The Hoover Institution's
Survey of India

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Huntington Program on Strengthening US-India Relations

7. Evolution of India's Energy System Post-Independence

A Brief History and Synthesis

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India's energy system is described in many ways: "growing rapidly," "catching up," "government controlled," "coal backbone," "oil dependent," "fully electrified," "low emissions intensity," and "renewables future." Although each of these descriptions is relevant, none comes close to describing the deeper nature and drivers of India's complex energy system, which is best described as an "all-the-above" approach to energy.

All the above, not just in terms of the sources of supply—which is the normal sense in which this phrase is used to describe energy—but rather across all dimensions that are relevant to understanding the energy system of a major world economy: public and private sectors, federal (center) and state governments, urban and rural, fossil and renewable, domestic and international, closed and open, monopolistic and competitive, and (technologically) catching up and advanced.

Several good sectoral studies already provide a solid overview of India's energy system.[1] The purpose of this chapter is not to rehash or simply synthesize these studies. Instead, this chapter proceeds by presenting a current snapshot of India's energy system (or just "system" henceforth) before delving into a consideration of the longer-term trends reflected in India's energy system since India's Independence in 1947. Next, through a synthesis of these long-term trends, this chapter identifies various core and persistent drivers of energy policy—what I call the "dynamic imbalances" in the energy system—that undergird these long-term trends. These dynamic imbalances include (1) issues having to do with the federal tensions in energy policy; (2) India's geographic distribution of resources; (3) the deployment of technological capabilities amid rapid advancements; (4) urban versus rural trade-offs; and (5) energy security issues. These dynamic imbalances are continuous themes that are likely to affect India's energy system in the years and decades to come.

ENERGY SNAPSHOT: CURRENT STATUS OF ENERGY IN INDIA

ENERGY SUPPLY AND SOURCES

India's primary energy needs are currently supplied through a combination of coal, oil, biomass, renewables, and some hydroelectric, nuclear, and natural gas sources.

A Chapter from The Hoover Institution's Survey of India

India's transportation sector is split between rail and road. The former is largely supplied through a combination of coal and electricity and the latter through oil (petrol/gasoline and diesel). Indian Railways—the government-owned rail public-sector undertaking (PSU)—is the primary mode of moving coal around India (48 percent), mostly from eastern India to other parts. A little appreciated fact is that in recent years, owing to rail bottlenecks, about a third of coal has been moved around India through road transportation (trucks), highlighting the interdependence between oil (i.e., diesel for commercial road transportation) and coal.[2] India produces over 80 percent of its coal needs domestically; coal imports, typically of higher-quality coal, mostly from Indonesia, South Africa, and Australia, help meet coking coal needs in steelmaking.

On the oil side, India consumes about five million barrels per day (mbpd), producing only about 0.6 mbpd of that at home.[3] In FY 2021–22, oil imports were mainly from Iraq (25 percent) and Saudi Arabia (17 percent), followed by the United Arab Emirates (UAE) and the United States (US) at roughly 10 percent each. However, following Russia's invasion of Ukraine, Indian oil imports from Russia increased dramatically, reaching ~40 percent of imports in FY 2022–23.[4] The increase is attributed to Russia selling oil to India at significantly discounted prices compared with open market global prices in the face of the G7 price cap of $60 per barrel on Russian oil since December 2022.[5] India's refining capacity stands at 5 mbpd, of which about half is government owned and a third owned by the private sector, with the rest in public-private joint ventures. About a third (i.e., 1.7 mbpd) of petroleum products refined in India are exported, most of which are in the form of petrol and diesel (with some amounts of naphtha—a fuel that can be used to dilute crude oil—and jet fuel). Given that both crude oil consumption and refining capacity are about 5 mbpd, the same amount of petroleum production is imported (as liquified petroleum gas, fuel oil, and petroleum coke).[6] The private-sector refineries, mostly located on India's west coast, are world-class facilities and are export oriented. About 1 mbpd new refining capacity is under construction or development, most of it by various government-owned entities. Diesel (for both commercial and passenger transport) and petrol (for passenger transport) are the primary petroleum products. Interestingly, oil forms about 30 percent of India's primary energy demand, similar to that in the US (36 percent). However, coal and natural gas constitute 57 percent and 7.5 percent of primary energy demand in India, respectively, compared with 10 percent and 33 percent in the US. Thus, the main difference is the amount of natural gas, which in India is primarily used for fertilizer manufacturing and some electricity generation (<2 percent), but in the US about 33 percent of electricity generation is from natural gas. As discussed further below, constraints on gas supply mean India relies heavily on coal for electricity generation (~75 percent).

Diversification and decarbonization efforts are underway in both rail and road transportation. Indian Railways has already been electrified up to 95 percent and is the largest consumer of electricity in India.[7] It has set a very ambitious target to become a net-zero carbon emitter by 2030, through a combination of efficiency, renewable energy (RE) installation and procurement, and integration of intermittent renewable electricity with electricity storage across its locomotives, stations, and buildings. Similarly, the Indian government has set aggressive targets for electric vehicles (EVs) through its EV30@30 campaign that envisions 30 percent of new vehicles sales will be EVs by 2030.[8]

A little appreciated fact is that ~10 percent of India's oil imports (or about 8 percent of total oil demand) are supplied by the US, the latest significant addition to the list of suppliers to India. Another recent feature of India's oil industry is the addition of strategic petroleum reserves (SPRs).

