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Harnessing India's Renewable Edge for Cost-Effective Energy Independence by 2047

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Abstract

India's heavy dependence on imported oil (90%) and industrial coking coal (80%) exposes the country to the volatility in global energy markets, impacting foreign exchange reserves & economy-wide inflation. This study assesses a pathway for India to meet its growing energy needs & 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 CO2 emissions. We find that India can achieve energy independence through aggressive deployment of clean technology – renewables, electric vehicles, and green hydrogen - reducing the fossil energy imports by 90% (or $240 billion). Clean energy deployment will inflation-proof India's energy expenditure, create $2.5 trillion in net consumer savings, and avoid over 4 million air pollution related premature deaths by 2047. India's electricity demand could increase nearly fivefold to over 6,500 TWh/yr by 2047, while CO2 emissions from power, transport, and industrial sectors will peak in the early 2030s before dropping to ~800 million tons/year. Clean energy deployment will be more capital-intensive, needing a net additional investment of $1.5 trillion. Managing the clean energy transition would require significant policy support, including deployment mandates for cost-effective clean technologies, financial support for emerging technologies, long-term infrastructure planning, accelerating domestic manufacturing, and planning for a just transition.

1 Introduction

India is the world's fifth-largest economy, and one of the largest energy consumers (Myers, 2020). 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).

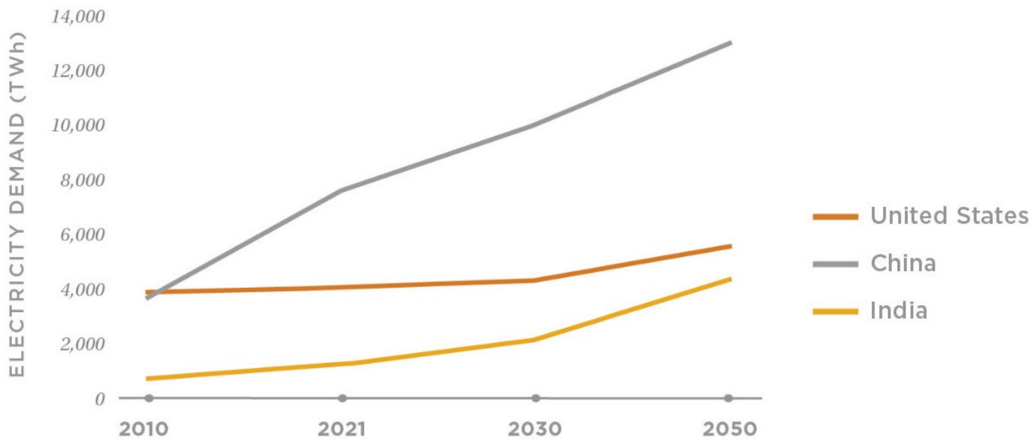

Figure 1: Total Projected Electricity Demand, India US, China (IEA, 2022)

Fossil fuel imports account for a significant share of India's overall energy consumption (e.g. 88% of oil consumption and 80% of industrial coking coal for iron and steel production), making India one of the largest net-importers in the world, and costing over $100 billion (INR 750,000 crores) per year, 3% of annual GDP (The Economic Times, 2022). This dependence is expected to increase due to the expected energy demand growth in the transportation and industrial sectors. 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. In light of this, 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), contributing over one million premature deaths per year (Pandey et. al., 2021). This is coupled with increasing greenhouse gas (GHG) emissions with India as the third largest emitter of CO2 after China and the United States. To address this, India made a commitment to achieve net-zero GHG emissions by 2070 at the Glasgow COP in 2021.

These commitments and the expected growth have 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. 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. 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) with India leading the way in the sales of electric two and three wheelers. The use of green hydrogen is gaining traction as a cost-competitive alternative in various industries, including fertilizer and steel manufacturing. This development holds significant importance for India, given its heavy reliance on imported feedstock such as natural gas and naphtha, as well as fuel like coking coal, in these sectors.

