Rapid and cost-effective transport electrification will require large-scale production and operation of electric vehicles of all classes, as well as accumulated experience across the value chain. This will require sustained public support over a long period until the electric vehicle industry in India reaches commercial maturity and viability. India has provided foundational policy guidance through the National Electric Mobility Mission Plan (NEMMP), the National Electric Bus Program (NEBP), and the Faster Adoption and Manufacturing of (Hybrid) and Electric Vehicles (FAME) schemes, which have spurred rapid innovation and investment in the industry. Many Indian states also have their own electric vehicle policies, including sales targets, point-of-sale subsidies, incentives and capital subsidies for research and development, and the development of state charging infrastructure, as well as efforts to procure electric buses from state government transport agencies. In the future, it is recommended that existing policy frameworks be scaled up to support ambitious deployment targets, backed by strong fiscal and non-fiscal supportive policies.

1. **Setting Zero Emission Vehicle (ZEV) sales targets.** ZEV sales targets mandate that a certain percentage of new vehicle sales be ZEVs, and are proven successful as they provide demand certainty, thereby enabling new production lines, innovation in consumer financing and business models for charging infrastructure. Just like RPOs, we recommend ambitious ZEV targets for each vehicle class so most of the new vehicles sold in India are electric by ~2035. These targets are in line with those in several major economies around the world including the EU and certain key US states.

2. **Providing tax credits for domestic manufacturing, consumer incentives, and other policy support.** As a complement to ZEV sales targets, tax credits for domestic EV manufacturing and point-of-sale consumer incentives would have the dual effect of incentivizing the development of a domestic clean automotive industry and further accelerating consumer uptake.

3. **Developing public fast-charging infrastructure and low-cost solar charging, prioritizing HDVs.** Public fast-charging infrastructure with 1C/2C (60 min/30 min) charging capability will be critical for scaling electric vehicle (EV) adoption in India, particularly due to the limited access to private charging. This is particularly important for electric heavy-duty vehicles (HDVs) that have larger batteries and higher charging power requirements (100 kW to 1 MW). Fast-charging networks along major trade routes and highways will be crucial for electrifying freight and long-distance passenger transport. As mentioned earlier, linking the EV charging tariff, especially for HDVs, to a low-cost solar power purchase agreement (PPA) that is fixed for 25 years could transform the economics of freight movement, which is heavily dependent on diesel prices.

4. **Coordinating between power and transport sectors at state and local levels.** Transmission and distribution utilities will be the key stakeholders in creating the public charging ecosystem. Easier siting and interconnection procedures for charging stations, network enhancements to accommodate load increases in dense areas, streamlined regulatory and interconnection procedures to minimize transaction costs of charging stations, and revised building codes to include charging stations would enable EV adoption.

5. **Exploring strategic reserves of lithium and other minerals.** As mentioned in the previous section, GoI should consider collaborating with other leading economies to invest in strategic lithium and other critical mineral reserves needed for domestic batteries manufacturing.

7.3 INDUSTRY

In contrast to the power and transport sectors, many of the technologies needed to achieve energy independence in the industrial sector have not yet achieved commercial deployment at scale. India is pursuing several innovative industrial policies, including the National Hydrogen Mission, large-scale procurement of green steel and cement, and participation as a founding member of the United Nations' Industrial Deep Decarbonization Initiative. Additional policies that build on these existing steps are listed below.

1. **Establishing a clean mandate on new industrial stock and hydrogen production.** It is important to ensure that most new industrial infrastructure is clean, using technologies such as electrification, green hydrogen, or emerging technologies like electrolytic metal reduction. For example, the iron/steel sector may be subject to a Renewable Purchase Obligation (RPO) equivalent new investment mandate. The Government of India (GoI) announced the National Hydrogen Energy Mission (NHM) with the goal of making India a global hub for hydrogen technologies, supporting manufacturing through incentives, facilitating demand creation, and mandating hydrogen use in specific industries. Expanding the NHM with more explicit sector-specific targets and/or hydrogen incentives, similar to those offered by the Inflation Reduction Act in the United States, could accelerate the production trajectory of green hydrogen.