First added in 2018, currently India's SPRs stand at 39 million barrels (i.e., ~8 days of India's oil demand), with an additional capacity of 48 million barrels under development. In 2021, India released 5 million barrels from its SPR as part of coordinated global efforts to increase oil supply to check high prices.[9]

Natural gas comprises 7.5 percent of India's primary energy demand. Most natural gas is used in the fertilizer industry (33 percent), followed by city and local gas distribution (20.5 percent) and power production (14 percent). Of the nearly 60 billion cubic meters (BCM) of gas India consumes annually, India produces about 60 percent of its natural gas needs at home, while importing the rest in the form of liquefied natural gas (LNG). Qatar (45 percent) is the largest and most consistent shipper of LNG to India, followed by the US and the UAE, each supplying 10 to 15 percent of LNG imports in the last couple of years (2022 and 2023). The US has recently emerged as a significant LNG supplier to India, starting from nearly zero in 2016. LNG imports are price sensitive and have been reduced by 20 percent in 2023 compared with 2021, during which the aggregate price secured for India's LNG imports nearly tripled.[10]

Electricity generation capacity in India is diversified, a trend that is further accelerating owing to rapid deployment of renewable energy sources, especially solar. As of May 2024, only about half of the total installed electricity generation capacity (444 gigawatts [GW]) is coal (218 GW) and over a quarter is nonhydro renewables (solar: 85 GW, wind: 45 GW). Hydro (large and small, 52 GW, but declining), natural gas (~25 GW and flat or declining), and nuclear (8 GW and slowly increasing) make up the remainder of the electricity generation capacity. In terms of electricity generation (as against installed capacity), the picture is more skewed toward coal, which currently accounts for ~70 to 75 percent of electricity generation, the remaining coming from hydro (~8 percent), solar (~7 percent), wind (~5 percent), and nuclear (2.5 percent). It is noteworthy that a little less than 60 percent of coal-based electricity generation is lost because of thermal losses at power plants, an important reminder that on a primary energy basis about 2.5–3 times the energy is needed as input (i.e., primary energy stored in coal) to supply one unit of useful energy (i.e., consumption in an end-use sector). Interestingly, coal, solar, and nuclear have a relatively flat (aggregate) generation profile on an annual basis, while wind and hydro have a more seasonal characteristic, as the best wind and hydro production come in the summer months from May to September.[11] As dominant as coal-based electricity generation mostly supplied through domestic coal production is in India, international energy markets still have a noticeable bearing on actual deployment on an annual basis: for example, during part of 2023 about half of the 25 GW natural gas generation capacity was not operational due to high LNG prices.[12]

Overall, ownership of generation capacity is spread almost evenly across the government (state: 24 percent, national: 24 percent) and the private sector (52 percent). However, ownership levels vary based on fuel type. Two-thirds of coal generation are government owned (roughly a third each in state and central [national] government ownership), while the remaining third is owned by the private sector. All nuclear generation capacity is owned by the central (national) government, while hydroelectric plants are mostly government owned (57 percent state and 34 percent central). In contrast, nearly all the installed solar and wind capacity (~130 GW) is in the hands of the private sector.

As of May 2024, India has twenty-four operating nuclear reactors across seven nuclear power stations with a combined capacity of 8,180 megawatts (MW), which accounted for 2.5 percent of total electricity generation in 2023. Most of India's operating nuclear reactors are pressurized heavy-water reactors (twenty reactors, 71.5 percent installed capacity). The latest ones to go into commission are at Kakrapar (2021 and 2024), each with

a reference power capacity of 630 MW; two pressurized water reactors make up about 24.5 percent of nuclear installed capacity (1,000 MW each). The earliest nuclear power reactors in India involved boiling water reactors (BWRs) in Tarapur (1969), which now account for less than 4 percent of installed nuclear capacity. Another seven reactors, with a combined capacity of 6,000 MW, are at various stages of construction. Based on current plans, India expects to nearly triple its nuclear generation fleet to about 22.5 GW by 2031–32.[13]

ENERGY DEMAND

In terms of total primary energy, industrial demand (~40 percent) is followed by demand in the building (13 percent: 11 percent residential and 2 percent commercial) and transportation sectors (8 percent).[14] In the residential sector, the main sources of demand are during the summer months for cooling and throughout the year for lighting and cooking purposes; unlike much of the Western world, heating load is not a big piece of residential electricity consumption in India. Residential demand, especially in urban areas, has been fueled by the rapid adoption of home appliances and especially air-conditioning. An estimated 40 percent of India's population still depends on biomass (firewood and cow dung), mostly for cooking purposes.[15]

On electricity consumption, industrial (~31 percent) and residential (i.e., domestic, ~31 percent) sectors dominate, trailed by agriculture (21 percent) and commercial (10 percent) sectors.[16] Indian Railways, which has an aggressive publicly stated goal of going net-zero by 2030, accounted for about 1 percent of electricity sales in 2023. The states of Gujarat, Maharashtra, and Uttar Pradesh (UP) are the largest consumers of electricity, both on an annual basis and on a peak demand basis: Maharashtra due to both a large population and industrial base, Gujarat due to its industrial base, and UP as India's most populous state (~240 million, or 17 percent).

