India’s Transition to Cleaner Energy Systems

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I. Introduction:

In the fifteen Millennium Development Goals (MDGs) adopted at the UN Millennial Summit in September 2000 for the period 2000-2015, energy did not find an explicit mention. In the seventeen Sustainable Development Goals (SDGs) that the UN adopted for the next period 2015-2030 to replace the MDGs, this oversight was rectified. The seventh SDG exhorts all countries to “ensure access to affordable, reliable, sustainable and modern energy for all.” In fact, the provision of modern energy services is central to, and a prerequisite for, the attainment of several other SDGs that seek to achieve or ensure: food security, good health, quality education, availability of water and sanitation, productive employment, sustainable industrialization and production, resilient infrastructure and above all, economic growth. Without exception, these are also the socio-economic sectors in which the Government of India (GoI) would like to make progress.

None of the sectors which lead to economic development, be it agriculture, or industry and manufacturing, or services and commerce, grow without some increase in energy consumption. While increases in energy efficiency cause declines in the energy intensity of the economy in most countries most of the time, these declines have thus far been unable to offset the increases due to growths in population and incomes. Whenever economic growth exceeds population growth, the increased per capita incomes lead to increased domestic consumption of energy for personal mobility and in the forms of services provided by electricity, both in positive feedback loops. The increased consumption of energy is not without consequences. Energy derived from conventional sources causes adverse impacts at all spatial scales--local, regional and global; and at all temporal scales—immediate, intermediate and long-term. Some of these impacts result from normal operations and some are accidental. The impact that has become increasingly worrisome in contemporary times is caused by carbon emissions leading to anthropogenic global warming and consequent changes in climate.

Analysts have often wondered whether economic growth causes an increase in electricity consumption or vice versa, i.e., increasing electricity consumption causes a growth in the economy. In a study on Indian data from FY1951 to FY1997, Ghosh (2002) found that the causality ran from economic growth to electricity consumption without any feedback effect. One recent analysis of the recent deceleration of the electricity demand in Karnataka (Prabhakaran, et al., 2016) provides evidence for this finding--it was the deceleration in state’s GDP that caused a deceleration in the growth of electricity demand and not vice versa.

Sections 1.1-1.3 take a backward look at how we got here. Section 2 provides a brief assessment of the coal, hydro and nuclear sectors, of the recent modelling efforts, and of the relatively high cost of energy in India. Sections 3, 4 and 5 take a forward look to see what would enable a transition to cleaner systems. Section 6 attempts a summing up.

1.1 Role of the Planning Commission in India’s Energy Sector:

Serious observers of India’s energy scene often find it perplexing. A recent international report opined: “Clarity of vision for the energy sector is difficult to achieve in India, not least because of the country’s federal structure and complex institutional arrangements” (IEA, 2015, p. 40). There are several reasons why this clarity of vision has been difficult to achieve, but we will review here, *with the benefit of hindsight*, the roles played by the Planning Commission (PC) and by expert committees in India’s energy sector, highlighting issues that have been of historical concern.

For more than six decades between 1951 and 2014, only the PC within the GoI had a mandate to adopt an integrated view of the energy sector. The ninth Plan document articulated issues facing India in the energy sector. These remain just as valid today. “The key issues facing India which have energy implications are rising population, need for economic growth, access to adequate commercial energy supplies and the financial resources needed to achieve this, rational pricing regime, improvements in energy efficiency of both the energy supply and consumption, technological up-gradation, a matching R&D base and environmental protection” (PC, IX, 1997, En. p. 7/11). Planning Commission documents largely, of course, reflect the times in which they were written. For example, the word “energy” only appears for the first time in the sixth Plan document in 1980, and the word “environment” appeared for the first time only in the seventh Plan document in 1985.

Energy chapters in PC documents are a mixture of statements of fact, diagnosis of the extant energy situation in the country, some technological and policy prescriptions, some exhortations and prognostications, and some amount of wishful thinking. Often, they reveal the perspective of the authors. Based on the energy/power chapters of these twelve plan documents, we briefly describe each ingredient of this mixture.

Planning Commission documents are the least controversial when they are making factual statements. Thus for example, the tenth plan document (PC, X, 2002, p. 770) states that “Lead has been removed from petrol in phases and from 1 February 2000 only unleaded petrol is being supplied in the country”. Although delayed, this has undoubtedly been an achievement of the energy sector in the country. In 2007, the PC reported that “over half of the country’s population does not have access to electricity or any other form of commercial energy” (PC, XI, 2007, p. 342). This reflects a persisting under-achievement. The twelfth plan chapter on energy states that some of the villages (nearly 6000 till December 2011, p. 144), which have been electrified, i.e., connected to the grid, have not been energized (PC, XII, 2012, p. 143). In addition, “in certain states”, where the grid had been energized, “even minimum required hours of supply (6-8 hours) could not be met” (PC, XII, 2012, p. 144).

These chapters on energy often contained perceptive diagnoses of the problems. For the rural sector, they point out that “connectivity by itself is only a part of the (RGGVY) programme. In many states there is also a real shortage of power” (PC, XII, 2012, p. 155). It had become clear to the authors of the eleventh Plan “that a capacity to provide additional energy is *always* (emphasis added) likely to lag behind the rising demand, unless consumption of energy is also economized” (PC, XI, 2007, p. 381). Other recent diagnoses identified “distribution is the weakest link in the power system” (PC, XII, 2012, p. 139) and the failure of the open access system. “Electricity Act of 2003 made Open Access mandatory from 1.1.2009 for all consumers with >1 MW loads. This has not been operationalised because of the reluctance of state governments and utilities” (PC, XII, 2012, p. 154).

Figure 1

During the sixth plan, the PC foresaw the evolution of thermal power plants from 210 MW units to 500 MW (PC, VI, 1980, p. 8/31). During the twelfth Plan, it expected half the plants to be based on super-critical technology and for the thirteenth Plan, it mandated all coal-fired capacity additions to be through super-critical units (PC, XII, 2012, p. 138). It has been less correct while forecasting the increasing thermal-hydro ratio and the amount of coal that would be required for power generation. In the third plan, extrapolating from short-term trends (see Figure 1), the PC was estimating 50% of the electricity could come from hydro and the remainder from thermal units (PC, III, 1961, p.12/18). In the eighth Plan, it expected 40% of electricity generated to come from hydro. In the second Plan, it stated that “only about 10% of the coal raised is being used for power generation at present, and as coal production steadily increases, the proportion required for power generation is not likely to exceed this percentage” (PC, II, 1956, p. 7/17). However, by the ninth plan, it had corrected the earlier claim and stated “presently about 71% of the total coal consumption is used for power generation" (PC, IX, 1997, En. p. 5/11). The PC has also invariably over-estimated the addition of new plants. Figure 2 shows the trends in percent achievements in installed capacity (over targets) in successive plans and indicates almost an inability to learn from experience.

Figure 2

Another area to have witnessed a technology prescriptive shift pertains to captive diesel plants. In the third plan, the PC had this say: "Expansion of (diesel) power generation will be confined mainly to isolated locations and small nursery schemes or for peaking purposes" (PC, III, 1961, p. 10/18). It reiterated the policy during the sixth plan. "In other cases (i.e., except for fertilizer, steel and aluminium and CHPs) the present policy of discouraging captive units will continue (PC, VI, 1980, p. 8/31). However, by the 11th Plan, there was a reversal. "Setting up of peaking power should be encouraged for both producers and consumers to overcome peaking shortages" (PC, XI, 2007, p. 363).

Often the PC (at least on paper) would continue to show support for alternate technologies long after their promise had faded. In the tenth plan, while emphasizing support for coal bed methane, it also expressed support for alternative fuels such as MS-ethanol and gas hydrates (PC, X, 2002, p. 777). In the eleventh Plan, it also supported "underground coal gasification, coal to liquid plants, biofuels, and oil shale" (PC, XI, 2007, p. 366).

The PC was most likely to be wrong when it indulged in prognostications. In the twelfth Plan document, it went out on a limb and predicted that "the prevailing (international) energy prices are not likely to soften" (PC, XII, 2012, p. 130). It has also expressed the view that "based on present technology, with a concerted push and a 40-fold increase in their contribution to primary energy, renewables excluding hydroelectricity may account for only 5-6% of India's energy mix by 2031-32" (PC, XI, 2007, p. 383).

From time to time, the PC has articulated policy goals. For the tenth Plan, it identified these to be "economic efficiency, energy security, access, and the environment". It also described the thrust of the reforms as "to deregulate the prices of commercial energy resources (which until recently were entirely administered), increase competition and reduce subsidies" (PC, X, 2002, p. 766). In the first plan itself, the PC recommended that "power generation should be regulated carefully and capital should not be sunk on electric plant much in advance of ascertained needs, and power should be sold at economic rates: (PC, I, 1951, p. 2.12). It complained in the fourth Plan that a "large part of electricity generated is sold in some states to bulk consumers below the cost of generation" (PC, IV, 1969, p. 4/9). It reiterated in the ninth Plan, that "electricity tariffs on average remained below the cost of supply" (PC, IX, 1997, ES, p. 4/7). Since then tariffs have risen and given rise to a new concern. "The scope for further tariff increases is limited since tariffs for paying customers are already amongst the highest in the world and it may make sense for them to opt out for captive generation" (PC, XI, 2007, p. 353). Until the end, the PC continued to make relevant policy recommendations. "The ability to meet peak loads is critically dependent on introducing time-of-day metering with a sufficient difference between peak and off-peak tariffs (PC, XII, 2012, p.148).

The PC highlighted consistently about the inadequacy of R&D in the energy sector. At the beginning of the sixth Plan, it stated that "in relation to the massive investments being made in the power sector, the overall R&D effort has remained inadequate (PC, VI, 1980, p. 12/31). In the eleventh Plan, it suggested that "utilities should aim at least about 1% of their profits to be utilized for R&D activities and the manufacturing organizations should consider 3-4% (of their profits) to be provided for technology development" (PC, XI, 2007, p. 361). Realizing that many utilities and public sector companies do not make a profit, it changed its recommendation in the same document to: "Each company in the field of energy should be mandated to spend at least 0.4% of its turnover on R&D" (PC, XI, 2007, p. 389). Sometimes the exhortations are made in passive voice in expectation of their non-compliance. "AT&C loss reduction of 3%/year in the next 5 years should be targeted by all states (PC, XI, 2007, p. 362).

The PC was often guilty of "wishful thinking" (Sengupta, 2015). For more than a decade, it had been predicting the complete electrification of the country. In 2007 it stated: "The National Electricity Policy aims at providing access to all in the next five years by overcoming energy and peaking shortages and having adequate spinning reserves by the year 2012" (PC, XI, 2007, p. 361). Five years later, the goal was still five years away. "The Government plans to provide electricity to each and every household in the next five years" (PC, XII, 2012, p. 131). There were similar expectations for the National Electricity Fund (NEF). "It is planned to set up a NEF for helping state utilities invest" (PC, XI, 2007, p. 359). Five years later, "A NEF has been set up. This will now be operationalised" (PC, XII, 2012, p. 154). Earlier, the PC had mooted the impractical idea of a single regulatory authority for the entire energy sector. "There is a need to examine the issue of a single regulatory authority for the energy sector with a view to developing the desired fuel-mix and related issues (PC, X, 2002, p. 766).

From the first plan onwards, the orientation of the "planners" has always been with those proposing the projects and not with the people who would be affected by them. In the first plan it prescribed—"What is essential is that people in every area should feel that the project included in the Plan is their own—intended for improvement of conditions in their area—and that they should make special sacrifices for getting it completed" (PC, I, 1951, p. 4/12). Further, it saw people as merely consumers of power. "For the successful implementation of any power project, a large measure of public co-operation is necessary for building up the load for the utilization of power generated" (PC, I, 1951, p. 5/12). In the tenth Plan, it calls for the development of "a national rehabilitation and resettlement policy to help accelerate the development of hydro and coal sectors" (PC, X, 2002, p. 767). The bias is undisguised. "It takes unduly long time for new projects to get (environmental and forestry) clearances. Further, charging of '[land?] expectation value' by the state governments is becoming a hurdle in project implementation and coal companies are being made to pay huge amounts in this regard adding to the cost of projects over and above the cost of afforestation" (PC, X, 2002, p. 785). Further, "it is important to amend certain provisions of other statutes to overcome hurdles in the way of private mining in notified tribal areas. The procedures for environmental clearance also need to be greatly simplified so that potential investors have to deal with clear and transparent rules" (PC, X, 2002, p. 787).