2. **Industrial Solar PPAs through Open Access.** The economic viability of industrial electrification and/or green hydrogen production will depend significantly on electricity cost. At current industrial electricity tariffs (exceeding INR 7-8/kWh), industrial decarbonization becomes economically unviable. However, large industries can procure renewable electricity as captive power through open access, allowing them to sign power purchase agreements (PPAs) at much lower prices (less than INR 2/kWh by 2030). Industries can also draw electricity from the grid during non-solar hours, or by oversizing the electrolyzer capacity and building diurnal hydrogen storage to obtain a 24x7 flat block hydrogen supply.

3. **Raising ambition on energy and material efficiency.** Expanding the Perform Achieve and Trade (PAT) program in terms of size, scope, and sectors could create energy savings and facilitate the transition to more energy-efficient processes. For example, electrification of many low to medium industrial heat applications is already cost-effective and could be targeted under the PAT program. Incentivizing the use of domestic steel scrap would also be critical for reducing the material and energy intensity of steel production in a cost-effective manner. Scrap-based steel production requires about a tenth of the energy of other methods, but due to low availability, India has expensive scrap compared to global averages. More domestic steel-based scrap is expected to be available in the coming decades as infrastructure, such as vehicles and buildings, reach the end of their lifespan.

4. **Investing in RD&D for industrial technologies.** The CLEAN-India pathway involves implementing many industrial technologies that have not yet achieved scale, so investments in R&D and pilot projects in the short-term (up to 2030) will be critical for demonstrating their commercial viability in the medium to long-term. In addition, new technologies such as electrolytic metal reduction for iron/steel production need further exploration.

8

KEY CAVEATS AND FUTURE WORK

This analysis has several limitations. The CLEAN-India pathway is not a projection; rather, it is intended to illustrate the potential energy independence, economic, and environmental benefits of accelerating the clean energy transition in India. Although this paper describes the system characteristics needed to accommodate high levels of renewable generation, transport / industrial electrification, and green hydrogen production, it does not address the institutional, market, and regulatory changes needed to facilitate such a transformation. Specifically, it does not evaluate the political, societal, or consumer-adoption issues surrounding the CLEAN-India Pathway targets. The previous section offers policy recommendations that address some barriers to such a transition, but these factors should be explored further in future analyses to inform decision making.

In addition, we do not evaluate the broader portfolio of all clean technologies in the power, transportation, and industrial sectors, but rather restrict only to assessing commercially available technologies. For example, we have focused only on electric vehicles as the energy independence strategy in the transport sector. Other technologies, such as hydrogen, can support transportation decarbonization efforts across heavier vehicle classes in the future. We also exclude consideration of other mobility measures—such as public transit, modal shifts to rail for freight transport, and smart urban planning to reduce vehicle miles traveled—but these measures are critical adjuncts to electrification for holistically reducing oil use in the transportation sector. Similarly, in the industrial sector, we focused primarily on electrification and green hydrogen. Newer technologies like electrolytic metal reduction have shown significant promise, which we have not considered. In the power sector, we do not assess non-lithium battery chemistries such as Iron-air, zinc-air, sodium-sulfur etc. that may be better suited for long duration storage, mainly because these technologies are not commercially available yet.

Finally, we assess the operational feasibility of the Indian power system using national level aggregated hourly dispatch, which does not assess the interstate / intrastate transmission requirement and challenges. Although this analysis does not attempt a full power-system reliability assessment, our hourly modeling in PLEXOS ensures that demand is met in all periods, including during extreme weather events and periods of low renewable energy generation, albeit at the national aggregate level. Significant further work is needed to advance our understanding of other facets of a 90% clean power system with increasing vehicle, building, and industrial electrification.