Buyers of electricity at the wholesale level mostly include state-level distribution companies (DISCOMs) and, increasingly, but still to a lesser degree, large industrial users. Since electricity generation is unbundled from transmission and distribution (T&D) and competitive (see more on this below), wholesale buyers must contract for new electricity capacity through long-term (typically twenty-five years) power purchase agreements (PPAs) based on reverse auctions (a competitive bidding process) or buy electricity in the day-ahead market (DAM) on the national power exchange trading system.[17] Over 85 percent of electricity purchase in India is through long-term PPAs and less than 10 percent happens over the power exchange. Although the volumes traded over the power exchange are not insignificant, recent analysis suggests that these volumes are on the lower side of expectations in a market that "opened up" two decades ago, and thus might be symptomatic of structural inefficiencies that have been built into the current electricity system market mechanism.[18] Those inefficiencies reflect some fundamental imbalances that continue to exist—the prime of them being center and state governments' uneven yet influential grip on the electricity system value chain—but which market reforms had to accept (rather than overcome) to lay foundational change in the electricity sector.

GREENHOUSE GAS (GHG) EMISSIONS

India is the third-largest annual emitter of CO_2, behind China and the US. However, on an intensity basis, at 2 tonnes per person per year India's CO_2 emissions are still relatively low, roughly one-seventh and one-fourth that of the US (15 tonnes) and China (8 tonnes), respectively.[19] India's energy intensity (energy used/GDP) has decreased by 30 percent in 2022 since its peak around 1990, while its carbon intensity (CO_2 emissions/energy produced) has increased by about 10 percent over the same period.[20] Rising industrial and residential demand over the next couple of decades is expected to strain India's energy supply and, unless

that supply is cleaned up, to contribute to worsening local and global pollution. To that end, at the UN Climate Change Conference in Glasgow in 2021 (COP26), India presented a five-pronged approach (Panchamrit, or five nectars) for its climate action:

1. Reach 500 GW nonfossil energy capacity by 2030.
2. Fifty percent of its energy requirements from renewable energy by 2030.
3. Reduction of total projected carbon emissions by one billion tonnes from now to 2030.
4. Reduction of the carbon intensity of the economy by 45 percent by 2030, over 2005 levels.
5. Achieving the target of net-zero emissions by 2070.[21]

MAJOR LONG-TERM TRENDS

OIL: INCREASED CONSUMPTION, STAGNANT PRODUCTION

As noted earlier, India consumes ~5 mbpd and produces about 0.6 mbpd.[22] The crude oil consumption-production gap (i.e., required imports) has grown from 190 million metric tons (MMT) in 2013–14 to 233 MMT in 2022–23 at a compounded annual growth rate (CAGR) of 2.32 percent, while production declined from 38 MMT to 29 MMT over the same period at a –2.83 percent CAGR; the concomitant increase in India's import bill has been 8.65 trillion Indian rupees to 12.6 trillion Indian rupees, a 45 percent increase over a decade.

In some ways, India's oil story is a nightmare come true, one that India had both anticipated and worked to avoid. The current situation of very high import dependence (90 percent) in oil is a combination of three factors: (1) population and economic growth driven oil demand growth; (2) relatively poor natural resource endowment; and (3) uneven regulation and management of resources that did exist at home.[23] Although, what "nightmare" entails for India in the case of oil has changed over the last couple of decades. Until the mid-2000s, the main apprehension was balance of trade, that is, the foreign exchange needed to pay for oil imports. In fact, earlier in the 1990s, a high oil import bill was a contributor to precipitating a financial crisis that eventually led to economy-wide reforms. However, as India's service economy took off in the mid-2000s, foreign exchange to pay for imported oil was less of a problem. Instead, the problem became the widening gap between domestic production and consumption: India's oil import dependency went from 75 percent in 2005–06 to 90 percent in 2022–23, while oil consumption nearly doubled during the same period.

NATURAL GAS: STAGNANT PRODUCTION, INCREASED LNG IMPORTS

Natural gas (or just "gas") has had the most stable consumption level among fossil fuels in India in recent years: both domestic production and imports have hovered around 30 billion cubic meters (BCM) each and consumption around 60 BCM annually in the last five years.[24] But that is not because of a lack of interest or effort in gas on India's part. On the surface, it might appear that natural gas consumption has stagnated while domestic production has declined over the last decade. But that hides a much more dynamic set of factors at play.