The NITI Aayog replaced the Planning Commission on 1 January 2015. Some of the earlier planning functions that was carried out the PC have now moved to the Prime Minister's Office and line ministries such as Coal and Power.

I.2 Roles of special expert committees:

In addition to relying on the Planning Commission, GoI has set up several expert Committees for conducting studies and providing recommendations for the energy sector, most of them overseen by the PC. The seven of the more important ones set up in the 50-year period from 1963 to 2013 are shown in Table 1 below. We only present a brief overview as this ground has been covered in several previous reviews, such as Sankar (1985), (Parikh and Parikh, 1992), Sengupta (1992, 1993), Chikkatur and Chakravarty (2008), and Mathai (2013).

Table 1

Energy planning, as does developmental planning, predates independence. There was a power and fuel sub-committee of the National Planning Committee (1938-45) that made a survey of resources available for power generation (Chikkatur and Chakravarty, 2008). However, the first serious effort was by the Energy Survey Committee created by the Ministry of Irrigation and Power in 1963 with a mandate "to study present and prospective (to 1980-81) demand and supplies of energy." Its recommendations were not considered useful, because it had relied mainly on overseas professionals (Sankar, 1985).

The Fuel Policy Committee (FPC) was appointed by the Department of Mines and Metals in 1970 to undertake a survey of the distribution of fuel resources, study efficiency in their use and estimate demand until 1990-91. Its report came after the first oil shock. It clearly recommended that coal should have the primary role in India's energy sector. It also recommended the continued role of hydroelectric power in the sixth FYP (1980-85) and the exploitation of nuclear power based on the thorium-plutonium cycle no later than the seventh FYP (1985-90). For the first time, it also talked about demand management and renewable energy. (Mathai, 2013). The Government accepted most of the Committee's recommendations but did not fully implement them (Sankar, 1985).

The Working Group on Energy Policy (WGEP) was constituted by the PC in December 1977 to estimate present and perspective energy demand and supplies, to recommend measures for optimum use of energy resources and to outline the national energy policy for the next 5/15 years and longer-term conservation policy. It recognized the reality of the energy crunch and endorsed the long-term importance of alternate sources of energy (Mathai, 2013, p. 94). It also devoted a chapter to rural energy policy. This Report came out on 5 November 1979 during the initial Janata Dal governments.

Almost immediately after the return of Mrs. Indira Gandhi, a new Committee was appointed to look into power sector reform. This was chaired by Mr. V. G. Rajadhyaksha, the former Chairman of Hindustan Unilever, Ltd. The Committee's Report had a longer shelf life than most other Reports and it sought to redress the balance of investments in favour of transmission from the then current emphasis on generation.

Although FPC and WGEP had emphasized the need for integrated energy planning, no formal institutional mechanism had been evolved for examining issues on an integrated basis. In this context, the Advisory Board of Energy (ABE) was set up in 1983 to provide recommendations for the formulation of the seventh plan that was to commence in 1985 (Ramachandra, 2007). The ABE made detailed projections of energy demand in different regions until 2004.

The softening of oil prices between 1985 and 2005 (inflation-adjusted less than $60 a barrel in 2015 $s) also correlated with a hiatus in energy studies and reports in the country. The next big exercise began in 2004 under the chairmanship of Dr. Kirit Parikh, PC Member for Energy. In an earlier paper he was critical of the approached hitherto followed in India. "An integrated approach concerning the energy demand and supply systems can help to identify steps which connect the appropriate primary energy forms with the required useful energy so as to increase the efficiency of the entire energy system. Such an integrated approach has not been followed in India" (Parikh and Parikh, 1992, p. 252). The Integrated Energy Policy Report was a commendable effort that formed an input to the formulation of the eleventh Plan. It recommended "providing clean and convenient 'lifeline' energy to the poor even when they cannot fully pay for it". It too, however, had a limited shelf-life, partly because it too made assertions that were not backed by analysis; for example, it claimed "saving daylight by introducing two time zones in the country can save a lot of energy" (PC, IEP, 2006, p. 85). In fact, of all the options available, dividing the country into two time zones saves the least amount of energy (Ahuja and Sen Gupta, 2012).

We end this discussion with a Report on the mainstreaming of renewables that was initiated by the Planning Commission in 2013 but completed by its successor NITI Aayog in 2015. The Report re-enunciates the principle that an "integrated approach to power sector planning including generation, transmission and distribution" be taken (NITI Aayog, 2015, p. 6). This as we have seen earlier has been the holy grail of India's energy sector, always desired, never achieved. The Report identified several legal, institutional and policy changes that will be needed. The other relevant principles articulated include providing targeted subsidies or incentives to make power purchasers indifferent to the cost between conventional and renewable sources until grid parity is achieved and, giving small-scale distributed renewable generation equal priority as large-scale, centralized renewable generation.

1.3 Historical Energy Trends in India:

We have seen that several good Indian assessments exist, but they have several loose ends and a coherent picture is yet to emerge. They have had limited shelf lives. Their impact on policy-making in the country is questionable. About half a dozen or so big trends (Ahuja and Tatsutani, 2009) have characterized the energy scene in India: increasing consumption, increasing efficiency, increasing cleanliness, diversification of technologies for electricity generation, changes in commercial aspects, and finally a trait that transcends the energy sector--the inordinately long time required for consensus making in the country. We will briefly describe these trends in the context of electricity generation, transport systems and cooking energy systems—the three areas that have garnered the most attention from policy makers.

While still low by global standards, both per capita primary energy and electricity consumptions have increased several folds since independence. These trends are reflected in Figure 3.

Figure 3

A continuing trend is the increasing efficiency observed in energy conversion devices through both fuel changes and technology improvements. Each change in pulverized coal plants from sub-critical to super-critical to ultra-super-critical to advanced-ultra-super-critical was marked by increases in conversion efficiencies. Although the total costs increase, the costs per unit of electricity generated decrease. Locomotives, cars, motorized two-wheelers have all become more efficient than in the past, and so have [improved] cooking stoves. All the devices that run on electricity, such as lights, fans, refrigerators, air-conditioners continue to provide the same or more service with lesser electricity consumption. We anticipate this trend will continue.

The third big trend is increased cleanliness or environmental performance of energy systems. Electrostatic precipitators replaced less effective cyclone filters in coal-fired power plants, and as we have mentioned lead has been removed from petrol. The cars went from having no controls to adopting Euro 1 standards in 2000, which then were tightened progressively. In 2016, major cities have Euro 4 (or Bharat 4) standards and GoI has recently announced skipping Euro 5 standards and adopting Euro 6 standards by 2020. Unfortunately, the increase in the number of vehicles swamps the lower emissions per vehicle and consequently the air quality in major metropolitan cities continues to deteriorate.

The fourth major trend is the diversification in the technologies that produce electricity. At the time of independence, electricity was mainly produced either in hydroelectric stations or in coal-fired power plants. Today in addition we have nuclear power plants, wind generators, solar plants, biomass-fired stations, co-generation, and mini, small and micro hydro stations. The first big technological change was the gradual continual dominance by coal-fired stations over hydro-stations. The sizes of thermal power stations have continually increased from 110 to 220 to 500 to 800 MWs. Future plants are likely to be sized at 1 GW.

There have been big changes in the commercial aspects in the energy sector. Prior to independence most of the energy consumed in the country was non-commercial. Today most (more than 80%) is commercial. Before independence, all electricity was generated in the private sector. After independence, it became almost an exclusive activity of the public sector. We are again moving to a mixed situation where generation has again been opened to the private sector. In addition, in retail sales of energy we have moved gradually from entirely administered prices to largely market-based pricing.

We have seen in this section some of the changes that have taken place in the energy sector. There are also instances where problems persist for a long time and although sensible recommendations are made, the consensus to implement them takes an inordinately long time. Just to give one example, Wallace Edward Tyner (1978, p. 129) quoted from the Fuel Policy Committee Report (1974, pp. 103-4) that "the Government of India is studying the possibility of implementing peak load pricing in India". We have seen the twelfth Plan document still stating in 2012 that the "ability to meet peak loads is critically dependent on introducing time-of-day metering" (PC, XII, 2012, Vol 2, 148).

II. Assessment of Current Status:

2.1 Coal Sector:

Coal dominates India's power sector. Although the installed capacity of coal-fired power plants in FY2016 was 61.3% (Figure 4), they produced more than 75% of the electricity generated. Two major changes have occurred in the coal sector in the last few decades. Prior to the nineteen seventies, most of coal production used to be in the private sector. Coal mines were nationalized and for a few decades almost all production was in the public sector. In the last two decades again the private sector has been allowed into the sector. The second major change is the shift from the original form of mining--underground mines to open cast mines. Despite the Expert Committee on Coal Sector Reform recommendation that the share of underground mining be increased from then about 15% to at least 25% in the next 15 years (Ministry of Coal, 2007), it has continued to drop to below 8% currently.

Figure 4

Relative to other fossil fuels, there are significant deposits of coal in the country. Because of the problems in how reserves and resources are estimated, earlier estimates of how long the coal would last have been revised downwards. Based on recent estimates, Indian coal reserves are about 87 billion tons (metric) out of a total resource inventory of 213 billion tons (IEA 2015). The earlier assumptions used to be that Indian coal would last more than 200 years. At the current rate of consumption, this would last about 140 years. With current push to increase production to 1.5 billion tons in 2020, the current reserves could be used up in 55 years. India is not as rich in mineable coal as many had believed earlier (Sethi, 2016, p. 13). However, for the next two decades, it is clear that coal will continue to dominate the Indian power sector.

The quality of Indian coal is poor and has become poorer over the past decades. The price paid by consumers is not linked to the quality of the coal. Also because of government specified linkages between plants and mines, effectively there is no coal market as such in India (Chikkattur et al, 2009). In 1997, the Ministry of Environment and Forests mandated the use of washed or beneficiated coal of ash content (<34%) for power plants located beyond 1000 km from the mine (later reduced to 500 km), in urban areas, in ecologically sensitive areas and in critically polluted areas. It however put the burden for ensuring this not on the coal supplier but on the coal user (Srikanth, 2016).

Most of the adverse impacts from coal mining result from not ensuring that the lands are restored to their pre-mining status and use, even though for obtaining environmental clearances, the mine would have filed procedures. There is no compliance mechanism in the country. Regarding coal utilization, while the newer plants are built with more stringent controls, the performance of grandfathered old plants leaves a lot to be desired. While newer plants use super-critical technologies it is unlikely that ultra-super-critical or advanced-ultra-super-critical plants would be required given the current opinion of the CEA that no newer coal plants are required, at least until 2027.

2.2 Hydropower:

The first plants for the generation of electricity were hydroelectric stations. By current standards they were small. A 130 kW plant was commissioned in Darjeeling in 1897 and the 4.5 MW Sivansamudram was commissioned in 1902. However, at its peak, after being 45.7% of the installed capacity in the country during the 3rd five-year plan in 1966, it has gradually declined to 19.1% in the twelfth Plan. This is shown in Figure 1. In absolute terms, the hydro installed capacity increased from 4.1 GW to 39.3 GW in the same period (Sharma et al., 2013).

At the inauguration of Bhakra-Nangal in 1963, Nehru had called it the new temple of resurgent India, a symbol of India's progress. In 1954, as he walked around the site of Bhakra-Nangal, he thought that it was the biggest temple and mosque and gurdwara. Later he seemed to have second thoughts. While addressing the Central Board of Irrigation and Power in 1958 he warned of the danger of "suffering from a disease of gigantism", what others have called an edifice complex. He drew attention to "upsets of people moving out and their rehabilitation associated with a big project (Guha, 2005). While problems of resettlement and rehabilitation have occupied national attention, ecological consequences of building large dams have largely been ignored. No ecological value seems to be placed on having a free flowing river all the way to the sea. It is still considered wasteful to allow fresh water to flow to the sea.

Two successive drought years caused Karnataka to close two of its hydro stations in April 2016, one of them at Sivansamudram (Shiva Kumar, 2016). The expectation is that climate change will further exacerbate the natural variability of the Indian monsoon and affect the operation of hydroelectric stations. Raje and Mujumdar have studied the possible impact of climate change on the Hirakud reservoir later in the 21st century. Hirakud project was constructed as a multi-purpose project with the objectives of flood control, municipal water supply, industrial supply, irrigation and power generation in that order. They show that hydropower generation is likely to decrease in most scenarios. However, by adopting an adaptive policy and changing the current rule curves for flood protection, while marginally sacrificing reliability with respect to irrigation and flood control, hydropower reliability and generation can be increased for future scenarios (Raje and Mujumdar, 2010).