9 | APPENDIX A | POWER SECTOR ASSUMPTIONS

Sector	Key Parameter	2020	2030	2040	2050
Power	Capital Cost $/kw by technology- Solar	624	446	373	373
Power	Capital Cost $/kw by technology- Wind (Onshore)	950	927	881	881
Power	Capital Cost $/kw by technology- Wind (Offshore)	1948	1392	1134	1134
Power	Capital Cost $/kw by technology- Coal	1150	1150	1150	1150
Power	Capital Cost $/kw by technology- Gas	900	900	900	900
Power	Capital Cost $/kw by technology- Hydro	1500	1500	1500	1500
Power	Capital Cost $/kw by technology- Nuclear	2000	20000	2000	2000
	Capital Cost $/kw by technology- Battery Storage (4-hr)	900	520	400	400
Power	Capital Cost $/kw by technology- Coal variable cost (pithead power plants) (Rs/kWh)	1.9	2.0	2.1	2.1
Power	Capital Cost $/kw by technology- Coal variable cost (non-pithead plants) (Rs/kWh)	2.5	2.7	2.9	2.9
Power	Capital Cost $/kw by technology- Coal variable cost (imported coal) (Rs/kWh)	2.8	3.0	3.2	3.2
Power	Capital Cost $/kw by technology- Gas variable cost (domestic gas) (Rs/kWh)	3.0	3.0	3.2	3.2
Power	Capital Cost $/kw by technology- Gas variable cost (imported LNG) (Rs/kWh)	4.0	4.5	5.0	5.0

10 | **APPENDIX B** | TRANSPORT ASSUMPTIONS

SECTOR	KEY PARAMETER	2020	2030	2040	2050
Transport	Crude Oil price ($/bbl)	$70	$75	$85	$90
Transport	Gasoline Price ($/lit)	1.3	1.6	1.8	1.8
Transport	Diesel Price ($/lit)	1.2	1.4	1.6	1.7
Transport	ICE 2-W upfront vehicle price (USD/vehicle)	$700	$700	$700	$700
Transport	ICE 3-W upfront vehicle price (USD/vehicle)	$1,500	$1,500	$1,500	$1,500
Transport	ICE Passenger Cars upfront vehicle price (USD/vehicle)	$8,800	$8,800	$8,800	$8,800
Transport	ICE Light Commercial Vehicles (<3.5 T) upfront vehicle price (USD/vehicle)	$15,000	$15,000	$15,000	$15,000
Transport	ICE Heavy Commercial vehicles (3.5T-7.5T) upfront vehicle price (USD/vehicle)	$17,430	$17,430	$17,430	$17,430
Transport	ICE Heavy Commercial vehicles (7.5T-12T) upfront vehicle price (USD/vehicle)	$19,000	$19,000	$19,000	$19,000
Transport	ICE Heavy Commercial vehicles / Rigid Trucks (>12T) upfront vehicle price (USD/vehicle)	$40,000	$40,000	$40,000	$40,000
Transport	ICE Heavy Commercial vehicles / Tractor Trailers (>12T) upfront vehicle price (USD/vehicle)	$50,537	$50,537	$50,537	$50,537
Transport	ICE Bus upfront vehicle price (USD/vehicle)	$69,180	$69,180	$69,180	$69,180
Transport	EV2-W upfront vehicle price (USD/vehicle)	$1,500	$853	$651	$588
Transport	EV 3-W upfront vehicle price (USD/vehicle)	$3,214	$1,869	$1,495	$1,390