In fact, one of the early major payoffs that resulted from India's opening of its oil and gas (O&G) sector to private investments since the 1990s was major gas discoveries in the eastern offshore Krishna-Godavari (KG) basin. Those discoveries—first of them by Reliance in 2002—significantly changed expectations of gas's future in India.[25] The initial excitement pulled in infrastructure investments (e.g., gas pipelines, gas power plants, and fertilizer manufacturing) and spurred visions of a national gas grid that would culminate

in urban gas supply networks across India.[26] However, production in the KG basin proved more difficult and expensive than first imagined and the early discoveries weren't replicated at hoped-for scale and speed, resulting in production declines over the last decade. This also explains the slow but continued rise of liquefied natural gas (LNG) imports in India. But given their exposure to spot markets, Indian LNG imports are quite price sensitive. Since 2022, global LNG trade has picked up in the wake of the Russia-Ukraine war, kicking LNG prices up, which has hurt LNG volumes coming into India.

COAL: FROM KING TO EMPEROR

India's energy system is most closely associated with coal. With all its downsides aside, it is the fuel India is most naturally endowed with. And largely for that reason, starting with the global oil crises in the 1970s, Indian policymakers and system operators have turned again and again to coal to serve as the backbone of the electricity generation sector. That homegrown confidence, not just in terms of resource availability, but also in technological capabilities (e.g., boilers, turbines, grid management, etc.), has firmly established coal as the most "reliable" source of supply in India.

But coal's story in India runs much deeper than that. As discussed later, coal is connected to one of the five fundamental imbalances that have driven and shaped India's energy system since 1947, namely the imbalance in the geography of resource distribution across India. Most of India's coal reserves—plentiful for the next couple of centuries or longer at current rates of production—are in the eastern states in a region aptly known as the "coal belt." Decades of upstream and downstream integration of local economies to coal production have created deep skills- and earnings-related dependence on the coal economy. Furthermore, the enmeshment of government-owned companies—such as the Coal India Limited (CIL), the largest coal producer in India and for Indian Railways, the predominant transporter of coal across India—in the socioeconomic fabric of the region through the provision of a near-full range of nonenergy services (schools, roads, hospitals, etc.) further deepens the lock-in, fueling a mutual codependence that is hard to piece apart.[27]

ELECTRICITY: ONGOING FULL-SCALE TRANSFORMATION

Of all parts of India's energy system, the electricity sector is arguably the most complex but also has changed the most in the last twenty-five years. The reforms set in motion in the late 1990s and early 2000s have transformed the face of India's electricity system. Among other changes, those reforms have resulted in (1) central and state-level regulatory bodies covering generation, transmission, and distribution systems; (2) significant private-sector participation; (3) more supply flexibility and contracting options for large customers; (4) increased transparency regarding power dispatch and pricing; and (5) international funding.[28]

One of the main and first things that the electricity reforms initiated over two decades ago was to unbundle electricity generation from transmission and distribution (T&D) and inject competition in the generation sector. Fast-forward two decades, and generation is now competitive (i.e., generators must bid competitively through a reverse auction process) and ownership of assets is spread across private and public sectors (center and state governments), further complicating incentives for transparent system operations. The main national power exchange—the Indian Electricity Exchange (IEX)—still sees less than 10 percent of power being traded on the day-ahead market (DAM), a measure of the depth of competitiveness and price transparency of electricity markets. However, a new set of rules is expected to push higher DAM volumes through open access to transmission, while also enabling new contractual arrangements whereby producers and users of electricity are directly (and more freely) able to contract for electricity supply.[29]

CLIMATE: ENGAGING PROACTIVELY AND PROMINENTLY AT THE INTERNATIONAL STAGE

India has been actively involved with global climate discussions and goals since the early days, but its position and role have evolved markedly over the last three decades. In the 1990s, India championed the "common but differentiated responsibility" approach, which focused on per capita GHG emissions and essentially argued that developed countries should be responsible for most of GHG emissions cuts and should also help developing countries like India both financially and technologically meet emissions reductions.[30] Internally, during the 1990s India was busy reforming its economy more broadly and the energy sector as part of that. Major reforms in both the O&G and electricity sectors were formulated in the late 1990s. Solar and wind were still very expensive energies during this period. So, besides engaging in some research and development (R&D) at home and abroad, the only real interest India had in low-carbon energy (i.e., RE) during the 1990s through mid-2000s was for energy access in rural and remote parts, which are typically more expensive to connect to the grid.

But with the core pieces of energy sector reform (Electricity Act 2003, National Electricity Policy 2005, and National Tariff Policy 2006) set by the mid-2000s, prices of RE in impressive decline, and global climate negotiations heating up, by the late 2000s India started a deeper and more serious evaluation of its energy future amid climate change. The National Action Plan on Climate Change (NAPCC) was issued in 2008 laying out the core principles of India's action vis-à-vis climate change:

> [The NAPCC] outlines a national strategy that aims to enable the country to adapt to climate change and enhance the ecological sustainability of India's development path. It stresses that maintaining a high growth rate is essential for increasing living standards of the vast majority of people of India and reducing their vulnerability to the impacts of climate change.[31]

The National Solar Mission was initiated as part of this along with seven other national missions focusing on energy efficiency and sustainability.