In addition to conventional hydropower, Pumped Hydro Storage (PHS) is the only energy storage technology deployed on a Gigawatt scale worldwide. It offers reasonable cycle efficiency, sometimes exceeding 80%. As the most widely adopted bulk electricity storage technology in the world, it has been deployed since 1890s in Alpine regions of Switzerland, Austria and Italy. The development of PHS worldwide remained slow until 1960 when many countries envisioned a dominant role of nuclear power and started installation of PHS plants to complement nuclear power in providing peaking power. However, the growth slowed down in 1990s when nuclear programs stalled in many countries and gas became cheap making open cycle gas turbines competitive for meeting peaking loads. With the increasing share of intermittent renewable energy sources like wind and solar in the energy mix, PHS is receiving renewed attention. Fifty-six sites have been identified in India by CEA for the development of pumped hydro schemes with an aggregate installed capacity of 94 GW (Sharma, et al. 2013, p.463). Heide et al (2010) have investigated the design of a possible future European power supply with a very high share of renewables. A 100% wind plus solar scenario requires energy storage anywhere between 1.5-1.8 times the monthly load. As long as fossil and/or nuclear power provide base-load and remain in the generation mix, the need for storage energy becomes smaller.

2.3 Nuclear Power:

Although nuclear power has played a marginal role in meeting India's electricity demand (its installed capacity has generally been less 3% of the total installed capacity in the country), it receives a disproportionate amount of attention and resources because of its real or claimed overlap with strategic weapons programme. The nuclear establishment has always sought a bigger role for nuclear in the power sector, but for various reasons, fallen short of the targets it sets for itself. As shown below in Figure 5, Nuclear power currently accounts for 1.9% of the total installed capacity in the country.

Figure 5

Though the under-delivery by its own expectations is what stands out, theachievements of the programme made under trying circumstances are impressive. After two decades of international cooperation, the programme struggled for the next three decades under technology denial regimes to construct 18 plants and add 5 GWs of capacity. After initial teething troubles, these plants have operated safely, with high plant load factors, and without any major accidents. With the exception of the recent protests in Kudankulam after Fukushima, the programme has avoided the large-scale protests that have been witnessed in some developed countries against nuclear power, and against large hydropower dams in India.

Even before there were civilian nuclear power plants anywhere in the world, Homi Bhabha in 1954 had formulated a sequential three-stage strategy for nuclear power development in the country, given our relative shortage of uranium and abundance of thorium. Each stage uses a different kind of reactor to produce electricity. The first stage uses natural uranium in pressurized heavy water reactors (PHWR). Plutonium and depleted uranium processed from the spent fuel in these reactors become inputs, along with thorium, to the fast breeder reactors in the second stage. This in turn produces U-233, which together with thorium become inputs to breeders in Stage 3.

The three-stage programme remains the official policy of the atomic energy establishment. Although India is the unquestioned leader in fast breeder technology, several recent developments warrant the re-examination of the three stage programme. Some of these developments are the removal of sanctions and the consequent availability of both natural and enriched uranium fuel for PHWRs and LWRs respectively, and the increased cost, complexity and unforgiving nature of the liquid sodium fast breeder reactors. An awe of Homi Bhabha, self-interest, and having been burnt by the denial regime for long, combine for the establishment to continue to profess its public allegiance to the three-stage programme. In actuality, it is hedging its bets by continuing to work on the development of an advanced heavy water reactor (AHWR), which uses light water as a coolant and heavy water as a moderator (Bhardwaj, 2013). By utilizing thorium in an alternative design, the need for having to go through stage 2 is avoided.

Besides public fears of catastrophic accidents, what works against more rapid diffusion of nuclear power is its higher cost. “The DAE has never published any comprehensive analysis of the economics of nuclear power in India. The DAE is perhaps being intentionally vague and evasive because they know that a realistic, conventional costing will show nuclear electricity to be still more expensive than its alternatives” (Gopalakrishnan, 2002, p. 390). For these reasons, and because of the difficulty in finding new sites (most new reactors are being constructed at existing sites), the share of nuclear power will continue to remain very low in the coming five or more decades (Tongia and Arunachalam, 1998). It is probable that nuclear power as a percent of total installed capacity will hover between 2 and 3%. However, under imminent climate change, nuclear power could play an increased role if cheap and scalable storage technologies fail to materialize. In this context, some studies highlight the role that nuclear power can play as a mature and reliable source of electricity. (Sukhatme 2012, Grover, 2013)

2.4 Review of modelling efforts:

Although electricity production accounted for 38% of the primary energy use in India in 2010, the energy sector as a whole is responsible for 77% of India’s greenhouse gas emissions. Dubash et al., (2015) have conducted a review of seven recent modelling studies (shown in Table 2) that explore the country’s energy and emissions futures. This section and the next are based largely on that review.

In the energy sector, GoI tries to achieve multiple objectives: energy for economic growth, energy security, inclusive growth, local and global environmental goals (including climate change). Because some models represent the energy sector in detail (bottom-up models in Table 2), whereas others capture economy-wide interactions (top-down models in Table 2), no one model is able to inform multiple-objective based decision-making. While all models more or less cover adequately energy supply and CO_2 emissions, energy demand, energy security, inclusive growth (distributive effects), local environmental effects, CO_2 emissions intensity and costs are unevenly covered across models. The thin treatment of non-commercial biomass by all the models neglects an important part of the demand by India's poorest citizens. The lack of attention to local environmental effects is a consequence of the differing spatial and temporal scales in the models. In addition, none of the models presents a sensitivity analysis.

Table 2

There is broad agreement across models that electricity generation will increase three- to four-fold in the reference scenarios between 2012 and 2030 Dubash et al., (2015). However, India's future electricity generation mix in the different models indicates widely divergent projections (Table 3). The ranges for gas and nuclear in the policy scenarios (a factor of 14) are too wide to be meaningful for policy purposes. The low end projected for coal (43%) for policy scenarios is highly unlikely as it would entail mothballing plants that are under construction today. The largest uncertainties relate to the growth rates of renewable energy. Even the upper ranges are more moderate than the recently announced government targets.

Table 3

Dubash et al. (2015, p. 16) recommend that "over time, modelling capacity should be extended to analyze social and environmental outcomes". In a more recent study, Kanitkar (2016) found that for a given set of assumptions, constraints and structural linkages, the results for a range of scenarios show that the impact of a high deployment of renewable energy on the economy and on incomes and income distribution are negative. That is, a higher deployment of renewable energy sources leads to a reduction in GDP and household incomes. Other modellers need to confirm these results, which depend on the relative pricing of fuels. Chikkatur and Chakravarty (2008) have stressed the need for a new Integrated Modelling Institution in India.

Because of the number and the heroic nature of assumptions invariably involved in all modelling efforts, most modellers themselves downplay the numerical results obtained by their models. For example, Paltsev and Reilly (2007, p. 21) have written: "Given the many assumptions that are necessary to model national and global economic systems, the precise numerical results are not as important as the insights into the general direction of changes in the economy, components of the energy system, and the approximate magnitude of price effects seen under alternative assumptions".

2.5 Import Dependence:

Dubash et al. (2015) have summarized the results from the 5 different modelling studies on fossil fuel import dependence. Studies seem to converge in a narrow range that coal use in 2032 would be 2.5-3.0 times the coal use in 2012. Even in the policy driven scenarios, most studies suggest coal use will at least double (see Table 4). There is far greater divergence between studies in oil (a factor of 2) and gas (a factor of 1.5) projections in the reference than either for coal or in the policy cases. The variation in gas is driven by different assumptions regarding its penetration in the electricity mix. Most studies predict a greater use of gas in policy scenarios than in reference cases.

Table 4

The implication of these patterns of fossil-fuel growth is that the overall fossil fuel import dependence increases to more than 50% in the reference cases and drops significantly over current dependence in the policy cases. In the reference case coal imports rise from the current 26% to between 40-52%, but decline to less than 21% in the policy scenarios. Oil imports uniformly increase and remain high across all scenarios.

2.6 The relatively high cost of commercial energy in India:

The characterization that a third of our people lack access to electricity hides a multitude of ills. At present, as percent, more villages are electrified than are households. Often, even when a wire reaches a village, electricity does not. Even when electricity is available, people have limited ability to afford it. As Sethi (2016, p. 13) has written—"Indians pay the highest prices in the world, when adjusted for capacity to pay, for all primary and secondary forms of commercial energy". He has also identified four reasons why this is so, high taxes, high coal prices, higher capital outlays, and unjustifiably high profit margins by those engaged in the electricity value chain, other than the electricity distribution companies (DisComs).

The total direct taxes imposed on the energy sector far exceed the subsidies on primary and secondary energy. As much as 15% of the central government revenue and about 20% of the combined revenue of the state governments are derived from energy taxes alone. Secondly, at the burner tip, Indian coal has attained the distinction of being the costliest in the world in terms of heat content corrected for coal quality. Thirdly, capital outlays on conventional power and transmission system are about 35% higher in India than comparable infrastructure elsewhere, and fourthly, despite being grossly inefficient by global standards, both public and private sector companies get the highest regulated returns in the world (Sethi, 2016, et passim, pp. 13-15).

As a consequence, the bulk power in India is at least 30% costlier than it should be, and is among the highest in the world (Sethi, 2016, p. 14). Since bulk power accounts for about 80% of the cost of supplying power, and the DisComs when aggregated together, barely recover 80% of the cost of supply, two consequences ensue—Indian consumers' average tariff is easily the highest in the world (when corrected for capacity to pay) and the DisComs on the aggregate do not have enough revenue to even meet their operational expenses.

Sethi believes that raising tariffs is not the answer. On the contrary, "India would need to cut prices of primary and secondary energy relative to income levels for those with inadequate access to even lifeline levels of commercial energy consumption" (Sethi 2016, p. 13). Only then could a meaningful improvement be made in the quality of life for India's poor.

This problem is acute in the cooking sector that contributes a significant share of the energy use of the poorer 80% of the population. Biomass like dung, firewood and crop residue are the primary sources of fuel for the cooking for this segment. Cleaner commercial fuels are either unaffordable or have an inadequate distribution network in most parts of the country. Incomplete and inefficient combustion of biomass contributes to the high disease burden from indoor air pollution that India suffers (Smith, 2012).

III. Powering a cleaner future

3.1 Renewables are the future of the power sector:

In 2015, the Indian Government announced ambitious goals for expansion of renewables by 2022: 100 GW of solar power, 60 GW of wind, 10 GW of biomass and 5 GW of small hydro. In its Intended Nationally Determined Contributions at the UNFCCC Conference of Parties, Paris 2015, India also set a 2030 target of 40% renewables capacity in electricity generation and 30%-33% reduction in the emissions intensity of GDP. The 2030 target will require about 300 GW of renewables.

India has been an early pioneer in wind energy with targeted policies to accelerate the penetration of wind in the last three decades. Consequently, India also has a large manufacturing and R&D base in wind turbines. India currently has 28 GW of wind power, bulk of it in the states of Tamil Nadu, Karnataka, Maharashtra, Gujarat and Rajasthan. Electricity from wind is often cheaper than a new coal plant in many parts of the country. In fact, wind is bigger contributor to power generation than nuclear power.

Figure 6

The National Solar Mission launched in 2010 with the ambitious target of a deployment of 20 GW of solar by 2022. In 2015, this target was scaled up by a factor of five. Solar photovoltaics (Solar PV) have seen a dramatic decline in prices in the last three decades and currently rank among the cheapest sources of electricity worldwide. The cheapest bid in India in 2017 for utility scale solar was Rs 3.30 per KWh, a price that is comparable to new wind- or coal-powered electricity in India (Aggarwal and Bhaskar, 2017[1,2]). Rooftop solar is about 1.5-2 times the prices of utility solar but it comes with the added benefit of being a distributed energy source near the load.

Solar and wind are likely to get cheaper over the next decades as improvements in technology and in manufacturing processes continue. The cost of lithium battery storage has also been declining rapidly. Rooftop solar in combination with battery storage is already at grid parity in some markets like Hawaii and Australia. It is likely that some Indian consumer segments will reach grid parity in a decade. Despite such explosive growth, renewables are unlikely to exceed 15%-20% of the energy share in the electricity sector.