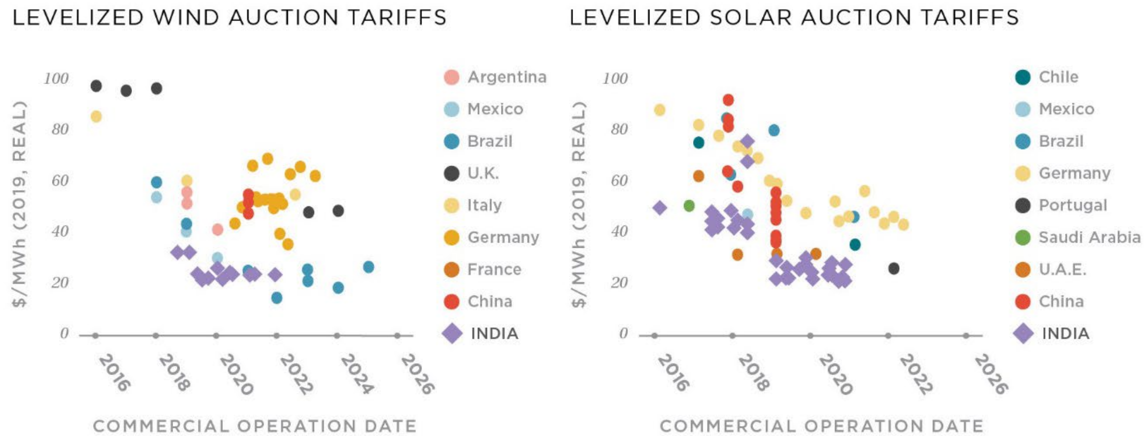

Figure 2: Solar and Wind Energy Prices in India and other Countries
Data Source: (BNEF, 2021)

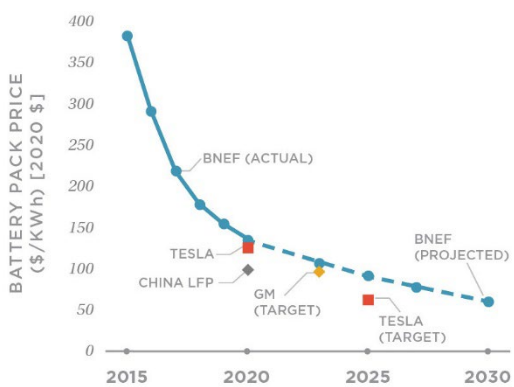

Figure 3: Global Average Battery Pack Price over Time
Data Source:(BNEF, 2021)

Given the significant reductions in clean technology costs, the objective of this paper is to assess a pathway for India to achieve energy independence by 2047. We focus primarily on the three sectors that are most energy intensive - power, transport, and industry - which together account for more than 80% of the country's energy consumption and energy-related CO2 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.

India’s long term energy and emissions trajectory has been evaluated in recent literature in reasonable depth. The International Energy Agency's India Energy Outlook 2021 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 that map a trajectory from today’s current policies, an acceleration of ambition, and a delayed COVID recovery (IEA, 2021). McKinsey (2022) propose 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 opportunities: green hydrogen, carbon capture, usage, and storage (CCUS), natural climate solutions, and material circularity. TERI (2021) relies heavily on biofuels, hydrogen, nuclear, and CCUS, with less consideration of electrification and batteries. 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. These pathways map trajectories for renewable electricity, biofuels, and electrified industrial production. Swamy et al. (2021) explore two climate policy scenarios for India through 2050, including the Long-Term Decarbonization (LTD) scenario, which outlines policies with high emissions reduction potential.

2 Methods

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

2.1 Power

We use PLEXOS, 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. 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. We project the native (i.e., without any new transport or industrial electrification or green hydrogen production) electricity demand using Central Electricity Authority's (CEA) 19th and 20th Electric Power Surveys (EPS) and historical load growths (CEA, 2017 and 2022). 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 renewable energy generation profiles and hydro dispatch constraints are assessed using historical weather and generation data (for the load-synchronized 2018 weather year). For projecting clean technology costs, we assume that they will reduce at 50% of the historical reduction rates until 2030. Between 2030 and 2040, we assume that clean technology cost reductions will 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.