The intensity and visibility of India's engagement in the global climate process significantly increased, though, after Narendra Modi became India's prime minister in 2014. Starting with COP21 in 2015 (Paris), Modi's approach to climate negotiations and India's positioning have generally been viewed as proactive and positive but not without controversy. At COP26 in 2021 (Glasgow), PM Modi announced the "five nectar elements" (Panchamrit) of India's climate action plan, the prime of which was the declaration that India will go to net-zero carbon emissions by 2070.[32]

Three main drivers have shaped India's climate goals and action over the last decade. First, private-sector appetite for building more coal in India has waned since its heyday in the late 2000s. After coal and electricity sector reforms in the 2000s, many Indian conglomerates (e.g., Adani, Reliance, and Tata) went on a coal-mining and plant-building spree. But financial operation of these long-lived assets within a complex web of electricity-market rules and actors have proved more challenging than originally anticipated. Besides, many of these conglomerates are global players with diversified assets and investments. As such, there is increasing reputational and investment pressure on them from the investment community.[33] Relatedly, tightening international credit in recent years for thermal power generation has made it harder to finance privately owned coal plants.[34] Second, RE prices have been in free fall over the last decade. That combined with preferential interconnection and scheduling policies (as part of India's climate push) make RE investments financially viable and attractive for the private sector, which, since the mid-2010s, has predominantly led RE deployment in India while also almost

entirely backing down from building new coal plants. This plays into the strong electricity-demand growth and generation-capacity needs anticipated in India over the next few decades.

And third, as India is the fifth-largest economy and the most populous country in the world that is still in the early phases of its economic ascension, its global position and aspirations are very different from two decades ago. India's growth and security needs necessitate a broader set of engagement with other major economies on trade, energy, and advanced technology, and climate action is part of that broader set of issues that needs to be tackled together. In particular, the US under the Biden administration since 2021 has increasingly combined climate action as part of broader bilateral trade and technology deals with India.[35]

IMPORTS: DIVERSIFICATION OF SOURCES

India imports about 90 percent of its oil, 50 percent of its gas, and 10 to 20 percent of its coal needs. Although coal imports have ticked up in recent years, generally India has kept domestic production up with its needs and there is still much room for improvement in the productivity of domestic coal production. Thus, while meaningful in its scale, coal imports are generally not viewed in the Indian business and policymaking circles as being a long-term source of concern. It is the continued uptick in the imports of oil and gas, even in the face of their increasing global prices, that has surprised India and upended some of the hopeful visions of dramatically increasing domestic production of these commodities following the reforms and the opening (to private investment) of the O&G sector starting in the late 1990s.

At this point, India's predominant planning approach to managing its O&G appears to have shifted from one being dominated by visions of vastly expanded domestic production to one of navigating a long-term, deep-import dependence. As in most other major countries, O&G has always been viewed through the "energy security" lens in India. But through decades of practical experience, India is closer than ever in accepting its role as a major long-term importer of both oil and gas.

And that shift directly influences India's strategy in securing the O&G supply it needs. As a result, EVs have become a lot more attractive in this situation. Thus, unsurprisingly, India has set a target for EVs to be 30 percent of new vehicle sales by 2030. Furthermore, India is now more interested in the robustness and reliability of the global O&G supply chain than ever. To be sure, India has always been a neutral, if not a positive, actor in terms of global energy supply chains. But given its outsized demand and internally acknowledged expectations of deep import dependence, the intent is much more serious. There's a lot more at stake now.

One immediate offshoot of India's positioning vis-à-vis O&G supplies is India's willingness to engage with available supplies anywhere in the world. Two instances exemplify this approach the best. First, following Russia's invasion of Ukraine in 2022, India's oil imports from Russia significantly increased owing to the discounted price of Russian oil in the face of international sanctions.[36] Second, in parallel, and more cross-cutting, in recent years India has increased imports of oil, gas, and coal from the US. In 2022–23, the US supplied nearly a tenth each of India's oil, gas (LNG), and coal imports.

ENERGY EFFICIENCY

Growing import dependence and pains at home to produce energy resources apace with energy-demand growth had another lasting effect on India's energy landscape: a well-resourced and institutionalized focus on energy conservation pushed by the Energy Conservation Act of 2001. This was initiated through the creation of the Bureau of Energy Efficiency (BEE) under the Ministry of Power. Since its formation in 2002, BEE has focused on building codes, lighting efficiency,

and appliance efficiency. Much of BEE's early efforts involved coordination of actors across the energy value chain, development of energy labels, and voluntary energy-efficiency goals.[37] Over time, many of these programs became more formalized and some even turned into national initiatives and rules, such as the Energy Conservation Building Code (ECBC) for commercial buildings established in 2007.[38]

Buildings efficiency has also been a target through the development and coordination of building codes. India's building stock is expected to double by 2040, and 70 percent of new construction is likely to be in urban areas.[39] Unlike the electricity sector, most emissions in the building sector will come from the construction and operations of new buildings, making the building sector critically important from a climate change and health perspective. However, multiple guidelines, voluntary ratings, and codes have emerged and coordination, adoption, and enforcement by local administrative bodies have been slow.[40]

Within buildings, air-conditioning (AC) systems have been the central plank of energy-efficiency efforts. Adoption of AC systems has skyrocketed over the last decade, with the future expected to hold more of the same.[41] A particular difficulty is that cooling load makes summer early evenings the peak hours, which is not aligned with solar generation. This has increasingly necessitated—and is starting to attract—the incorporation of more short-duration battery storage on the grid. This need is expected to explode over the next decade.