Coal continues to be India's most reliable source of electricity although it is unlikely to stay the cheapest. In recent power auctions for renewable energy, levelized costs of wind and solar PV are lower than the cost of power from many new coal power plants in operation. India has sufficient coal reserves for the next few decades. Coal will continue to be the backbone of the Indian electricity sector, at least for the next 15-20 years, though its share in generation capacity and energy generated will reduce over time. Coal generation has to be made cleaner and more environment-friendly, and the move to supercritical coal is a step in the right direction. Natural gas is a cleaner source of electricity and has the added benefit of being a flexible backup for intermittent renewables. India will continue to import expensive natural gas though its use might be restricted to peaking and flexible backup.

The proposed rapid growth of renewables throw up several financial, technological, regulatory and coordination challenges which could potentially hobble rapid expansion unless careful planning and execution protocols are put in place. We will discuss these shortly.

3.2 Environmental impacts of energy use

India currently has ten of the twenty most polluted cities in the world (WHO, 2016). Environmental degradation, pollution, displacement caused by land acquisition for mines and other mega-projects, etc. have led to many civic awareness movements. Civic society, academia, the political process, the state and the judiciary have been mindful of these and they have responded with a slow and unsteady progress towards laws and regulations for environmental protection and restoration.

The recent past has seen several regulations that attempt to clean up the extraction and energy transformation industries like mining, electricity generation and transportation. Unfortunately, in many cases the implementation and administration of the laws have been spotty.

The most notable recent pollution control regulations that affect the electricity sector are for sulphur oxides, nitrous oxides, particulate matter, mercury and water use that were promulgated in December 2015. These regulations were a political response to civic action and research that measured and quantified the human cost of pollution from coal (Coal Kills, 2013). Other regulations like the Clean Environment Cess on coal and the Renewable Purchase Obligations are directed towards reducing the emissions intensity of electricity generation and promoting penetration of clean technologies. The Clean Environment Cess of Rs 400 per ton of coal is a backdoor carbon tax that is supposed to pay for various clean energy projects. The establishment of the Bureau of Energy Efficiency and the promulgation of Star Rating standards for appliance efficiency, the promotion of LED lighting and similar policies have led to energy efficiency becoming embedded in civic consciousness.

Vehicular emissions, burning of crop residues and garbage, and industries are among the major contributors to air pollution. Delhi saw hazardous levels of pollution in October and November of 2016. Other cities in India might have similar or higher levels of pollution but these are unlikely to be reported as these cities often do not have sufficient number of pollution measuring stations. While there is a lot of public awareness on the harmful impacts of air pollution, pollution control regulations are often piece-meal, and poorly thought through. One reason for this is the absence of research studies with a long time horizon that have studied the pollutants and attributed these to different economic activities.

Perhaps the most important source of pollution related health impacts is indoor air pollution from cooking using biomass. The share of Indian households who use solid fuels/biomass for cooking has been stubbornly high despite the economic growth India has seen recently. Clean commercial fuels remain expensive and supply networks in rural India are weak or non-existent. Efficient and clean-burning cook-stoves do not exist at scale despite almost five decades of research and policies to promote them. It is likely that a combination of education and awareness, economic growth and targeted subsidies and direct benefits transfer will eventually get rid of this source of indoor air pollution. Until then, the existence of inefficient and polluting biomass based cooking is a severe indictment of the Indian development story. Increased awareness of the environmental impacts of pollution and climate change have led to the formation of a coalition of civic society, NGOs and concerned government officials which also lead the country in the direction of cleaner energy systems.

3.3 Managing change in technological and human systems

The rapid growth of renewables in the Indian electricity sector will be a significant challenge. In this section we will try to unpack some of these challenges and propose possible solutions.

Wind and solar are front-loaded with significant up-front capital investment during installation, but come with zero fuel and low maintenance costs. The capital payback period is likely to be as long as any other energy investment. These are very different from fossil fuel plants in that they are primarily financial investments and the returns depend quite significantly on the cost of capital (the interest rate) and the tariff. Therefore, the primary concern will be that of availability of capital at low interest rates. Approximately, 8 trillion rupees will be required by 2022 for the stated renewable expansion goal to succeed.

The second major capital investment is required in transmission corridors to connect the centres of renewable power with load centres and to move power around in order to spatially even out the variability of renewable power. Various estimates suggest about 1-1.5 trillion rupees for this expansion. Significant advance planning and coordination is required to construct the transmission network for various renewable power projects, as it usually takes longer for the construction of the transmission line than for the power project.

The Indian electricity network, as currently managed, is robust but unreliable and inflexible. The robustness and inflexibility of the system come from the fact that it mostly manages dispatchable base-load generators, and peak power is met by a combination of hydro, load following and power cuts. There is low reliability as power supply is not guaranteed.

Renewables, on the other hand, are power sources with high variability with some statistical predictability but they are not as dispatchable as fossil-fuel generators. Managing a significant share of renewables requires accurate load forecasting, and statistically good forecast of renewable power. This calls for the use of real time data, sophisticated statistical algorithms and a good numerical weather forecast model. Flexible scheduling of the rest of the generators and a combination of demand response and ancillary services have to provide the flexibility in order to balance the inherent variability of renewables. Base-load plants such as coal have to be retrofitted to provide some ramping and load-following services. Pumped hydro and grid scale battery storage will also be required. Innovative demand response measures like air conditioners and refrigerators with thermal storage, and time of the day pricing will be required in the absence of a lot of cheap natural gas generators to provide system flexibility. Innovative power contracts will also be required. Consider, for example, a contract that guarantees a fixed amount of power in a certain window of time. Electric vehicle owners could be counter-parties for such contracts.

All of these require significant training or retraining of skilled personnel. Grid and dispatch management will evolve from the current mostly manual mode to an automated mode with significantly more data and computer infrastructure requirements. There will be need also for constant modelling and scenario building exercises to anticipate and prepare for low predictability events.

The transition of the electricity sector from the current regime to a flexible and responsive regime will also require a lot of innovation in the regulatory and policy arena. This will require a combination of openness, knowledge and learning of rapidly evolving energy and energy control systems and learning and scenario building from modelling exercises.

3.4 Built environment and efficient energy use

We focus on the electricity sector because it is responsible for 38% of the total primary energy used in India. With economic growth, a significant share of energy will be consumed in buildings (household sector and services) and in transportation. In more developed economies, the share of buildings and transportation in total energy consumption is about 60%-70%.

The built environment refers to the artificial landscape of human activities: buildings, civic infrastructure, public utilities and transportation infrastructure. Inhabitants of the United States and parts of Europe have comparable standards of living but they differ significantly in the energy consumed per inhabitant. To a significant extent, this can be attributed to path dependency and choices made in the design of the built environment. Even in the United States, older cities like New York built in the pre-automobile era are significantly more energy efficient than cities like Atlanta that grew in the automobile era.

As India goes through its urbanization, by 2030 there will be about 0.6 billion urban inhabitants, at least 70 urban agglomerations with a population above a million, where most jobs and economic opportunities will be created. India is expected to add the equivalent of Chicago of built environment every year (McKinsey, 2010). This will be the era of explosive growth and rapid transformation of the built environment all over the country. The infrastructure that is currently being built can be expected to last a few generations. The design and geography of the built environment will influence energy consumption for decades. It is equally important to ensure that environmental impacts are minimized and that climate adaptation and resilience are built into the design.

In the past, the Indian built environment reflected the overwhelming rural character of the country. Most interactions were local in nature and the primary means of transport were human- or animal-powered (cycles, rickshaws and horse- and bullock-carts). Railways were the only means of long distance transport. Even in urban areas, the primary means of transportation were non-motorized. The three colonial metropolises, now called Chennai, Mumbai and Kolkata developed along railway lines that also ran suburban transit trains. This, whether by design or accident, is an early form of what is currently termed "Transit-oriented development (TOD)". Incidentally, these three cities still have the best public transit in India. Hong Kong and Singapore are considered the best examples of TOD in Asia. These cities have very high population density areas connected by fast, frequent and efficient public transit. Indian cities, on the other hand, despite similar levels of population density have transformed from public transit, pedestrian and cyclist friendly spaces to increasingly automobile oriented and automobile dominated spaces. Delhi, despite having India's largest and fastest growing metro system, is still a city dominated by the automobile. The planned city of Chandigarh has the highest vehicle ownership rate in India.

India's urbanization in the next couple of decades provides a great opportunity to plan cities and urban spaces that are pleasant places to live and work in, and efficient from the point of view of energy consumption and transportation. Unfortunately, there is a fear that this opportunity is being lost to the rent-seeking, disorganized and unplanned urbanization being witnessed in India today.

Good planning, better use of technology, right policies and regulations with proper implementation can still retrieve the situation. Urban India needs integrated land use and transportation planning. The first and foremost requirement is a planning and development process that is long-term and requires coordination across multiple sectors and departments. This needs to be supported by "robust institutional framework and regulatory and planning tools that facilitate regional collaboration and cross-sector cooperation" (Suzuki, 2013). It is also very important to give a lot of attention to detail (especially in design) and to get the timing right. We list some of the salient points for successful TOD below:

> a. Every growing urban area should have a strategic long-term growth plan or master plan with transit integrated into the planning process and the urban fabric. The plan should have the vision to imagine how proper land use and mass transit can lead to satisfying and socially inclusive urban spaces that serve the needs of the community, and can be market friendly and fiscally prudent.
>
> b. The success of TOD depends significantly on the ability of large and complex institutions at the metropolitan and regional level to coordinate and cooperate on the execution of large and complex plans. A planning and development institution with the right regulatory, planning and legal basis should be entrusted with developing the plan and coordinate with different departments and agencies to execute it. The entire process should be open and should include public participation.

Transit oriented development leads to energy efficient, high density, mixed-use (residential, commercial and service sector) urbanization along mass transit corridors, thereby minimizing energy consumption in civic services and transportation. Walker 2012 best conveys the process of TOD:

> "The land planners do a long-range sketch of urban structure and this goes up on the wall in the transit planner's office, so that it guides daily thinking as well as long-range planning. The transit planner does a similar sketch of a long-range transit network, and this goes up on the wall in the land-use planner's office. That way, when development [projects]are being approved, the short-term land-use planner can check whether the location is a good or bad one for transit and can judge developments accordingly. Meanwhile, as the long-term land-use planners stare at the transit map, they have new ideas for how to build communities around the proposed line and stations."

The other equally important aspect of the built environment is efficient energy use in buildings. Indeed, one should start with building technologies and materials that are energy efficient to begin with. Energy use in buildings is primarily for cooking, space heating and cooling, devices and appliances. Besides, energy consumed in the commercial and service sector is also considered part of energy use in the building sector. According to a study in 2010 (McKinsey, 2010) about 70%-80% of India's buildings were yet to be built. There are many opportunities to make each energy use segment in buildings more efficient, and to integrate distributed renewable sources of energy in the built environment. These efforts ensure that the built environment minimizes its climate footprint. It is equally important that the built environment be adaptable to potential climate change impacts.

The Jawaharlal Nehru National Urban Renewal Mission (JNNURM), the National Mission for Sustainable Habitat (NMSH), the National Urban Transport Policy (NUTP), and the recently launched Smart Cities Mission (SCM) are policy, regulatory and investment initiatives launched by the GoI to address some of the issues listed above.

The JNNURM was the first attempt by the GoI to strengthen urban infrastructure and governance, and invest in basic urban design like city development plans, roads and public transit, sewerage, footpaths and pedestrian walkways, e-governance, etc. The JNNURM ran from 2005 to 2014 in 67 cities and invested about 0.6 trillion rupees. The JNNURM was a very modest beginning in the path towards TOD. The NMSH attempts to address the issue of environmental and climate change sustainability of urban habitation while the NUTP is perhaps the first step in the direction of integrated transport planning and TOD. The SCM is the most recent iteration of these ideas. A hundred cities have been selected for this mission. The mission aims to provide basic infrastructure, sustainable solutions and quality of life using better institutions leveraged with cutting edge technology like IT and "internet of things".

While steps are being taken in the right direction, we have a long way to go in order to create institutional frameworks and empower bodies that make transit oriented sustainable urbanization with energy efficient and environmentally sustainable buildings a reality.

3.5 Key energy technologies of the future

Here we focus on the key technological pathways that India has to develop and deploy for a successful transition to a cleaner energy system. While some of these are fairly well-developed and mature technologies where deployment is the main uncertainty, there are others where considerable opportunities for innovation and R&D exist.