2.2 Transport

The starting point for our analysis is calculating the Total Cost of Ownership (ECO) for EVs and Internal Combustion Engine (ICE) vehicles on a per-kilometer basis over the useful life of the vehicles. We calculate TCO for nine vehicle classes based on the number of wheels for light passenger vehicle and gross vehicle weight for commercial vehicles. The TCO calculation includes the vehicle's upfront purchase price along with average maintenance and fuel costs. The EV TCO also includes the cost of public charging infrastructure and the cost of battery replacements if the vehicle's useful life is longer than that of the batteries; we assume a battery life of 10 years (approximately 3,000 full charge-discharge cycles). To model the dynamics of the nationwide vehicle fleet once EV sales targets are introduced, we use a custom vehicle stock turnover model – Faster Adoption of Clean Transportation (FACT). The FACT model estimates ICE vehicles and EVs retired per year using a survival function modeled separately by vehicle class. We estimate the total number of vehicles sold per year using historical sales data from the Ministry of Road Transport and Highways (MORTH, 2021). Annual vehicle sales are allocated between ICE vehicles and EVs based on the EV sales target for that year. Combining the vehicle-level TCO and the vehicle populations from the stock model, we arrive at total fleet-level costs per year.

2.3 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. 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 CO2 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.

We evaluate the following two scenarios in each sector:

1. **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 (>400 GW 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.

2. **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.

Additional details on methods and data are provided in the supplementary information.

3 Key Findings

3.1 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 per year). In contrast, the CLEAN-India scenario would reduce crude oil imports by over 90% to $15 billion per year (INR 112,500 crores per year) by 2047. Overall fossil fuel imports reduce from $275 billion (INR 2.1 million crores per year) to $15 billion per year (INR 112,500 crores per year) by 2047, with oil imports decreasing to 27 mtoe per year and industrial coking coal imports decreasing to below 5 mtoe per year (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).[1] 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.

[1] It should be noted that the reserves mentioned are inferred reserves, and the economically recoverable reserves have not been determined yet. However, noteworthy Lithium discoveries have been made in recent times in regions like Rajasthan and Karnataka in India. Nevertheless, the precise estimation of reserves and the determination of economically recoverable portions remain uncertain.