PRIVATE PLAYERS: UNSHACKLED (ONCE MORE)

Structurally, the substantial increase in private ownership of and investment in energy infrastructure and services delivery represents the biggest shift in India's energy system since 1947 and especially in the last two decades. In some ways, this is going back to where it all started in 1947 post-Independence, albeit through a circuitous, tumultuous, perspiring, and at times scandalous route.

At the time of India's Independence much of the oil sector, mostly refining, was under private operation (there was little gas-based operation then). The same was true for coal production and electricity generation, which, at 1.36 GW, was a tiny fraction of generation capacity today (444 GW).[42] There was no gas, nuclear, or even hydropower to speak of.

India's fundamental aspirations of modernization and economic growth, to which energy was a critical input, did not always square with the profit-focused, often exploitative, operations of the private operators at the time.[43] The frustration to steer the energy-ship in desired socio-economic directions combined with a broader socialist-leaning, centrally planned approach to India's future led to the increasing nationalization of India's energy system—a transformation that was nearly complete by the mid-1970s, a time when the world was rocked by two back-to-back oil crises and India in particular was going through the most tumultuous period politically post-Independence.

Aspiring to drive India's economic engine through nationalization of energy production and infrastructure was one thing. But delivering on that promise pivoted around frontier technological capabilities, which India was just beginning to develop systematically through a national system of higher-education and R&D institutions. So, India desperately needed help. Following, India's first nuclear explosion test in 1974, the US slowed down and eventually stopped fuel supplies for India's first nuclear reactors in the Tarapur Atomic Power Station (TAPS), pushing India closer to the Soviet bloc.[44] In the years following, India would develop close collaborative relationships with Soviet-bloc countries—the effects of which are salient even to this day. As a result, India's most major oil discoveries on the west coast in the

offshore "Bombay High" field were made in 1974 with Russian help.[45] Similarly, Russian and Czechoslovakian assistance was instrumental in helping India build thermal power generation manufacturing capabilities.[46]

As fruitful and promising as those relationships were at the time, over the next two decades India was strapped for foreign exchange to pay for ballooning oil import bills in the face of flat oil production and increasing demand. The national oil company, Oil and Natural Gas Corporation (ONGC), struggled to succeed in exploration and mismanaged producing assets. To address such shortcomings across the energy sector in India, regulatory reforms and injection of competition (by opening to private investment) were among the central pillars of the economic reforms in India initiated in the early and mid-1990s at the requirement of foreign institutions, notably the World Bank.[47]

THE FIVE DYNAMIC IMBALANCES IN THE INDIAN ENERGY SYSTEM

1. CENTER VERSUS STATE POLITICS AND AUTHORITY

A fundamental source of complexity arises from electricity being on the "concurrent" list of both the center and state governments to work through jointly. That coordination is difficult and shape-shifting, given the ever-changing political winds at local and national levels.

More important, while the central government sets policies and regulations in national and interstate matters (e.g., power trading, transmission access, etc.), state governments have jurisdiction over electricity distribution, a function delivered through DISCOMs. Decades of politics-driven meddling to artificially keep electricity rates low for electoral gains have left the DISCOMs in dire financial states. Yet DISCOMs are responsible for contracting for all power to meet statewide electricity demand now and in the future.

Some DISCOMs, especially those in some of the largest metros like Ahmedabad (Gujarat), Delhi, Mumbai (Maharashtra), Noida (UP), and Kolkata (West Bengal), have been privatized, a change that is generally regarded as having improved reliability and quality of service in these areas.[48] Since 2020 efforts have been underway to possibly privatize DISCOMs in the eight union territories of India, areas that are under the central government's administrative purview. But progress has been slow and checkered.[49] Regardless of that, it still leaves most of India's electricity demand under state-owned DISCOMs. This is the mother of all the problems that Indian policymakers and investors face vis-à-vis the electricity system and is one of the root causes of the complex web of regulations, infrastructure, pricing, and finances. The Ujwal Discom Assurance Yojana (UDAY) was launched in 2015 to push states to assume 70 percent of the DISCOM debt, aiming to improve their operational efficiency and financial health. But results have been mixed.[50] An updated plan with 2027 targets—the Revamped Distribution Sector Scheme (RDSS)—was introduced in 2022 to continue the progress made.

2. GEOGRAPHY OF RESOURCES: THE EAST BASKS IN COAL GLORY WHILE THE SUN RISES IN THE WEST

Past and current landscapes of India's electricity system are deeply imprinted by coal and hydro resources in the east. But the energy transition in India is not just one from fossil-based to increasingly more renewable sources; it is also a transition from the east of India to its west (and the south), where most of India's solar and wind resources are located. If the concentration of massive coal reserves along India's coal belt (the region mostly in the eastern states) has deeply intertwined India's current energy system with broader socioeconomic-political dimensions, the concentration of solar and wind resources combined with private enterprise and progressive regulation in the west and the south has spawned

a spectacular growth of RE in India that was unimaginable even a decade ago. If one considers that coal is the past, then this view would suggest that the sun might be setting in the east and rising in the west for the energy system in India.