The energy technologies can be categorized under the headings of 1. Renewable energy technologies 2. Mobility technologies, 3. Autonomous and interconnected technologies

3.5.1. Renewable energy technologies

Renewable energy technologies have made significant progress in the last few decades and their costs have declined significantly. In many parts of the world including India the costs of electricity from solar PV and wind have become cheaper than the cost of power from fossil fuel sources like coal or gas.

The cost of solar photovoltaics (crystalline or amorphous silicon) has declined at a rate of approximately 20-25% per doubling of installed capacity. In the period 2010-2015, the global average cost of solar PV fell by 60% (IRENA 2016) and it is projected to fall by another 60% in the period 2015-2025. This fall in costs is a combination of increasing efficiency (20-25% for silicon), efficient manufacturing technologies for solar PV modules, and cost reduction in the inverter and balance of systems. There has also been a lot of research in new materials and structures like organic cells, perovskites and multi-junction cells for concentrating solar PV which promise to increase conversion efficiency and lower costs.

Figure 7

Wind energy, while a mature technology, is still seeing progress in terms of a decrease in costs of about 12% per doubling. The latest wind turbines have a wider range of operations increasing their availability factor. This has been achieved primarily through an increase in the size of the blades (which improves the aerodynamic efficiency) and the height of the turbine while reducing the weight of the blade through the use of innovative materials and extensive computer aided design and simulations. Today's turbines can also provide other ancillary services to the grid like frequency stabilization. As the height of the wind turbine increases there has been significant research into developing cost effective towers that minimize material use. Off-shore wind is still a developing technology offering a lot of potential for innovation, especially in foundations and moorings [Yaramasu et al, 2015].

Renewable technologies, by their very nature, are intermittent sources of energy. Electricity dispatch, on the other hand, is a market that is required to always balance supply and demand. Renewable power forecasting, generation and demand side management and storage are key technologies that can aid in increasing the share of renewable sources of energy.

3.5.2. Mobility technologies

Transportation is currently the second largest user of fossil fuels, right behind electricity generation. Fuels derived from petroleum have excellent energy density, stability and ease of storage. For electric vehicles to compete with fossil fuel technologies, battery technology is the most important driver.

Battery storage has developed rapidly in the last two decades, cost per kilowatt hour have declined significantly while the density of energy storage has increased significantly. Improvements in Lithium ion battery technologies have been primarily responsible for this.

Automobile companies like Toyota and Honda gave the key push to electric vehicles by developing hybrid electric vehicles that use both an internal combustion engine as well as a motor, and a small battery this is charged by the engine and regenerative braking. Companies like Nissan, General Motors and, most importantly, Tesla have invested in developing fully electric vehicles. Tesla, in particular, has played a significant role in pushing down the cost of Lithium batteries to approximately $200/kWh. This is expected to decline to $100/kWh by 2020. Tesla is also one of the biggest battery manufacturers in the world.

Electric vehicles reached total cumulative sales of 1.2 million worldwide in 2016 and are expected to reach 150 million by 2030 (IEA Global EV Outlook 2016). Electric scooters and other two wheelers have reached 30 million in annual sales in 2016, almost all of it in China. The global stock of electric buses was 173,000 in 2015, also primarily due to China.

In India, we expect electric two wheelers to play a bigger role in the future provided the right incentives are available. Electric two wheelers are also unlikely to require an extensive change of the electricity distribution network. Electrification of the public bus transit system in urban India can also be a significant step in reducing urban air pollution by replacing polluting diesel buses by zero emission vehicles. The National Electric Mobility Mission Plan (NEMMP) aims to reach 6-7 million electric vehicle stock by 2020, and the Indian government is also considering 100% electric vehicles sales by 2030 (Hindu Business Line, 2016). It remains to be seen if the right policies to incentivize these goals will be put in place soon. India, given the strength in automobiles and two wheelers, could become a big player in the electric mobility segment.

The other important mobility technologies that India should invest in are neither futuristic nor particularly high-tech: These are high speed rail, metro and light rail public transit. These require significant public capital investments and a long planning horizon. India is densely populated with many major cities which are less than 500 km from each other. Consequently, India is particularly well suited for a high speed rail network. Metro and light rail are an integral part of transit oriented development.

3.5.3 Autonomous and interconnected technologies

The trend in technology development is towards devices that will autonomous and can operate without any human control or intervention. These devices have sensors to monitor the external environment, and sophisticated algorithms to respond to these stimuli. Some algorithms that are based on Artificial Intelligence or Neural Networks can be trained on data and can also learn from experience. These devices are often faster, cheaper and more efficient that human controlled devices.

Autonomous or self-driving cars have already reached a level of maturity which enabled a taxi company in Singapore to offer this service on selected routes. Autonomous vehicles can save fuel through smoother driving, driving in closely packed convoys on highways. Autonomous cars convert mobility into a service that is available when needed leading to efficient use of resources like materials and road infrastructure. The most important hurdle in the rapid expansion of autonomous cars pertains to uncertainties surrounding legal liabilities in the case of accidents which are bound to happen.

Technologies like smart grids or the Internet of Things (IoT) consist of devices that can communicate with each other for optimum performance. For example, demand response in electricity grids can be automated using devices like air-conditioners, refrigerators and other space cooling and heating systems that communicate with the grid operator and can respond to price signals and other incentives like time of day pricing. Similarly, a connected electric car can provide energy storage as a service to the grid. A "virtual power plant" is a collection of distributed sources and connected load controlled by software that provides both power as well as demand response. These devices and technologies also help increase the penetration of renewable technologies.

IV. Fostering innovation in the energy sector

4.1 The role of universities and research laboratories

Independent India has given a lot of importance to Universities and centres of higher education and research. Since independence, there has been a manifold expansion of Universities and colleges. The state also started specialized research and educational institutes, such as the Indian Institutes of Technology, Indian Institutes of Management, Indian Institutes of Scientific Education and Research, the Indian Statistical Institutes, Tata Institute of Fundamental Research, Central Universities (JNU, HCU etc.), and scientific research laboratories of the Council of Scientific and Industrial Research (CSIR) , the Department of Atomic Energy (DAE), the Defence Research and Development Organization (DRDO), the Indian Council of Agricultural Research (ICAR) and Indian Space Research Organization (ISRO).

The success of these organizations in promoting research and education and in helping translate the research to products and technologies that improve lives has been quite mixed. CSIR, IIT, IISER and the IISc rank in the top 200 of the world's research institutions (Nature Index 2015). Some organizations like ISRO have been very successful in developing space technology for the country. All is not well though. In a special report on "Science in India", the journal Nature noted that, "Indian research is hampered by stifling bureaucracy, poor-quality education at most universities and insufficient funding. Successive governments have pledged to increase support for research and development to 2% of India's gross domestic product (GDP), but it has remained static at less than 0.9% of GDP since 2005" (Nature 2015).

One major complaint about the university system in India is that it consists of a few centres of relative excellence while most are worse than the average university in the

West. There is acute shortage of good teachers and facilities at institutions devoted to teaching and training. Research establishments often see a shortage of equipment and bureaucratic delays in procuring them. India lags behind significantly on indicators of like researchers per thousand people, patents per thousand people, etc. Another major lacuna is the lack of an ecosystem that takes research and innovation out of academia and converts them to products via academia-industry tie-ups and start-ups.

These issues are currently being tackled. Research funding has steadily gone up over the last decade and better systems of proposal evaluations and grant making have been put in place. International collaborations with American, Australian, British and European institutions and research agencies have been encouraged. One such promising collaboration is SERIIUS, the Solar Energy Research Institute for India and the United States, a joint effort between many Indian and American Universities and research laboratories to target research in solar power (Nature, 2015). Academia-industry joint efforts and start-up incubators have been set up in many institutions to accelerate the pace of development from research and innovation to products. The suburb of Powai has become Mumbai’s Silicon Valley as a large number of start-ups that started nearby at IIT have moved there. A lot more needs to be done to reach the levels of Germany and the USA, the best examples of countries that have pioneered the art of taking research and innovation from the laboratory to the marketplace.

4.2 Capacity building for the long-term

India is the world’s largest and arguably also the most complex democracy. The decision-making processes that determine the short-term and long-term trajectory of the country are the result of many social and political compromises and, therefore, often myopic and short-sighted. It is in the interest of every nation to invest in some institutions that can take a long-term view and are insulated from the short-term political decision making process. National research and policy-making institutions, think tanks, universities, development planning boards, research grant making organizations, etc., could perform this role.

To a limited extent, the NITI Aayog (formerly, the Planning Commission), ISRO, BARC, some city development agencies and other institutions play this role in India. One is hard-pressed to find enough such institutions that straddle the difficult overlap zone of open-ended research, technology development, policy-making and long-term socio-economic prognostication. This is especially true for institutions in policy-making and long-term planning; these either do not exist, or have been subverted to serve special interests. This is an exceptional gap for a large and complex country like India.

A comparison with the USA is apt. The USA has several national laboratories and scientific research organizations (similar to CSIR in India) with ample budgets and long time horizons. The National Oceanic and Atmospheric Administration (NOAA), the National Renewable Energy Laboratory (NREL), the Energy Information Agency (EIA), the Advanced Research Projects Agency-Energy (ARPA-E) etc. to name a few. NOAA and NREL monitor and measure climate change, wind speeds, etc., and also develop technologies/models to harness wind and solar power and predict climate change. The EIA collects all energy related data, develops draft policies and regulations, and runs models to project different energy use scenarios and implications of policies in the energy sector. ARPA-E funds R&D in high-risk energy technologies. The USA also has many private think tanks and NGOs like the Ford Foundation, the Brookings Institution, the Natural Resources Defence Council, etc., that work with a long time horizon and combine research, policy-making, grant making and advocacy.

Similar institutions are needed if India is to make a successful transition to cleaner energy systems. We list areas in which we need these institutions and their expected characteristics below:

a. **Centre for Energy data and modelling**: A centre is required that collects all energy data mandated by law, and develops and maintains energy models of the country with sufficient geographical and temporal detail for use in scenario making, policy analysis and energy projections. Models and documents should be open and transparent, and subject to the Right to Information Act. Energy and resource data can also be open while taking into consideration privacy and competitiveness (Chikkatur and Chakravarty, 2008). The EIA would be a good model for this.

b. **Institute for Environment data, research and climate modelling**: There is need for a single centre to collect environmental, climate and pollution data, to analyze and model impacts, and draft policy recommendations and regulations. Long-term climate change impacts should also be modelled and studied. Models and documents should be open and transparent, and subject to Right to Information Act. This institution can be modelled on the NOAA.
c. **Centres for Urban planning**: Integrated transit and city planning and implementation institutions with requisite legal, policy and regulatory support are needed for all large urban agglomerations. The Urban Redevelopment Authority of Singapore is an inspiring model for these institutions.
d. **Agency for Funding Advanced Energy Technology Research**: A special agency to fund innovative research and product deployment in the energy sector. This institution could be modelled on ARPA-E.

4.3 Energy, Economy, and Climate Models:

India’s complex energy challenges require the interaction of several stakeholders in different domains, such as resource extraction, energy transformation technologies, energy transportation, transmission and distribution companies, the different consumption sectors (residential, industrial and commercial), regulatory and policy-making bodies, etc. As mentioned in the previous section, analysing these issues requires an institution with the mandate of collection and analysis of energy data, modelling of country’s energy system along with its interplay with the economy, environmental and climate impacts. India is currently suffering from the environmental impacts of energy extraction and use and witnessing a growing carbon footprint of its energy sector. In this section, we discuss the proposed energy modelling and research institution (Chikkatur and Chakravarty, 2008).

a. The proposed energy research institution should be mandated by law to collect energy data and release it to the public in usable and open data formats. There should be a legal reporting requirement for all energy-related data. The institution should archive all past energy and economic data and make them publicly available. Currently, energy supply and consumption data are available to researchers and the public from several Government sources but with variable quality and coverage (Prayas, 2014).

b. The institution should develop and maintain multiple energy-economy models depending on scope, scale, level of detail and time horizon. For example, the institution should release reports for weekly, quarterly, annual forecasts and 30-year time horizon studies. These should integrate environmental, economic and climate related impacts. The models should be sufficiently rich and detailed to analyze policy and regulatory impacts. Geographically detailed studies should also be mandated for state and district level policy and regulatory demands.

c. Over time, the institution should develop global energy-economy-climate models to provide inputs to the Indian government for UNFCCC negotiations.

d. An important role of the institution would be to model multiple future energy technologies scenarios in order to prepare for future regulatory and policy requirements before such scenarios are politically and technologically feasible.

e. The institution will also be mandated to work closely with researchers in academia and other research labs and be open to sponsor or commission research whenever required.

f. All data (subject to privacy and contract laws), studies and models should be fully documented and freely available under a “duty to publish” mandate and subject to the Right to Information Act.

