Towards better technology policies for the Indian coal-power sector

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Coal is projected to be a mainstay of the Indian power sector in the decades to come, given the availability of significant domestic resources and the limited availability of other options that could make major contributions to the growing power needs of the country. However, further capacity addition in coal-power generation needs to be based on a careful consideration of not only the country's near-term growth and security needs but also present and emerging environmental challenges, including local pollution control and mitigation of carbon dioxide emissions. This paper assesses the suitability of current and emerging advanced power generation technologies for the Indian context and presents some technology policy implications of this assessment and analysis to help the Indian coal-power sector meet the country's energy needs in a sustainable manner.

1. Introduction

Energy services underpin almost all aspects of human activity. These services provide basic needs such as cooking, heating, and lighting, fuel a range of industrial activities, and sustain today's transportation and communication systems [UNDP, 2004]. Generally, as countries become richer, energy consumption per capita rises correspondingly to satisfy increasing demand for energy services from both the industrialization process and rising living standards. Conversely, limited availability of energy often constrains human and economic development, and can prevent the realization of basic human needs. Thus, there is a broad correlation between the human development index (HDI) and per capita energy consumption across countries[1]. Given the central role of energy in societies and economies – in fact, expenditures on energy account for 7-8 % of countries' gross domestic product (GDP) on average[2] – the energy sector plays a prominent role in the national policies of all countries.

While expansion and modernization of India's energy sector is an important goal, the focus cannot narrowly be on increasing overall supply of energy, but must be on ensuring fair access and availability of energy and energy services in rural areas, especially for meeting basic needs[3]. Therefore, even as the supply of primary energy is increased, one must be concerned about its efficient conversion to useful forms and equitable distribution to the end-use level.

Within the energy arena, electricity perhaps plays a pivotal role as a modern energy carrier, as it allows the provision of essential energy services such as lighting and refrigeration, and enables a range of activities such as the operation of industrial machinery, computers, and electronics that lie at the heart of most modern societies.

India, like all developing and modernizing economies, has seen increasing demand for electric power from its residential, commercial, and industrial sectors. This, in turn, has driven the efforts to rapidly expand the power sector. Energy technologies play a central role in such an expansion and enhancement of the power sector. However, given the complexity of major power technologies, their development (including adaptation) and introduction into the marketplace can involve long time-scales and significant investment. In the absence of specific incentives, private players often are unwilling to take the risk to invest the resources necessary to develop/adapt and deploy suitable technologies even if they benefit society more widely[4]. Furthermore, the long lifetimes of high-investment power technologies, such as coal-fired power plants, also magnify their significant economic and environmental ramifications, which add further impetus for forward-looking government polices in the development and deployment of suitable technologies.

Thus, there is a strong rationale for government policies that support the research, development, demonstration, and early deployment (RD^3) of appropriate power technologies[5]. This is particularly true in the Indian case since the government and public sector units in the country play a crucial role in determining the direction and focus of the power sector, with the private sector and "markets" having a limited role[6]. Thus, a robust technology policy based on empirical data and analysis could greatly facilitate and further the energy technology development and deployment processes in India, but there is insufficient effort towards this end.

It is with the intention of attending to this lacuna that we present a preliminary assessment of emerging technologies in the Indian context as a first step to the development of better technology policies in this sector. Some technology policy implications of this assessment that

could help the coal-power sector meet the country's energy needs in a sustainable manner are also highlighted.

1.1. Projected rise in electricity demand

While India has made enormous strides in electricity growth, the availability of electricity in India falls far short when compared to the global averages. In 2002, per capita consumption was 420 kWh, in contrast to the non-OECD average of 1100 kWh and the OECD average of 8000 kWh [IEA, 2004], and the country has been routinely experiencing energy shortages of 6-12 % and 11-20 % inability to meet peak electricity demand over the last decade. Lack of power availability is widely seen as a bottleneck to industrial development as the country aims to rapidly increase its pace of economic growth [World Bank, 1999][7]. Long-term projections indicate that an installed capacity of nearly 800 GW by 2030 is required to maintain an average annual GDP growth of 8 % [PC, 2006]. Furthermore, as a clean energy carrier, electricity for lighting, household use, and small-scale industrial activities is an important element of increasing economic and social development for the poor. Recent government plans aim to increase the per capita consumption of electricity to 1000 kWh, up from 480 kWh in 2005, as well as to extend the electricity distribution network more rapidly, with at least one substation being located in each community development block[8] of India's rural districts [MoP, 2005; 2006].