But that view is misplaced, at least for the time being. Private-sector investments might have been replaced to some extent by the meteoric increase in private-led RE deployment, but coal's central position as the backbone of India's electricity system has only *strengthened* post-COVID-19. Integrating intermittent RE at low levels—as has generally been the case so far (~10 percent or less of RE-based generation on an annual basis)—may be largely handled through operational changes and low-lift grid enhancements. But at much higher levels, RE integration requires a much tighter market design, lots of grid-scale storage, and deeper investments in the grid infrastructure, both in transmission and distribution. A multilayered market design whereby layers and layers of incremental dispatch and pricing rules bind atop each other to serve the financially and regulatorily fragmented state-level distribution systems is not conducive to such integration.[51]

Two important issues arise in the face of this dual-faceted energy geography in India. First, ever since Prime Minister Modi's COP26 (2021) declaration of net-zero India by 2070, coal's future in India has become an intense matter of debate.[52] That debate is less about the immediate future, over which coal will continue to remain a big part of India's energy supply. But the debate certainly has some overtones of large parts of the coal ecosystem—from mining to transport to power generation—eventually coming to a grind and possibly even phasing out in the next four or five decades. If not planned carefully, such a transition, even at less than full scale (i.e., "phase down" instead of "phase out"), could mean profound disruptions to the social and economic life in the coal belt and even political upheaval more broadly. This is not something India has ever planned for. In fact, this is not something even the scholarly and analyst communities have focused much on until very recently.[53]

Second, as part of progressive rules and incentives for supporting large-scale RE deployment, Renewable Purchase Obligations (RPOs) have been imposed on DISCOMs.[54] Currently, RPOs require DISCOMs to buy a minimum of about 25 percent of their electricity through power purchase agreements (PPAs) with RE-generators; and this requirement is slated to go up to 43 percent by 2029–30. Given that much of RE generation is happening in the west and the south, this amounts to a flow of monetary resources from the east to the west, further exacerbating the divide.[55]

3. TECHNOLOGICAL CAPABILITIES: CATCHING UP AMID WAVES OF GLOBAL CHANGE

Over the last seventy-five years—as the global energy system focused in waves first on coal, oil, nuclear, hydro, and natural gas, back on coal, and, most recently, on wind and solar—India has been trying to ride each of those waves, with varying degrees of success. A common position India has found itself in all these waves is a lack of world-class technological capability to not just ride these waves but rather power them indigenously, inside out. This has led India to work on all channels of acquiring such capabilities—bilateral national partnerships, government-owned production and funded R&D, and opening to foreign direct investment (FDI).[56]

Except for coal-based thermal generation, most of these efforts haven't really panned out as hoped. Self-sufficiency in coal technologies was built over decades through the National Thermal Power Corporation (NTPC), a PSU under the Ministry of Power, and Bharat Heavy Electrical Limited (BHEL), a PSU under the Ministry of Heavy Industries. NTPC builds and operates the power plants, while BHEL manufactures the key components (e.g., boilers and turbines). Soviet assistance was

instrumental in helping India's budding thermal-generation industry build technological capabilities over time and eventually becoming self-sufficient. That coal-based power generation is one of the few energy areas where India is fully self-sufficient further adds to the techno-institutional lock-in and contributes critically to the "coal means energy security" paradigm. This technological history and the international relationships that enabled India to count coal in its corner from a resource and technological security perspective continue to shape India's worldview on technological capabilities.

Throughout the past seventy-five years India has chased energy infrastructure and technologies one after another as the global picture of resources, economics, and innovation has shifted. And in all these instances, including in the current wave of RE and storage technologies, India has tried to play catch-up. As discussed above, some of the causes for this outcome have entailed intricate and often corrupt bureaucracy, inefficient government-owned production systems, low-intensity government and private R&D spending, poor integration of R&D and commercialization, and so on.[57]

Given the importance of coal, cleaning up coal-based generation is a top priority. Yet after years of fits and starts in coal gasification and carbon capture and storage (CCS) R&D, India doesn't really have deployable commercial scale technologies. To change that, India is planning more significant investments in coal gasification.[58] India has had better luck with wind technologies, and some Indian companies have produced world-class wind components for both domestic usage and exports.[59] However, growth of wind has slowed down in recent years, while solar has already taken over wind in India by a big margin (85 GW to 46 GW). Moving forward, solar is widely expected to be the RE mainstay in India. In the solar space too, India finds itself in a similar position all over again. As with the rest of the world, most solar cells and modules in India are imported from China. To help grow an indigenous solar-manufacturing industry, India has levied import duties on solar technologies and instituted production-linked incentives to support Indian companies as they get a foothold amid a brutally competitive global solar industry with China in the front seat. Success is anything but guaranteed and India will need to tread very carefully.