4.4 Development and deployment of new technologies

The path from research and innovation in laboratories and universities to development and deployment of products and technologies that make a meaningful difference to people's lives is a challenge that is often more difficult than getting the idea that led to the research in the first place. This is the D&D part of RD&D (research, development and deployment).

The scorecard for RD&D in CSIR, DAE, DRDO, ICAR and ISRO is good but the development and deployment are primarily for meeting in-house demand. The record of research in the IITs, IISc and other Universities translating to product and technology development needs improvement. A majority of research and technology development that happens in the country is inside large research laboratories of Indian and multinational companies like Tata Consultancy Services (TCS), Google, Samsung, General Electric (GE), Texas Instruments (TI), Shell, etc. The pharmaceutical, healthcare, automobile, electronics, telecommunication and software industries are the bright spots in the Indian RD&D landscape (IBEF Innovation and Patents, 2016). Bengaluru ranks fifth in the global top destinations for setting up R&D centres. India is among the world’s top ten R&D spenders with an estimated investment in 2016 of 1.2 lakh crores. About 3.7% of global R&D investment will be in India. India spends only 0.9% of GDP in R&D compared to 2.5% for the USA and 2.0% for China.

India has to accelerate the quantum of research and the number of researchers in the country, and the conversion of good research to products that improve life. The first was discussed in a previous section, we devote this section to strategies to improve D&D.

One of the most important improvements that can be done in the country has less to do with RD&D and more to do with enabling start-ups. One of the reasons for the higher innovation levels of the US is a very well developed start-up and venture capital ecosystem. Research ideas with potential are “spun-off” by universities into start-ups that can take more risk. These start-up companies are funded by venture capital firms that acquire an equity share in the companies in exchange for funding high-risk, high-reward ideas. To begin with, universities must be prepared with patent offices and start-up incubators to streamline the process. The regulations governing registration of new companies should be less cumbersome and venture capital sufficient to fund ideas. While there seems to be sufficient venture capital available, the biggest gap in India currently is the un-readiness of universities for this mode of development. The GoI is proactively relaxing cumbersome company registration rules.

A second approach borrows from the successful German model of close collaboration between industry and academia. The German research ecosystem has a lot of diversity spanning universities (Universitäten), universities of applied sciences (Fachhochschulen/Hochschulen für angewandte Wissenschaften), National Academies, the Max Plank Society research institutes (basic research), Helmholtz Association research institutes (for large research projects), Fraunhofer Institutes (applied research for public or private partners) and corporate research. Some of the research is joint work between academia and industry (in Fraunhofer Institutes, for example) which lead to faster development of research ideas. These institutes span the entire spectrum from pure research to joint academia-industry development.

Incidentally, the American research university system initially borrowed heavily from the German original but created a more democratic and flat structure. There is a need to enable stronger industry-academia joint research initiatives in India, following the German model.

The strategies discussed above can be described broadly as those that take ideas to the market faster and spread the risk among many stakeholders. There are some research projects where the risk is too high for market-based actors and the state has to step in as the “venture capital firm of last resort”. There are some research projects where the time line to a marketable technology is too long for most companies and these are also unlikely to progress without the state’s help. Finally, some technologies are too “out of the box” and state funding might be required to get the idea to a “proof of concept” stage before there is sufficient buy-in from universities or industrial R&D. All these examples point to the really important role a properly designed state research funding agency can have to accelerate research development and deployment scenarios. This has been amply recognized in most developed countries and there are specialized funding agencies (besides the regular science funding agencies) that fund these high-risk cases. The best example is the Defence Advanced Research Projects Agency (DARPA) of the U. S. Department of Defence. Stealth fighters, the internet, GPS, unmanned aerial vehicles (drones), infra-red cameras, machine translation, have all come out of DARPA projects (DARPA, 2015).

The Advanced Research Projects Agency-Energy (ARPA-E) of the U. S. Department of Energy follows the same model. It was set up in 2009 following the US National Academies report to the US Congress, “*Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*” which recommended the establishment of an Advanced Research Projects Agency modelled on DARPA. The stated goal is “The ARPA-E advances high-potential, high-impact energy technologies that are too early for private-sector investment. ARPA-E awardees are unique because they are developing entirely new ways to generate, store, and use energy.” In seven years, ARPA-E funded $1.3 billion in 30 different themes that have lead to 1104 papers, 101 patents, 36 companies and has raised $1.2 billion in private investments (ARPA-E, 2016). ARPA-E has invested in a diversified portfolio of battery technologies, sensors, electric grid management technologies, power electronics, solar cells, LEDs, wind turbine technologies, energy efficiency, and cooling technologies.

The Technology, Information, Forecasting and Assessment Council (TIFAC) was set up under the Department of Science and Technology to perform a similar role but it does not award significant research grants. The Science and Engineering Research Board also supports this kind of research under the High-Risk High-Reward Research Scheme that is aimed at “supporting proposals that are conceptually new and risky, and if successful, expected to have a paradigm shifting influence on the S&T”. There is a great need to establish an ARPA-E type institution, perhaps as a public-private consortium involving CSIR, ISRO, DAE and DST. It should be given significant institutional and financial resources to fund high-risk high-reward research ideas.

4.5 A new industrial policy

India will consume a massive amount of industrial goods and services as it transforms to a clean energy economy not only because it has to slowly transform out of a fossil-fuel based energy system but also because it will grow at a fast pace and perhaps consume five times as much energy by 2040. India will require about 750 billion rupees per year for the next 25 years (IEA, 2015). India will also urbanize and the urban population will increase by 250 million in 2030 and 350 million in 2040 (IEA, 2015), the stock of buildings will increase four to five times (McKinsey, 2010). This massive and relentless expansion of the Indian economy, especially the energy sector, can be a great opportunity to Indian manufacturing if a significant share of the technologies and products are designed, developed and manufactured in India.

The “Make in India” campaign of the Indian government intends to increase the share of manufacturing in the country’s GDP from the current 16% to 25% by 2022, and a projected 30% by 2040 (IEA, 2015) and to make manufacturing one of the engines of job growth and skilled employment. The proposed expansion of the manufacturing sector is likely to be both a significant source of new energy demand as well as significant source of the technologies and products that will meet this demand. It is important to have the right policy support and infrastructure to enable R&D, innovation and manufacturing. This is also important from a national security point of view as India’s dependence on imported energy resources like oil and gas and energy technologies like solar PV, supercritical coal power plants has continued to rise in the past decade. Strengthening R&D, local manufacturing of energy efficient devices, solar and wind power, batteries, electric vehicles, sensors, the internet of autonomous devices (the “Internet of Things”) and the smart grid, etc., will improve energy security. Another benefit will be the likely expansion of skilled manufacturing jobs by 50% by 2040 (IEA, 2015).

Consider the success of policy-induced growth in India of the Information Technology (IT) sector (Salazar-Xirinachs et al, 2014). The IT sector has grown from 1% of GDP in the early1990s to 9.3% of GDP in 2016. The state sector invested heavily in higher education, especially science and engineering, and heavy industries and technologies of export substitution in the first four decades after independence. This policy led to the development of a base of skilled manpower, which could be employed by the budding IT industry, especially in the city of Bangalore. The IT industry benefited from generous tax and financial incentives, the establishment of software parks with excellent infrastructure, publicly funded software training institutes and the explosive growth of private engineering colleges, and the setting up of R&D laboratories in IT by global multinationals. Export-led growth of the IT industry has also led to competitive pressures, international exposure and learning experiences that have encouraged the Indian IT industry to climb the value chain from being generic IT service providers to companies with deep domain knowledge in various high-value segments. India’s successful Diaspora in the IT sector in the United States, also helped substantially by bringing technologies, managerial skills and financial investment to the Indian IT sector. A lively start-up ecosystem is leading to a third phase of revolutionary growth in the Indian IT sector, especially in Bangalore, Mumbai and Delhi,. India has the third highest number of start-ups globally, and a large number of successful and fast growing companies. While the success of the IT industry can be attributed to decades of enabling state policies, it is arguable if it can be attributed to an overarching and visionary industrial policy similar to the industrial policies of South Korea or Japan where state role was more involved (Balakrishnan, 2006).

The country needs an industrial policy for the energy sector that could replicate the success of the IT sector. The real difference is that, unlike the organic growth in the case of the IT sector, a multidisciplinary and visionary policy framework is required for coherent policies across the exceptionally diverse energy sector. The Chinese Industrial Policy for National Strategic Industries provides a model for such a policy (Ahrens, 2013; Heilmann, 2012). This policy was an important goal for India’s twelfth five-year plan (2012-2017). It identifies seven strategic industries and twenty key projects that are likely to be the engines of growth for the future and provides R&D and technological innovation support, and fiscal and financial incentives for their growth. The new industrial policy for energy technologies and services, should likewise identify critical technology sectors for the next decade. The policy should focus attention on these with R&D initiatives, technological innovation support via pilot projects, and fiscal, financial and tax incentives. Finally, it should enable the growth of a large domestic market for these technologies as well as support the development of an export market. The policy should be designed to be “indicative” and should not choose winners or losers. The end goals and the implementation details would be discovered in an exploratory manner by the private sector, policymakers and other stakeholders.

V. Institutional frameworks and policies for the transition

India is a country with a very complex democratic and bureaucratic structure with many overlapping layers of administration and responsibilities. Decisions regarding the energy infrastructure affect all stakeholders: the administration, the economic actors and the citizens. In this section we discuss some of the political and administrative institutions and processes required to make the difficult transition to a clean and green future in a consultative and democratic manner.

5.1 A participatory process with stakeholder engagement

The decision making process should have sufficiently long lead times to engage potential stakeholders in government, industries, academia and civic society in order to arrive at a set of common goals and ideas regarding the future energy infrastructure.

As discussed in Section III, the first requirement is the existence of institutions that do long-term thinking and put out research and policy papers that inform the rest of the stakeholders about different future scenarios. These institutions could be state run, non-profit, or private: the primary requirements are independence, competence and credibility. This should be followed by a consultative process that involves all relevant stakeholders, in smaller groups, to reach a consensus on broad goals and objectives. This process would require the commissioning of more focused studies with, perhaps shorter time-horizons.

The policy-making and regulatory process for new technologies will require extensive stakeholder engagement before, during, and after new regulations are drafted and implemented. This policy “discovery process” involves a lot of “learning by doing” and tinkering to arrive at good and effective policies. At the project implementation stage, another set of consultative processes is required to take into account environmental impacts, land acquisition, and socio-economic costs and benefits.

Numerous decisions in India are taken by the executive branch, with little inputs from stakeholders. The Indian regulatory process, on the other hand, is consultative by design. While significant progress has been made to broaden the decision-making process in India, such consultation and stakeholder engagement do not constitute the norm.

5.2 Institutional innovation and business model innovation

India’s impending transition to clean and green energy systems will have winners and losers--institutions, businesses and professions will get replaced by others that will thrive in the new energy sector. At the same time, there will be a need for innovative institutions and mechanisms that will guide us through this transition by discovering and developing policy and regulatory frameworks. One set of key players will be companies that will disrupt the existing business models and develop new ones; another set of players will be forced to evolve rapidly in order to survive the transformation.

Consider a future green energy sector that will depend significantly on intermittent renewables like solar and wind. This will require flexibility in supply and demand until storage technologies become cheap enough. In addition, the cost of power from fossil fuels should internalize environmental costs. This will require regulatory institutions to innovate and come up with policies such as, time-of-day pricing, valuing services like frequency stabilization, peak power, demand response, efficiency improvements, distributed generation, etc. Time of day pricing, frequency stabilization, storage services, distributed generation, etc., also provide opportunities for disruptive business model innovation by start-ups and new companies. These developments will put a lot of pressure on our distressed power DisComs who are mostly loss making public sector companies. The DisComs will need fiscal help and rapidly changing business models to survive.

5.3 Building an Innovation-based Economy

In Section III, we looked at the energy technologies and the long term planning processes required to transition to a green and energy efficient development path. In Section IV, we looked at the institutions and strategies required for sustained innovation in the energy sector. The energy sector, a very important cog of the economy, does not exist in isolation.