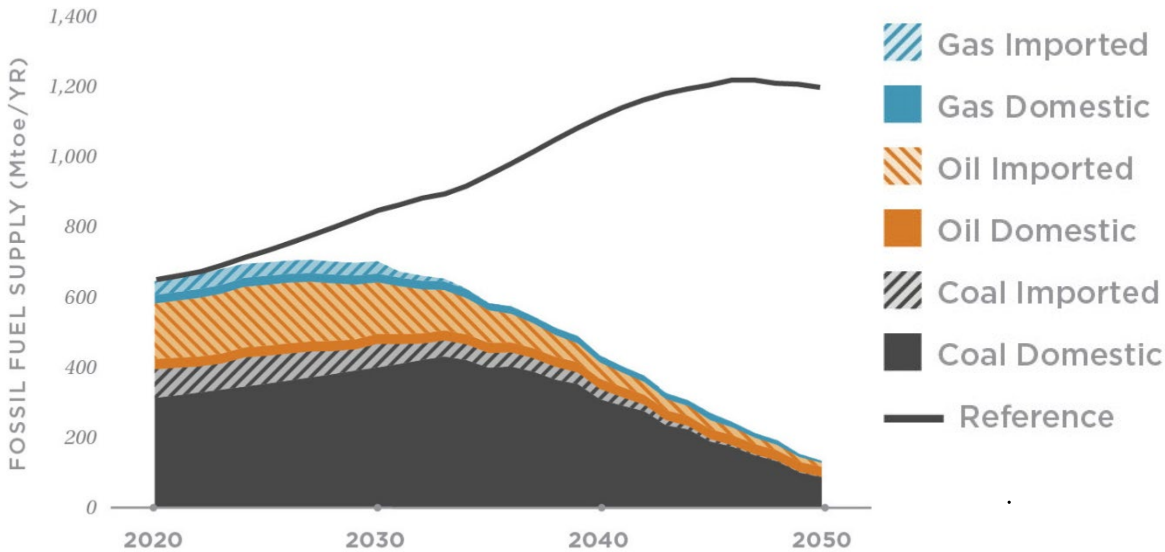

Figure 4: Fossil Fuel Imports, Reference Vs. CLEAN-India Scenario

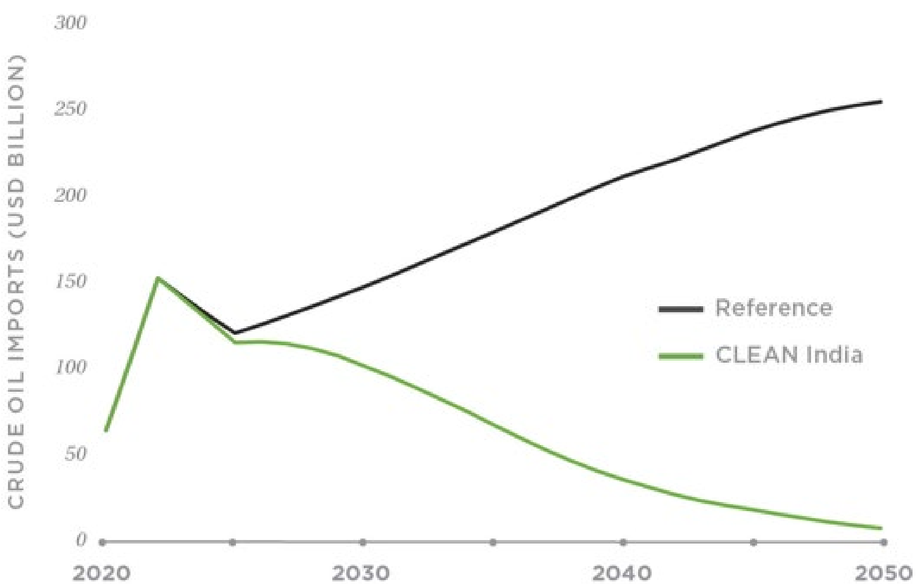

Figure 5: Crude Oil Import Costs, Reference vs CLEAN-India Scenario

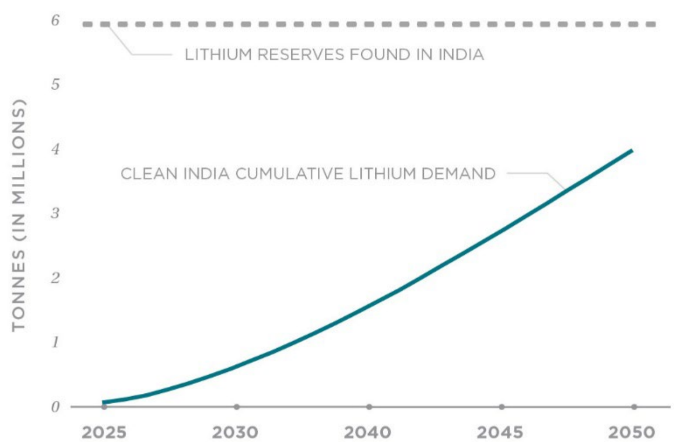

Figure 6: CLEAN-India Cumulative Lithium Demand vs Estimated Lithium Reserves

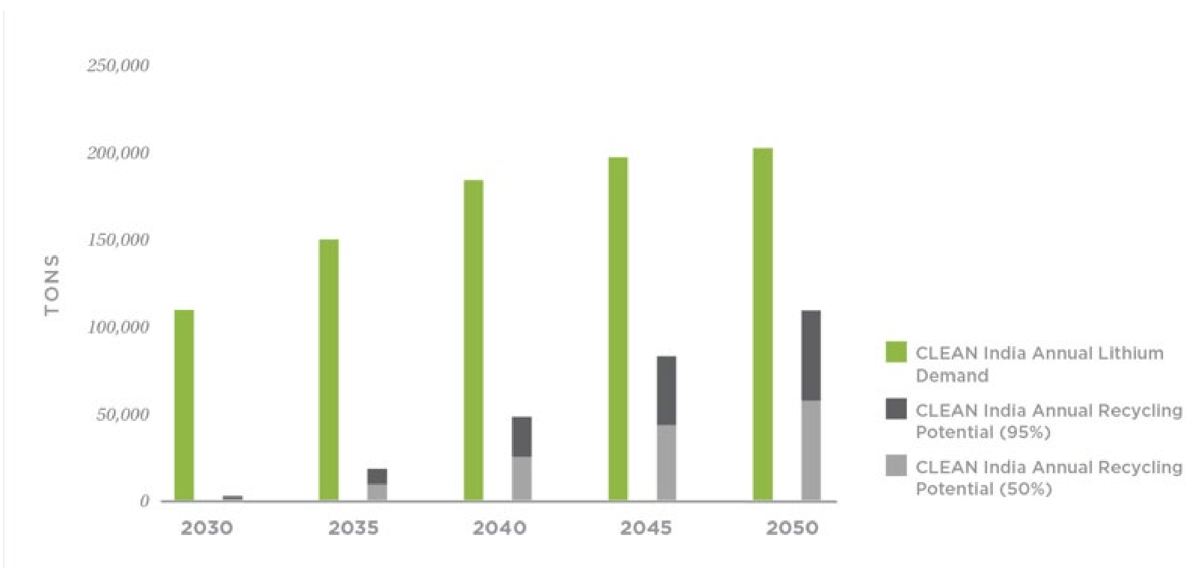

Figure 7: Annual Lithium Demand and Annual Potential Recycled Lithium

While the CLEAN-India scenario can avoid expensive fossil fuel imports in the transport and industrial sectors, one could envision a domestic coal dominant energy independence scenario for the power sector. However, such a scenario 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 8-10 hours of 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).

3.2 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.

3.3 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.