The demand for utility-generated electricity by 2016-17 was projected to be nearly three times the demand in 2001-02, with an average annual growth rate of about 8 % [CEA, 2000]. In the fiscal year 2004-05, about 594 TWh was generated by utilities, with coal- and lignite-based generation accounting for about 80 % of total generation [CEA, 2006]. Longer-term scenarios indicate demand to be around 3600-4500 TWh/year by 2031-32 [PC, 2006]. In the short term, the Government of India intends to install 100 GW of new capacity in the 10th and 11th Five-Year Plan periods (2002-2012), with an investment of nearly Rs. 8 trillion (about US$ 200 billion at the exchange rate of mid-November 2007), to meet its goal of providing "reliable, affordable and quality power supply for all users by 2012" [MoP, 2001]. The Planning Commission estimates [PC, 2006] that the installed capacity (including captive power) will need to be about 800-1000 GW by 2031-32, depending on GDP growth.

1.2. Dominance of coal in Indian electricity sector

Coal-based power plants have dominated the power generation sector since the 1970s. As of March 2004, coal-based plants constituted 57 % of installed capacity of utilities, while generating about 72 % of utility-supplied electricity in the country [CEA, 2005]. This domination of coal in the power sector is likely to continue in the future, as other resources are uneconomic (as in the case of naphtha or LNG), have insecure supplies (diesel and imported natural gas), or are simply too complex and/or expensive to build (nuclear and hydroelectricity) to make a dominant contribution to the near-to-mid-term growth [Chikkatur and Sagar, 2007]. Furthermore, increased use of domestic coal is also expected to increase India's energy security, as India has significant domestic coal resources.

About 50 GW of new coal-based capacity is planned for the 11th Plan[9], and longer-term scenarios explored by the Planning Commission [PC, 2006] suggest that coal will continue to dominate the power sector consumption at least for the next three decades. According to the [PC, 2006] scenarios, coal-based capacity of utility power plants is likely to be in the range of 200-400 GW in 2030, up from about 68 GW in 2005.

1.3. Assessing coal-power technologies

The projected rapid increase in coal-based capacity necessitates a better understanding of coal-power technologies and an assessment of emerging technologies that meet the existing and expected future challenges (see Section 2). Currently, the country's thermal power stations are almost exclusively based on subcritical pulverized coal (PC) technology. While this technology offers certain advantages – a well-established manufacturing base, low costs, and relative ease of maintenance – it is also apparent that relying on it will be increasingly problematic given the issues that are likely to become important in the future.

At the same time, there are now a number of different existing and emerging power generation technologies that potentially can help the coal-power sector meet its goal of rapid capacity addition in a manner consistent with its other challenges. Combustion based on supercritical steam, offering higher efficiencies than subcritical PC, is a commercial technology. Ultra-supercritical PC, which offers even higher efficiency, is also being deployed, while oxy-fuel combustion for facilitating capture of carbon dioxide (CO_2) is under development. Integrated gasification with combined-cycle operation (IGCC), with significant potential for high efficiency and for cost-effective reduction of CO_2 and other emissions, is likely to be commercially available in the near future. The availability of these different (and evolving) technology options and the need to assess their suitability in the context of existing and expected future challenges (see Section 2) highlight the need for a systematic and careful technology decision-making process to develop suitable technology policies in this sector. This situation is very different from the past when only subcritical PC dominated the global technology landscape and the focus in the Indian coal-power sector was mainly on adaptation and multiplication of the technology rather than choosing between widely disparate options.

Currently, technology investment decisions in the Indian power sector are primarily driven by the need to increase generating capacity, which has had the result of deploying the least risky and cheapest technology (subcritical PC). The historical shortages of power, partly due to increasing demand as a result of population and economic growth and partly due to lack of sufficient capacity additions, have lent strong urgency to increasing capacity without necessarily placing this growth in the context of longer-term strategy, especially regarding the kinds of technological choices that the country must make for the future and the elements of a technology innovation program to support this approach. In general, there has been less attention paid to technology policy for the future of

the coal-power sector, although the recent Integrated Energy Policy Report [PC, 2006] does call for technology missions in various coal utilization technologies.