The success of the transformation of the energy sector depends on a similar transformation of the entire economy. India has to transform to a state where innovative research and development are supported, and the investment and business environment support the risks of innovative companies and disruption of established technologies and business models.

To begin with, this requires us to focus strongly on providing good universal education in our schools, and an open-minded research-oriented outlook in the institutes of higher learning. The emphasis on innovation should be a part of the mandate not just of universities and research institutes but should be a part of the public culture, and should permeate government, business and civic society.

Innovations are inherently risky, and success requires a lot of enabling factors. The most important ones are an appetite for risk and a stomach for failure. Ease of starting businesses, flexibility in employment laws and unemployment benefits, financial infrastructure like venture capital and start-up investment funds and a helpful start-up ecosystem are the key enablers to help and mitigate innovation risk.

An innovation-based economy is also a rapidly evolving one. Constant negotiations between various stakeholders are required to maintain stability in a complex society. A participatory and consultative decision-making process is the last and final requirement for the transformation of India and the Indian energy sector.

VI. Summing-up:

It is time to recapitulate and attempt a score-card. The achievements of the Indian energy sector are many. The growth in total primary and secondary energy consumption in the country since independence is nothing short of impressive. Many complex nuclear power plants have operated safely without major accidents for several years. Energy efficiencies of appliances have gradually improved. Lead has been removed from petrol and tailpipe emission standards have also gradually been made more stringent.

The list of persisting problems is longer. In terms of the sheer number of people affected, the lack of access to electricity and other modern fuels must rank at the top. The issue of displacement of people due to energy projects and their insensitive resettlement and rehabilitation would be a close second. The poor quality of electricity and its unreliability imposes huge distributed uncounted costs on the economy in the form of captive generators, uninterrupted power systems, voltage stabilizers, burnt out appliances, etc. The financial unsustainability of the business model of the DisComs has been worrisome now for decades. So has been the inadequacy of R&D in the electricity sector. The persistence of coal fires, the failure to ensure that surface mines can be restored to their pre-mining status, continue to plague the coal industry.

In our Reports and in our pronouncements we are quick to adopt new jargon: self-reliance, energy access, energy security, sustainability, inclusiveness, climate change all have become part of the standard lexicon. We are content to get merely the rhetoric right. Reality on the ground is a lot slower to change. It is common to make assertions not based on evidence or analysis. Senior and important people do not themselves do any real analytical or modelling work and leave it to their junior colleagues.

Nonetheless, the transition in the Indian energy sector to cleaner systems has begun. It will not be complete by 2030, but a lot more would be by 2050.

In the second half of this chapter, we have discussed the policy and regulatory conditions that would enable a transition from the currently robust to cleaner, more flexible and responsive system. We recommend the establishment of an independent Centre/Institute for energy data and modelling, and of an agency to fund innovative research ideas. Nevertheless, the *sine qua non* of fostering innovation in the energy sector, as elsewhere in the economy, is the flourishing existence of an ecosystem that encourages competition and rewards risk taking. Availability of long-term financing with lower interest rates will make this easier, and also a faster diffusion of clean renewable energy sources.

One wishes for a technological equivalent of Occam's razor, which postulates that "plurality should not be posited without necessity." When there are, say two, competing technologies that can perform the same task we ought to choose the simpler, safer and cheaper option. In technology as well, complexity should not be introduced without necessity.

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List of Tables and Figures

Table 1: Selected special energy sector committees set up by the Government of India (1963-2013)

Name of the Committee	Chairpersons	Year formed	Year Report Published	Main Recommendations
Energy Survey	M. R. Sachdev, W. Cisler, A. Robinson	1963	1965	Develop coal as the primary source; increase fire wood supply; review energy sector every 5 years.
Fuel Policy	S. Chakravarti/ R. Venkataraman	1970	1974	Substitute all uses of oil, except in the trans-port sector, by coal or coal-based forms.
Working Group on Energy Policy	N. B. Prasad/R. V. Subrahmanian	1977	1979	Explore reducing overall energy demand, without affecting gross national product.
Power Sector Reform	V. G. Rajadhyaksha	1980	1980	Invest same or more on transmission and distribution as on power generation.
Advisory Board on Energy Study	B. B. Vohra	1983	1985	To provide recommendations for the formulation of the seventh plan.
Integrated Energy Policy	K. S. Parikh	2004	2006	Meet demand through safe, clean and convenient forms of energy that are least cost, technically efficient, economically viable and environmentally sustainable. Meet lifeline energy needs of all households.
Renewable Electricity Roadmap 2030	NITI Aayog/ CII/ Shakti Foundation	2013	2015	Aggregating and managing RE for its most efficient use will require updated grid operations. Identifies needed legal, institutional and policy changes.

Table 2: Indian modelling studies reviewed by Dubash et al. (2015)

Name	Institution	Date	Model Type	Timeline
Climate Change Impact on the Indian Economy-A CGE Modelling Approach	National Council for Applied Economic Research (NCAER)	Dec 2009	Computable General Equilibrium (CGE) Model (Top-Down)	2004- 2031
The Energy Report—India. 100% Renewable Energy by 2050	The Energy and Resources Institute (TERI-WWF)	Dec 2013	MARKAL model (Bottom-Up)	2001-2051
Energy Intensive Sectors of the Indian Economy: Path to Low Carbon Development	The World Bank	Feb 2014	World Energy Model (Bottom-Up)	2007-2031
Expert Group on Low Carbon Strategies for Inclusive Growth (LCSIG)	The Planning Commission, GoI	Apr 2014	Activity Analysis Model (Top-Down)	2007-2030
Energy-Emissions Trends and Policy Landscape for India	Indian Institute of Management, Ahmadabad	Jan 2015	Integrated Assessment Model (IAM)	2005-2050
A Sustainable Development Framework for India's Climate Policy	Centre for Science, Technology and Environment Policy	Jan 2015	Integrated Energy Model (Bottom-Up)	2012-2030
India Energy Security Scenarios 2047 (IESS web tool)	The Planning Commission, GoI	--	Excel based simulation model (Bottom-Up)	2012-2047

Table 3: Trends in electricity supply (from Dubash et al, 2015, p. 9)

Source	Current (2012) Generation Share (%)	Reference Scenario (2030-32) Share (%)	Policy Scenario (2030-32) Share (%)
Coal	70.2	56-90	43-63
Gas	8.6	3-8	1-14
Nuclear	3.5	1-8	1-14
Hydro	13.1	4-11	7-14
Solar	0.1	0-4	5-11
Wind	2.8	1-7	8-19
Biomass	1.0	0-2	0-3
Others	--	--	--
Total	100	100	100
Renewable Energy Share	3.9	2-12	12-31
Non Fossil Fuel Share	20.5	7-32	25-55

Table 4: Projected fossil fuel import dependence (Source: Dubash et al., 2015, Tables 4-5, pages 6-7)

	Current Use in 2012		Reference Scenarios 2030-32		Policy Scenarios 2030-32	
	Use	**Import Share (%)**	**Multiples of Current Use**	**Import Share (%)**	**Multiples of Current Use**	**Import Share (%)**
Coal	1.0	26	2.5-3.0	40-52	1.5-2.8	0-21
Oil	1.0	78	1.5-3.1	88-93	1.5-2.4	81-86
Gas	1.0	30	2.1-3.5	40-70	2.2-4.0	20-73
Overall Import Dependence	--	43	--	51-52	--	24-36

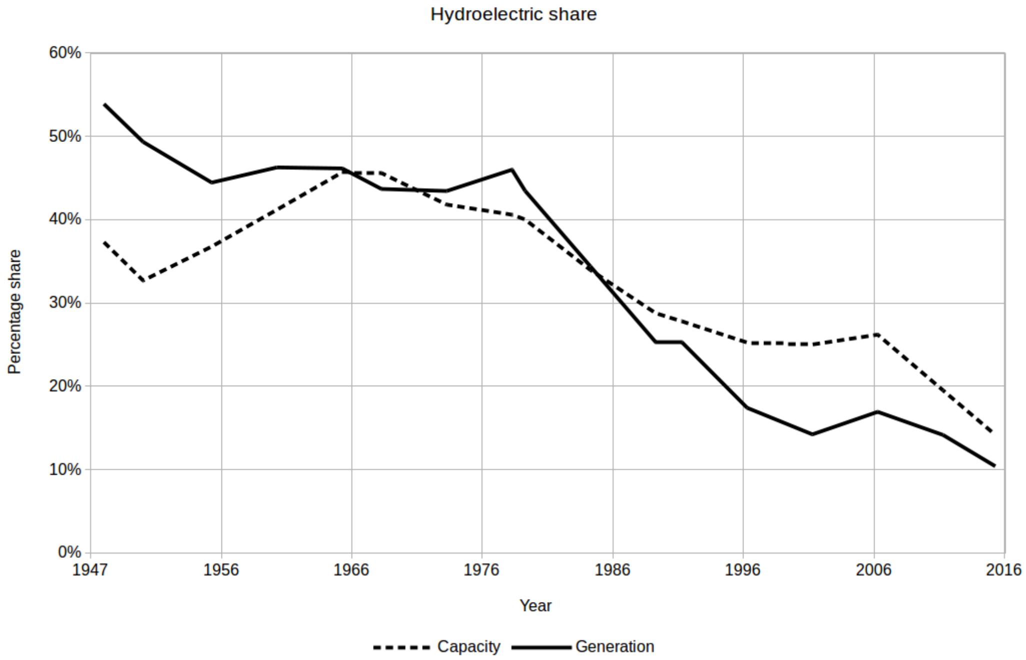

Figure 1: Decline in the share of hydroelectric generation in the Indian electricity sector (Source: CEA).

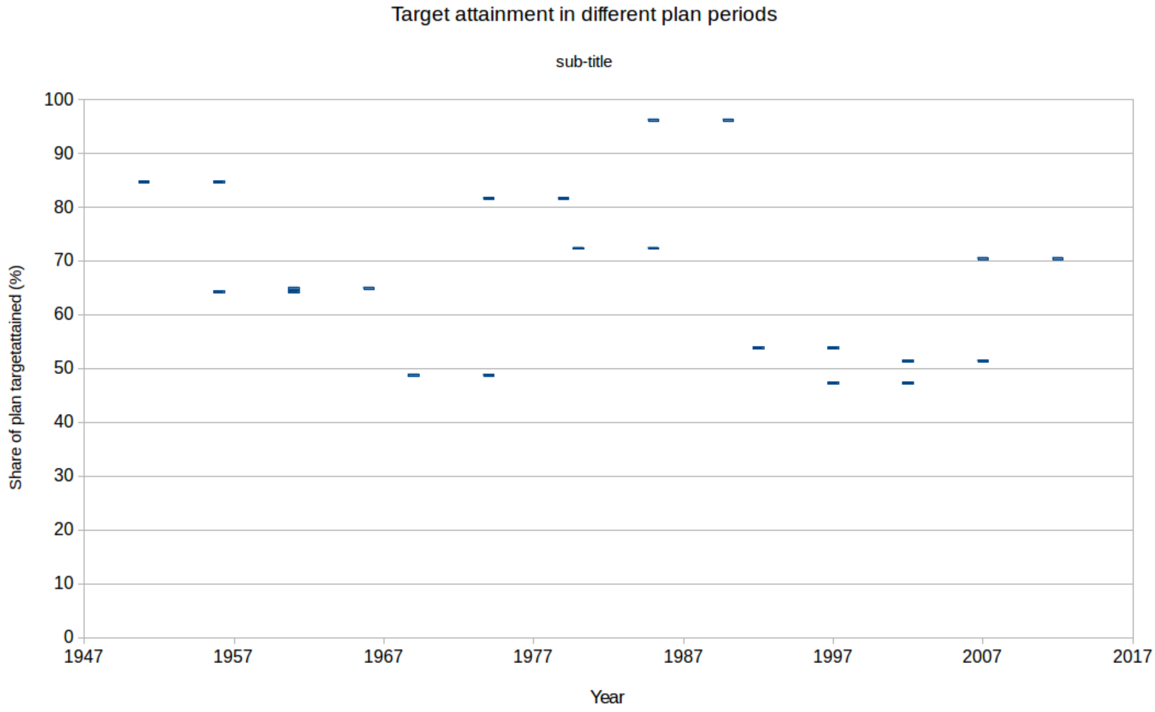

Figure 2: Percentage achievement of targets in different plan periods. Source: Planning Commission documents.