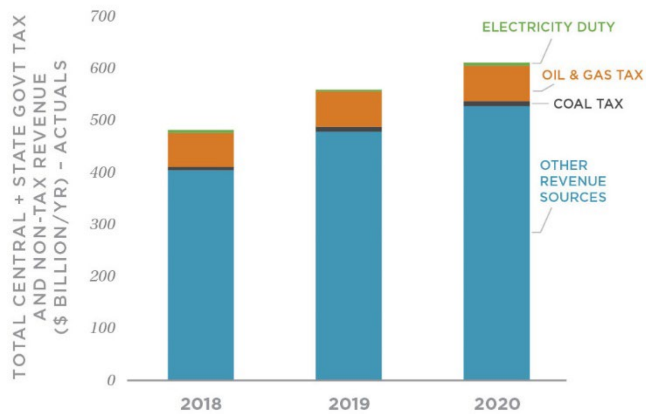

Figure 8: Total Central and State Revenues for Fossil Fuels and Electricity

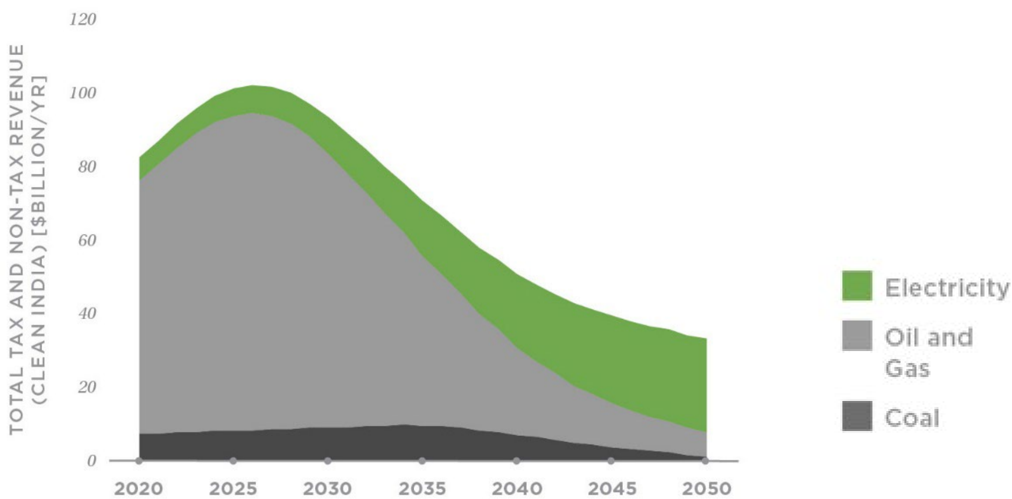

Figure 9: Total Tax and Non-Tax Revenue Changes by Sector, CLEAN-India Scenario

3.4 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. The current rate of renewable energy deployment in India is approximately 15-20 GW per year, indicating that a substantial transformation of the policy and regulatory framework is necessary to meet the required pace of deployment (MOSPI, 2022).

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 scenario primarily focuses on electrification and green hydrogen across the iron and steel, cement, and fertilizer, chemical and petrochemical sectors. 20% of steel (2585 MT/yr) of steel (620%) will be manufactured using green hydrogen and 42275 MT/yr (~1065%) (275 MT/yr) with electrification by 2050. In the cement sector, 480 MT/yr of cement production (65%) will be manufactured using electrification and 184 MT/yr (25%) will be manufactured using green hydrogen based production by 2050. 67 MT/yr (100%) of fertilizer production will be green hydrogen based by 2050, and 82 MT/yr (100%) of chemical and petrochemical production will be green hydrogen based by 2050.

Currently, the adoption of electrified and green hydrogen-based heavy industrial processes in India is minimal, except for electric arc furnace based steel production. However, there is growing global traction for green hydrogen-based manufacturing in the steel and fertilizer sectors. This is attributed to reduced costs of electrolyzers and hydrogen infrastructure, as well as the technological maturity of direct reduced iron (DRI) for steel production. Conversely, in the cement sector, other studies such as IEA (2021) propose a decarbonization pathway focused on material efficiency, fuel switching to natural gas, and carbon capture, utilization, and storage (CCUS), which also includes significant technological uncertainty. Promising new research and lab-scale pilots have been conducted on electrifying the cement production, with a specific focus on microwave heating-based cement production, which has demonstrated improved cementitious properties (Buttress et al, 2015 and Makul et al, 2014). However, the main challenges lie in achieving technology maturity through pilots and reducing costs through widespread deployment. Because India has abundant solar energy resources, a substantial portion of the required green hydrogen could be generated in close proximity to industrial plants. However, it is important to note that substantial investments in hydrogen pipeline, transportation, and storage infrastructure would still be necessary. These infrastructure requirements, which have not been thoroughly examined in this study, need to be carefully assessed.

The CLEAN-India scenario 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 scenario 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).