2. Challenges and constraints in the coal-power sector

The assessment of technological options can only take place in the context in which the technologies will be deployed. Hence, we outline here what we believe to be the key challenges and constraints for the Indian power sector.

The key challenges facing India's power sector include: (1) an urgent need to increase energy and electricity availability for human and infrastructure development; (2) increasing energy security; (3) local environment protection and pollution control; and (4) control of greenhouse gas emissions (particularly carbon dioxide). The task of meeting these broad challenges is further complicated by several constraints: (1) availability and quality of domestic coal; (2) limited financial resources; (3) inadequate technical capacity for research and development (R&D), manufacturing, and operations and maintenance (O&M); and (4) the institutional characteristics of the Indian power sector. A brief description of the challenges and constraints and their implications for future technologies are contained in Table 1.

3. Coal-power technology options and analysis

As mentioned earlier, there is a range of existing and emerging technology choices for coal power. While direct combustion of coal continues to remain the dominant pathway, a number of advanced coal technologies have been developed to meet the worldwide challenge of making power generation cleaner, more efficient, and more able to utilize coals of varying qualities, characteristics that are also relevant in the Indian context. PC technologies have improved, resulting in increased efficiency and reduced local pollution. New combustion pathways using circulating fluidized beds have been introduced to utilize lower-quality coals, including waste coal, washery middlings, and even biomass. Combustion with pure oxygen (oxy-fuel combustion) instead of air is also being considered for ease of carbon capture and storage (CCS). Efforts are also under way to commercialize coal-gasification-based systems. Entrained-flow gasifiers have been used commercially for converting coal into an energy-dense gas that can be converted to methanol and hydrogen, which in turn can be used for making chemicals or Fischer-Tropsch (F-T) liquids such as synthetic diesel.

On the basis of a detailed assessment of coal-power technologies [Chikkatur and Sagar, 2007], we believe that a number of advanced technologies are (or may be) particularly relevant in the Indian context. These technologies include:

- supercritical pulverized coal (SC-PC);
- ultra-supercritical pulverized coal (USC-PC);
- circulating fluidized-bed combustion (CFBC);
- oxy-fuel PC/CFBC; and
- integrated gasification combined cycle (IGCC) based on:
  - entrained-flow gasifiers; and
  - fluidized-bed gasifiers.

The performance and cost characteristics of these technologies are shown in Table 2. While the technologies chosen above reflect our view of the most relevant technologies in the Indian context, the list is by no means inclusive of all possible technologies; we believe that this is a good starting-point. In the long run, other technologies (such as pressurized pulverized coal, chemical looping, and fuel cells) might gain applicability, and they would need to be considered at that time.

The performance and cost characteristics of technologies can vary significantly depending on technical and economic assumptions. Generally, technology analyses use a range of data from international sources, and it is not clear how comparable these analyses are and how translatable they are to the Indian context. Therefore, engineering-based analyses with technical and economic factors/assumptions representative of the Indian context are critical. Such engineering-based comparative assessments for the Indian context are generally lacking, except for a recent Nexant [2003] study[10].

Even in the absence of such engineering-based analysis, one could take further the kind of analysis shown here by, for example, assessing the relative performance of technologies for the Indian context. Such an assessment can also allow for a quantitative comparison of these options as an aid to decision-making and policy analysis, and eventually the development of a technology roadmap. While the details of such an analysis are presented elsewhere [Chikkatur and Sagar, 2007], we only highlight the key results below.

We find that supercritical PC and CFBC rank as the best overall technology options in the present circumstances: supercritical PC because of its efficiency, maturity, and relatively low cost, and CFBC because of its fuel flexibility and reduction in SO_x and NO_x emissions. Although subcritical PC is the cheapest and most reliable technology today, it is not the best overall option, because of its poor efficiency and environmental drawbacks. Gasification-based technologies, as well as the more advanced technologies such as oxy-fuel combustion, are currently not suitable because of their low maturity and relatively high costs, in spite of their better efficiency and environmental advantages. Nonetheless, these advanced and emerging technologies are important for the future, and therefore kept under consideration (see Section 4). Finally, we note that our analysis is a first step towards more detailed techno-economic assessments for India that incorporate the key challenges and constraints for the Indian coal-power sector.