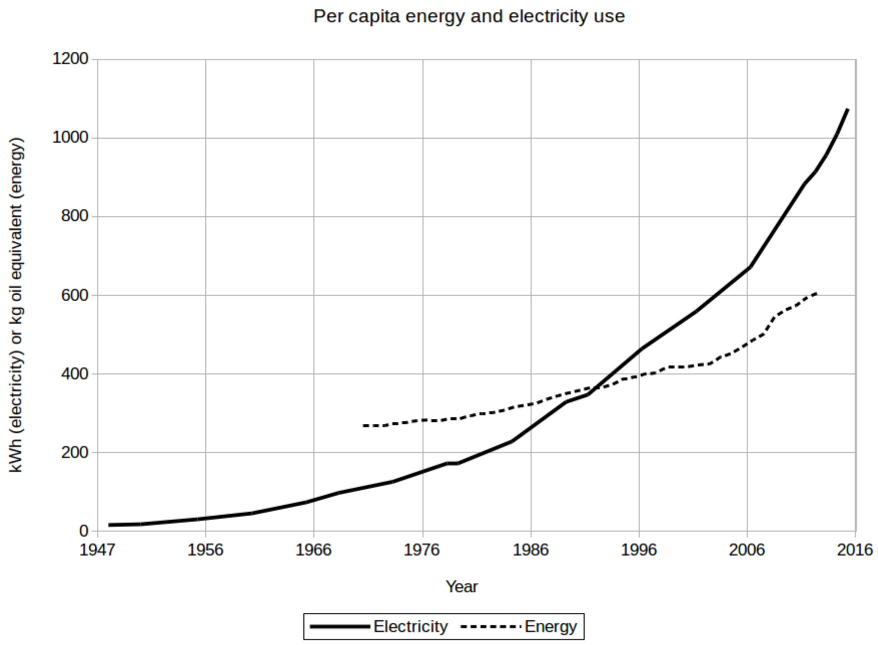

Figure 3: Historical trends in per capita electricity and energy use in India (Sources: electricity data, CEA; energy data, World Bank).

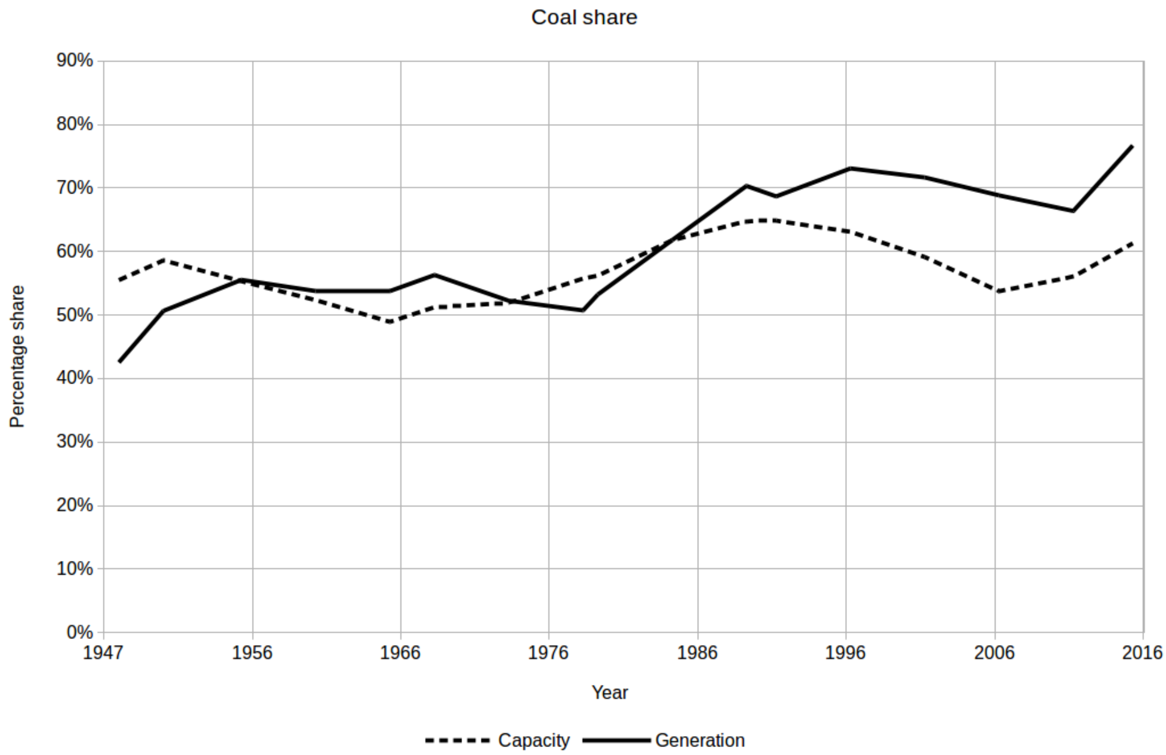

Figure 4: Share of coal in the Indian electricity sector (Source: CEA).

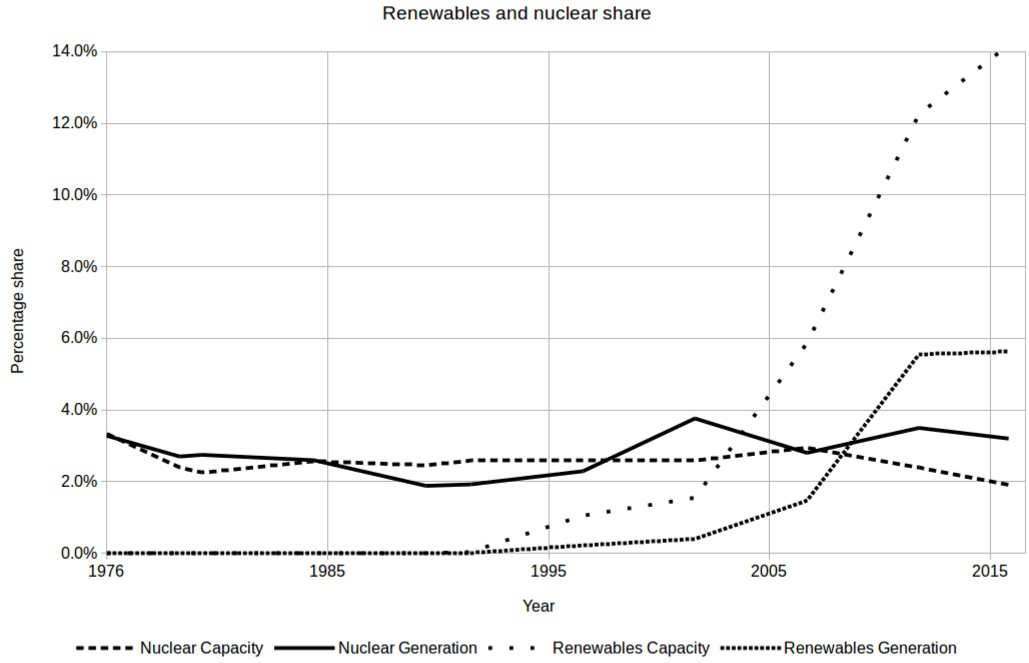

Figure 5: Shares of renewable (not including large hydro) and nuclear power in the Indian electricity sector. Renewables generate 1.75 times the energy that nuclear power does (Source: CEA).

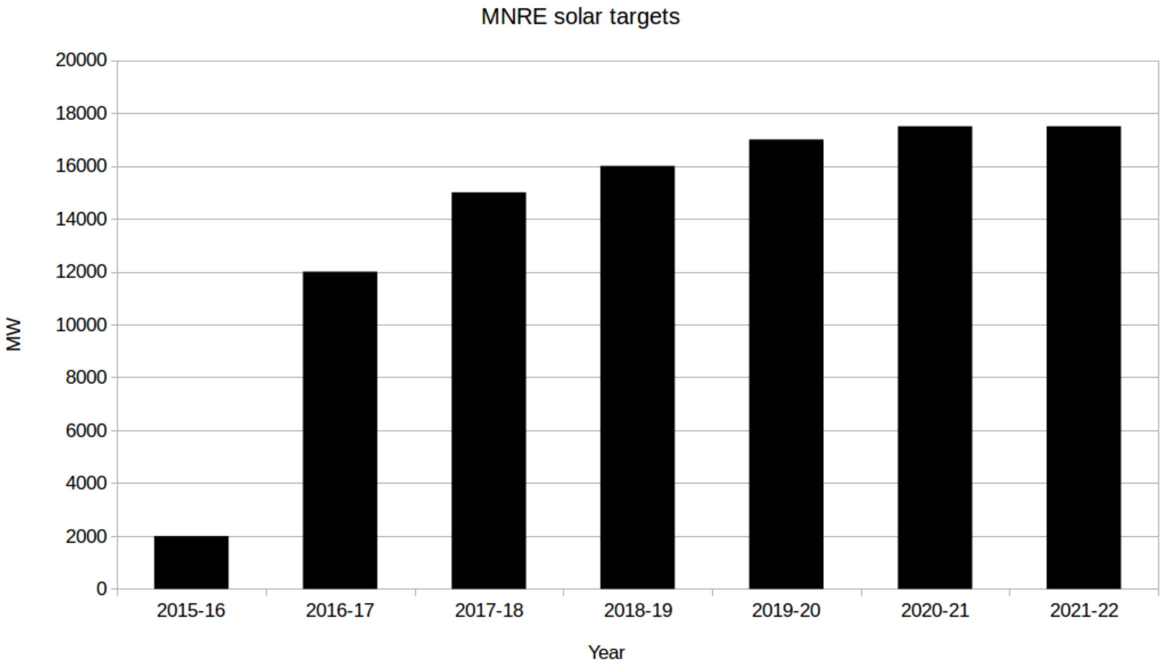

Figure 6: Planned additions of solar capacity (Source: MNRE).

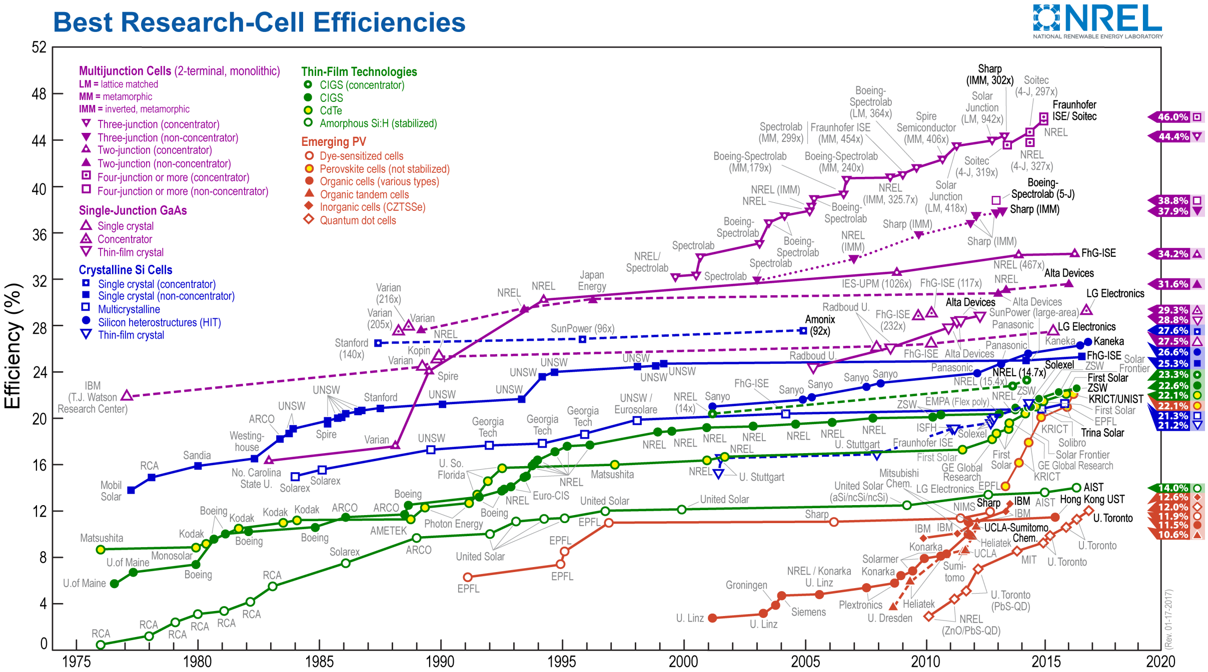

Figure 7: Efficiencies of state of the art solar PV technologies (Source: National Renewables Energy Laboratory)