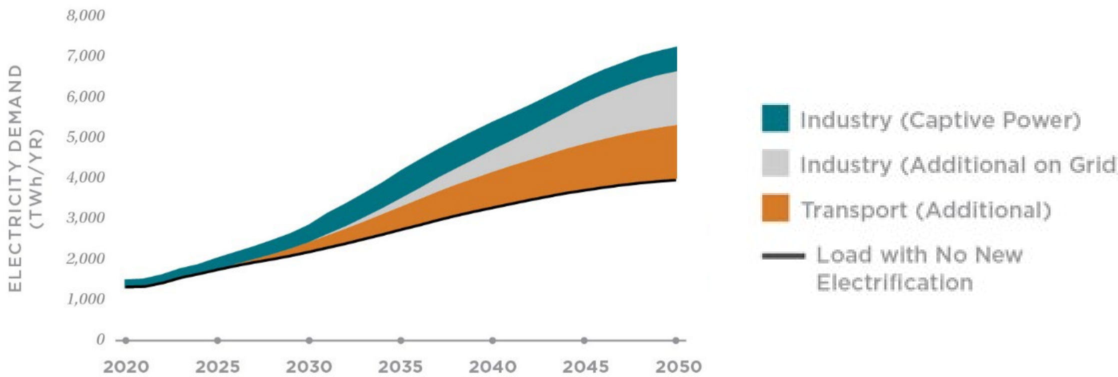

Figure 10: Additional Electricity Demand, Reference vs. CLEAN-India Scenario

3.5 Environmental Benefits

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 11). 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 cumulative premature deaths related to air pollution could be avoided between 2022 and 2047.[2]

[2] 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.

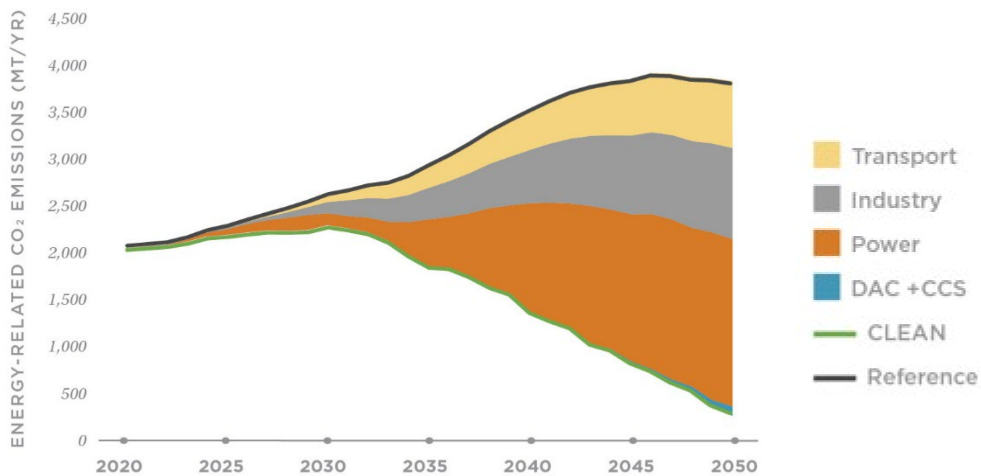

Figure 11: Energy-Related CO_2 Emissions, Reference vs. CLEAN-India Scenario

4 Policy Framework

To achieve the CLEAN-India Scenario, an enabling policy and regulatory system will be needed. 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. This is visualized in Table 1.

Table 1: Policy Ecosystem to Achieve the CLEAN-India Scenario

Sector	Mandates	Incentives	Domestic manufacturing	Infrastructure Planning	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 EVProcurement (e.g. buses)		Public Fast Charging, Low-Cost Solar Charging	
Industry	Clean Mandate on new Industrial Facilities and	Green hydrogen pilots, RD&D		Hydrogen Infrastructure and Low-Cost Solar	

	Hydrogen Production, energy and material efficiency standards (e.g. expand PAT)			PPAs	

More specifically, in the power sector, 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.

4.1 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.

4.2 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.

4.3 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).

4.4 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.

4.5 Planning for a just transition will be critical. 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 (Abhyanker 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.

5 Conclusion and Key Caveats

This analysis showcases a potential pathway by which India can achieve energy independence, economic development, and environmental/climate benefits. Yet, this analysis also has several limitations and must be considered as a high-level pathway that will require further nuanced sectoral analysis. 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 although it does provide some high-level policy recommendations.