SECTOR	KEY PARAMETER	2020	2030	2040	2050
Transport	EV Passenger Cars upfront vehicle price (USD/vehicle)	$16,029	$9,988	$8,305	$7,837
Transport	EV Light Commercial Vehicles (<3.5 T) upfront vehicle price (USD/vehicle)	$32,143	$18,151	$14,254	$13,169
Transport	EV Heavy Commercial vehicles (3.5T-7.5T) upfront vehicle price (USD/vehicle)	$30,000	$19,296	$16,315	$15,485
Transport	EV Heavy Commercial vehicles (7.5T-12T) upfront vehicle price (USD/vehicle)	$51,000	$26,130	$19,204	$17,275
Transport	EV Heavy Commercial vehicles / Rigid Trucks (>12T) upfront vehicle price (USD/vehicle)	$101,000	$52,660	$39,197	$35,447
Transport	EV Heavy Commercial vehicles / Tractor Trailers (>12T) upfront vehicle price (USD/vehicle)	$158,750	$73,382	$49,607	$42,985
Transport	EV Bus upfront vehicle price (USD/vehicle)	$135,000	$82,519	$67,903	$63,833
Transport	ICE 2-W maintenance price (USD/km)	$0.0065	$0.0078	$0.0092	$0.0105
Transport	ICE 3-W maintenance price (USD/km)	$0.0130	$0.0146	$0.0161	$0.0177
Transport	ICE Passenger Cars maintenance price (USD/km)	$0.0130	$0.0146	$0.0161	$0.0177
Transport	ICE Light Commercial Vehicles (<3.5 T) maintenance price (USD/km)	$0.0776	$0.0869	$0.0962	$0.1055
Transport	ICE Heavy Commercial vehicles (3.5T-7.5T) maintenance price (USD/km)	$0.1422	$0.1592	$0.1763	$0.1934
Transport	ICE Heavy Commercial vehicles (7.5T-12T) maintenance price (USD/km)	$0.1580	$0.1769	$0.1959	$0.2149

SECTOR	KEY PARAMETER	2020	2030	2040	2050
Transport	ICE Heavy Commercial vehicles / Rigid Trucks (>12T) maintenance price (USD/km)	$0.1950	$0.2184	$0.2419	$0.2653
Transport	ICE Heavy Commercial vehicles / Tractor Trailers (>12T) maintenance price (USD/km)	$0.1755	$0.1966	$0.2177	$0.2388
Transport	ICE Bus maintenance price (USD/km)	$0.2969	$0.3578	$0.4186	$0.4795
Transport	EV 2-W maintenance price (USD/km)	$0.0033	$0.0039	$0.0046	$0.0052
Transport	EV 3-W maintenance price (USD/km)	$0.0065	$0.0073	$0.0081	$0.0088
Transport	EV Passenger Cars maintenance price (USD/km)	$0.0065	$0.0073	$0.0081	$0.0088
Transport	EV Light Commercial Vehicles (<3.5 T) maintenance price (USD/km)	$0.0388	$0.0434	$0.0481	$0.0528
Transport	EV Heavy Commercial vehicles (3.5T-7.5T) maintenance price (USD/km)	$0.0711	$0.0796	$0.0882	$0.0967
Transport	EV Heavy Commercial vehicles (7.5T-12T) maintenance price (USD/km)	$0.0790	$0.0885	$0.0980	$0.1074
Transport	EV Heavy Commercial vehicles / Rigid Trucks (>12T) maintenance price (USD/km)	$0.0975	$0.1092	$0.1209	$0.1326
Transport	EV Heavy Commercial vehicles / Tractor Trailers (>12T) maintenance price (USD/km)	$0.0878	$0.0983	$0.1088	$0.1194
Transport	EV Bus maintenance price (USD/km)	$0.0986	$0.1104	$0.1222	$0.1341
Transport	EV charging infra costs ($/KW) (LDV)	200	200	200	200
Transport	EV charging infra costs ($/KW) (MDV/HDV)	316	316	316	316