4. URBAN VERSUS RURAL

Although most of the Indian population is still rural (65 percent), the urban population in India has grown fast. The vote bank of a large rural population has meant that politicians have pandered for decades to improve connectivity and quality of services for rural energy, including lighting, sustenance electricity for basic appliances, and clean cookstoves.[60] But progress has been much slower to materialize until the last decade. At present about 98 percent of India has some level of grid connectivity, although the quality of services remains variable.[61] Recent studies show that both electricity connectivity and quality of electricity supply to rural public health centers (PHCs) are strongly correlated to health services and gender outcomes in rural areas across India.[62]

However, the perennial problem with rural energy services is the ability of the low-income and poor households to pay for them routinely. That is, even though on paper electricity services enhance health and educational outcomes for poor and rural households, thus potentially aiding upward economic mobility, those linkages are not uniform and fully developed. A positive development in this area is the rise of decentralized renewable energy–assisted machines, for example, solar+battery-powered sewing, roti-making, and milking machines. By directly coupling a *reliable and flexible* source of electricity with increased income, such distributed, small-scale machines offer a promising avenue to activate social and economic mobility in rural India.[63]

On the emissions front, the carbon intensity of energy consumption of urban residents is roughly double that of rural residents, to the extent that sometimes this has been referred to as "two Indias" and "the rich hiding behind the poor" (i.e., India's per capita emissions are lower because of the large poor population, which consumes only a small part of India's overall energy demand).[64] A 2022 study, though, paints a more nuanced picture:

> The richest 10% of Indians only emitted 20% more emissions from direct primary energy use than the poorest 10% in 2012 (excluding direct emissions from transport). . . . Results suggest that addressing pressing welfare issues connected to energy use in India, such as indoor air pollution from solid fuels, can be aided by a transition to modern energy carriers, with little consequential increase in CO_2 emissions.[65]

Relatedly, pollution in urban areas from coal-based power generation and diesel-dominated road transportation, especially in high-population-density areas across vast swaths of northern/central India, is a major health issue. Not surprisingly, NGO-based environmental action and activism is well supported in urban areas, especially by the urban middle class.[66]

5. ENERGY SECURITY

Energy security has been a constant factor in India's energy decision making. But the specific form that energy security considerations have taken has evolved through the decades. Right after independence, energy security was about *affordability* of supply to the masses and India's budding industrial base. If prices were considered unaffordable for the people or economically high for the industry, they were subsidized.[67] During the oil crises of the 1970s, energy security took the face of (self-reliant, i.e., inward-looking) *security* of supply, leading India to take a decisive and deep turn toward coal, just as the US did in those years. In the 1980s and 1990s, energy security was about *financial sustainability*. High oil import bills amid dwindling foreign exchange reserves abroad combined with poor operational performance of O&G and electricity PSUs at home to help precipitate economy-wide policy, regulatory, and institutional reforms. If the 1990s were about laying the foundations of economic liberalization, in the 2000s energy security took the form of robust *market design* (arm's length regulation, competition, price transparency) as the bedrock for all other parts of the energy security equation—affordability, supply security, and reliability (of service quality)—to build off from. In this sense, the 2000s entailed some of the most detailed and painstaking work by Indian policymakers and institutions in energy. Finally, in the 2010s energy security became synonymous with *diversification* of fuels in the energy system and their supply sources. This has entailed in electricity the rapid growth of RE alongside coal and in O&G the diversification of originating countries from which India sources its supplies.

It was also during the early 2000s that the "clean" part of energy security got some initial attention in India, particularly in the metro area in Delhi, through the court-directed use of compressed natural gas (CNG) in commercial vehicles.[68] But the focus was still on local health effects. Only by the late 2000s did the clean part of energy security start to truly reflect national and international considerations.[69]

These five cycles of energy security foci that India has gone through in the last seventy-five years—namely, affordability, self-reliant supply security, financial sustainability, robust market design, and diversification of supply with clean supply now layered on top—are an important reminder of the immense thoughtfulness, hard work, perseverance, collaboration, innovation, and resilience that India has exhibited regarding its energy journey

postindependence. India truly has had an "all the above" energy journey post-Independence.

CONCLUSION

Almost eight decades ago India started with relatively small energy production and consumption, near-zero technical capacity in the sector, no energy markets to speak of, and little financial wherewithal to write its energy story. At present, India is one of the largest consumers and producers of primary energy, with a diversified supply base and no runaway energy prices. It has one of the highest installed RE capacities globally and nearly complete electrification.

As highlighted in this chapter, there have been many challenges and missed opportunities as well during these decades that have taught valuable lessons. The challenges and opportunities of tomorrow, however, are quite different from those of the past. Moving forward, it is going to be about efficiency, electrification of transportation, large-scale RE integration, reimagining of urban growth and transportation, cleaning up and ramping down coal generation, development of functioning carbon markets, and integration of the demand side in the energy equation. As India embarks on this new journey over the next few decades it will increasingly look to leverage international cooperation and collaboration to meet its technological and fuel-supply needs. Primary among them will be the opportunity to redefine and grow the US-India energy relationship, which currently is at an all-time high as the US has emerged as a significant supplier of oil, LNG, and even coal to India. The hard part is that India must corral all domestic and international resources, cooperation, and collaboration in real time given its fast-paced economic growth. But, on the flip side, that is also the promising part: high growth also means that India has room for trial-error-and-learn in real time by experimenting in parallel. To materialize that opportunity, the key for India will be to refine its all-the-above approach into a more coordinated energy strategy and pursue it with intention and persistence through building reliable and stable coalitions domestically and internationally.

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