In addition, we do not evaluate the broader portfolio of all clean technologies in the power, transportation, and industrial sectors, focusing on commercially available technologies. We examine electrification as a strategy for the transport sectors, not considering other technologies like hydrogen for heavier duty vehicles as well as the critical role of public transit, rail, and green urban planning to reduce vehicle miles traveled. These measures are necessary to reduce fossil fuels in the sector. Similarly, in industry we focus primarily on electrification and green hydrogen vs new materials and industrial processes like electrolytic metal reduction. In the power sector, we do not assess emerging non-lithium battery chemistries such as Iron-air, zinc-air, sodium-sulfur etc. that may be better suited for long duration storage.

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 intricacies. Although this analysis does not attempt a full power-system reliability assessment, our hourly modeling in PLEXOS ensures that demand is met nationally in all periods, including during extreme weather events and periods of low renewable energy generation. Further work is needed to advance our understanding of other facets of a 90% clean power system.

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Supplementary Information

India's Path towards Energy Independence and a Clean Future

Harnessing India's Renewable Edge for Cost-Effective Energy Independence by 2047

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Methods and Data

Table 2 shows each scenario in detail.

Table 2: Details of 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
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: 50% by 2025, 100% by 2035 • Cars: 50% by 2025, 100% by 2035 • MDV/HDV: 20% by 2025, 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

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

[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.

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 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).

Transport

The starting point for our analysis is calculating the Total Cost of Ownership (ECO) for EVs and Internal Combustion Engine (ICE) vehicles on a per-kilometer basis over the useful life of the vehicles. We calculate TCO for nine vehicle classes based on the number of wheels for light passenger vehicles (e.g. two-wheelers, three-wheelers, and cars) and gross vehicle weight for commercial vehicles. The TCO calculation includes the vehicle's upfront purchase price along with average maintenance and fuel costs. The EV TCO also includes the cost of public charging infrastructure and the cost of battery replacements if the vehicle's useful life is longer than that of the batteries; we assume a battery life of 10 years (approximately 3,000 full charge-discharge cycles). To model the dynamics of the nationwide vehicle fleet once EV sales targets are introduced, we use a custom vehicle stock turnover model – Faster Adoption of Clean Transportation (FACT). The FACT model estimates ICE vehicles and EVs retired per year using a survival function modeled separately by vehicle class. We estimate the total number of vehicles sold per year using historical sales data from the Ministry of Road Transport and Highways (MORTH, 2021). Annual vehicle sales are allocated between ICE vehicles and EVs based on the EV sales target for that year. Combining the vehicle-level TCO and the vehicle populations from the stock model, we arrive at total fleet-level costs per year.

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. Our power sector module includes the impact of these goals on the reliability and functionality of the electric grid.

[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.

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 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 CO2 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.

Power Sector Cost 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	**900**	**520**	**400**	**400**

	$/kw by technology-Battery Storage (4-hr)				
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**

Transport Sector Cost 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**
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**
Transport	ICE Heavy Commercial vehicles / Rigid Trucks	**$0.1950**	**$0.2184**	**$0.2419**	**$0.2653**

	(>12T) maintenance price (USD/km)				
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 ($/KW) (MDV/HDV)	**316**	**316**	**316**	**316**
Transport	Electric vehicle charging cost ($/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 /	**90,000**	**90,000**	**90,000**	**90,000**

	Rigid Trucks (>12T) km/year				
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**

Industry Assumptions

Iron and Steel

	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), 0.65 by 2040, 0.90 by 2050
Electric 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 (H2 based)' = 0%	'DRI EAF (H2 based)' = 0% by 2030, ~1% by 2040, ~5% by 2050	'DRI EAF (H2 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
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

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)	'H2 rotary kiln' = 0%	'H2 rotary kiln' = 0% by 2030, ~2% by 2040, 5% by 2050	'H2 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

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)	'H2-fired heaters' = 0%	'H2-fired heaters' = 'PC, C&F': 0% by 2030, 25% by 2050	'H2-fired heaters' = 'PC, C, &F': 50% by 2030, 100% 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

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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