SECTOR	KEY PARAMETER	2020	2030	2040	2050
Transport	Electric vehicle charging cost ($/kWh) - across vehicle classes	$0.0775	$0.0775	$0.0775	$0.0775
Transport	Battery pack replacement cost ($/kwh) - across vehicle classes	N/A	$62	$50	$50
Transport	2-W km/year	7,000	7,000	7,000	7,000
Transport	3-W km/year	30,000	30,000	30,000	30,000
Transport	Passenger Cars km/year	12,000	12,000	12,000	12,000
Transport	Light Commercial Vehicles (<3.5 T) km/year	15,000	15,000	15,000	15,000
Transport	Heavy Commercial vehicles (3.5T-7.5T) km/year	35,000	35,000	35,000	35,000
Transport	Heavy Commercial vehicles (7.5T-12T) km/year	65,000	65,000	65,000	65,000
Transport	Heavy Commercial vehicles / Rigid Trucks (>12T) km/year	90,000	90,000	90,000	90,000
Transport	Heavy Commercial vehicles / Tractor Trailers (>12T) km/year	120,000	120,000	120,000	120,000
Transport	Bus km/year	65,000	65,000	65,000	65,000

11 | **APPENDIX C** | INDUSTRY ASSUMPTIONS

11.1 IRON AND STEEL

Notes on abbreviations:

- EAF: Electric Arc Furnaces
- DRI: Direct Reduced Induction
- H_2: Hydrogen
- CCUS: Carbon Capture Utilization and Storage
- SR: Smelting Reduction
- BOF: Basic Oxygen Furnace
- BF: Blast Furnaces

	BASE YEAR (2020)	REFERENCE	CLEAN-INDIA
Efficiency	Average process ‘Energy Intensity’ = ~26GJ/tonne steel	Improvement: 10% between 2020-2050	Improvement: 25% between 2020-2050
	‘Scrap ratio’ in Recycling (i.e., Scrap based EAF) = 0.45	0.45 by 2030 (same as 2020 level), 0.50 by 2040-2050	0.45 by 2030 (same as 2020 level), 0.60 by 2040, 0.90 by 2050
Electrified production (% of total)	Mixed Scrap based EAF = ~28%	Mixed Scrap based EAF = ~28%	Mixed Scrap based EAF = ~28% by 2030 (same as 2020 level) ~25% by 2050
	‘Electrolysis’ = 0%	‘Electrolysis’ = 15% by 2050	‘Electrolysis’ = 35% by 2050
Green hydrogen-based production (% of total)	‘DRI EAF (H_2 based)’ = 0%	‘DRI EAF (H_2 based)’ = 0% by 2030, ~1% by 2040, ~5% by 2050	‘DRI EAF (H_2 based)’ = 10% by 2030, 40% by 2040, 60% by 2050
CCUS application (% of total)	‘SR BOF with CCUS’ = 0%; ‘BF BOF retrofitted with CCUS’ = 0%; ‘DRI EAF retrofitted with CCUS’ = 0%	‘SR BOF with CCUS’ = 0% by 2030, ~1% by 2040, ~2.5% by 2050; ‘BF BOF retrofitted with CCUS’ = 0%; ‘DRI EAF retrofitted with CCUS’ = 0%	‘SR BOF with CCUS’ = 0% by 2030, ~1% by 2040, ~2.5% by 2050; ‘BF BOF retrofitted with CCUS’ = 0% by 2030, ~2% by 2040, ~2% by 2050; ‘DRI EAF retrofitted with CCUS’ = 0% by 2030, ~1% by 2040, ~1% by 2050

	BASE YEAR (2020)	REFERENCE	CLEAN-INDIA
Rest of the production (% of total)	'BF BOF' = 42%; DRI EAF (coal+gas based) = 30%	'BF BOF' = ~47% by 2030, ~46% by 2040, ~42% by 2050; DRI EAF (coal+gas based) = ~27% by 2030, ~25% by 2040, ~20% by 2050	'BF BOF' = ~39% by 2030, ~19% by 2040, ~0% by 2050; DRI EAF (coal+gas based) = ~23% by 2030, ~12% by 2040, 0% by 2050

11.2 CEMENT

	BASE YEAR (2020)	REFERENCE	CLEAN-INDIA
Efficiency	Average process 'Thermal Energy Intensity' = ~3.15GJ/ tonne clinker; 'Electricity Intensity' = ~80kWh/tonne cement	Thermal energy improvement: 1.5% by 2030, 3% by 2040, 6% by 2050; Electricity improvement: 1% by 2030, 2% by 2040, 3% by 2050	Thermal energy improvement: 4% by 2030, 8% by 2040, 15% by 2050; Electricity improvement: 3% by 2030, 5% by 2040, 8% by 2050
	'Clinker to cement ratio' = 0.73	0.71 by 2030, 0.68 by 2040, 0.66 by 2050	0.69 by 2030, 0.64 by 2040, 0.60 by 2050
Electrified production (% of total)	'Electric rotary kiln' = 0%	'Electric rotary kiln' = 0% by 2030, 15% by 2050	'Electric rotary kiln' = 65% by 2050
Green hydrogen-based production (% of total)	'H_2 rotary kiln' = 0%	'H_2 rotary kiln' = 0% by 2030, ~2% by 2040, 5% by 2050	'H_2 rotary kiln' = 1% by 2030, 15% by 2040, 25% by 2050
CCUS application (% of total)	'Conventional rotary kiln with CCUS' = 0%	'Conventional rotary kiln with CCUS' = 0% by 2030, ~0.5% by 2040, ~2.5% by 2050	'Conventional rotary kiln with CCUS' = 0% by 2030, ~2.5% by 2040, ~5% by 2050
Captive heat-based production (% of total)	'Captive heat-based rotary kiln' = 0%	'Captive heat-based rotary kiln' = 0% by 2030, ~0% by 2040, ~1% by 2050	'Captive heat-based rotary kiln' = 0% by 2030, ~0.5% by 2040, ~2.5% by 2050
Rest of the production (% of total)	'Conventional rotary kiln' = 100%	'Conventional rotary kiln' = ~100% by 2030, ~97% by 2040, ~75% by 2050	'Conventional rotary kiln' = ~99% by 2030, ~45% by 2040, ~0% by 2050

11.3 CHEMICALS, PETROCHEMICALS, AND FERTILIZERS

	BASE YEAR (2020)	REFERENCE	CLEAN-INDIA
Efficiency	Average process 'Energy Intensity' = 18.5GJ/tonne fertilizer; 15.8GJ/tonne chemical and petrochemical output	No Improvement	Improvement: 2% by 2030, 4% by 2040; 15% by 2050
Green hydrogen-based production (% of total)	'H_2-fired heaters' = 0%	'H_2-fired heaters' = 'C&F': 0% by 2030, ~1% by 2040, ~2.5% by 2050 // 'PC': 0% by 2030, ~2.5% by 2040, ~5% by 2050	'H_2-fired heaters' = 'C&F': 0.5% by 2030, ~8% by 2040, ~15% by 2050 // 'PC': 0% by 2030, ~4% by 2040, ~10% by 2050
Demand Reduction in Petrochemicals (e.g. due to material substitution, recycling, elimination etc.)	Demand Reduction = 0%	No Demand Reduction	Demand Reduction' = 3% by 2030, ~25% by 2040, ~50% by 2050
Rest of the production (% of total)	'Conventional crackers' = 100%	'Conventional crackers' = 'PC, C, , &F': 99% by 2030, 85% by 2040, 75% by 2050	'Conventional crackers' = 'PC, C':': ~70% by 2030, 0% by 2040 // 'F': 60% by 2030, 0% by 2040

12 | **APPENDIX D** | CROSS SECTORAL ASSUMPTIONS

SECTOR	KEY PARAMETER	2020	2030	2040	2050
Cross-sectoral	Imported Coal Price ($/ton)	96	70	70	70
Cross-sectoral	Interest Rate (%)	8%	8%	8%	8%
Cross-sectoral	Real Discount rate (%)	3%	3%	3%	3%
Cross-sectoral	Rupees/Dollar	75	75	75	75
Environmental Benefits	Premature deaths per kWh of coal based power generation (without PCT)	78.4	78.4	78.4	78.4
Environmental Benefits	Premature deaths per kWh of coal based power generation (with PCT)	56.15	56.15	56.15	56.15

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