4. Technology policy implications

Our technology assessment and analysis indicate that the menu of coal-power technologies, as well as the technical and environmental performance of any particular technology, is rapidly evolving globally. Therefore, it is prudent for India not to place its bets (at this time) on a particular technology for its coal-power sector for the long-term, but rather to keep its technology options open. For example, India should continue to explore both gasification and

Table 1. Challenges, constraints, and their implications for technology decision-making (adapted from [Chikkatur and Sagar, 2007]).

	Description	Implications for technology decision-making
Challenges		
Need for rapid growth	• Meeting socio-economic goals requires a rapid increase in electricity capacity and consumption[1].	Technologies must be commercially mature to be rapidly deployed in the short-to-medium term.
	• A large fraction of the new growth in electricity is expected to be based on coal.	
Enhancing energy security	• Coal is the only significant domestic resource, and increased use of coal is linked to increased energy security.	Technologies should be able to use domestic coal or be flexible enough to utilize other fuels, such as petroleum coke and biomass.
	• Energy security is also enhanced when power generation feedstock can be sourced from diverse locations.	
Protection of local environment	• Coal-power plants strongly impact the local environment by causing pollution of air, water and land resources. Reducing these impacts is an important priority for the government.	Technologies with high efficiency, combined with better pollution clean-up technologies, are needed.
CO_2 emission reduction	• Coal combustion accounts for about 40 % of total CO_2 emissions of the country [MoEF, 2004]. Given that more than 70 % of the coal consumed in country is used for power generation [MoC, 2007], reduction of CO_2 emissions will entail a significant impact on coal-power plants.	Although there is no current need for capturing CO_2 from power plants, installing high-efficiency technologies will allow for economic carbon capture from retrofitting. Furthermore, better control of pollutants such as particulates, SO_x and NO_x will also help with CO_2 capture[2].
	• The nature and timing of emission targets are, however, unclear and will likely not be determined in the short term.	
Constraints		
Coal availability and quality	• There is significant uncertainty about the exact quantity of coal reserves in the country. While there are an estimated 250 billion tonnes (Gt) of geological coal resources, techno-economically extractable reserves may only be 45-70 Gt[3].	Technology choices will likely be constrained by the quality of domestic coal. Furthermore, the extent of available domestic coal reserves will also impact technology choices in the long term.
	• Coal demand is expected to outstrip domestic supply – leading to increased imports.	
	• The quality of domestic coal is poor, with high ash content and low calorific value.	
Finance resource limitations	• Financial resources are limited, particularly in the state sector. Although equity shortfalls are of primary concern in the short term, enormous outlay of capital is required for accelerated growth in the power sector.	Cost is a key criterion for technology selection, and technologies with high efficiency and low capital costs are favored. Technology costs are interlinked with maturity and indigenous capacity.
	• Low cost of generation and supply is important for increasing electricity access for the poor.	
Limited technical capacity (R&D, manufacturing, and O&M)	• There has not been enough investment in developing coal-power technologies in India, and most of the existing efforts have been limited to the Indian manufacturing giant, Bharat Heavy Electricals Limited (BHEL).	Technology choices need to be consonant with indigenous capacity. Limited investment might affect indigenous technology development.
	• There is significant manufacturing and O&M capacity within BHEL, National Thermal Power Corporation (NTPC) and other manufacturers and utilities.	
	• Capacity for innovation in the country is limited, with little R&D coordination between academia, government and industry.	
Institutional issues	• Historical power shortages have created a panic mode of operations, wherein there is more emphasis on mitigating short-term problems, rather than developing a long-term strategy. This has led to a narrow focus on generation and risk-averse attitudes towards new technologies.	Focus on rapid capacity additions has emphasized technology replication rather than innovation. Limited competition, dominance of government-owned enterprises, and lack of long-term technology planning limit the development and deployment of new technologies.
	• Lack of significant domestic policy research capacity has hampered systematic technology planning.	

Notes

1. In addition to increase in capacity, it is important that efficiency in transmission and distribution of electricity is improved by minimizing transmission loss and commercial theft.
2. See, for example, [Chikkatur and Sagar, 2007].
3. See, for example, [Chand, 2005] and [Chikkatur and Sagar, 2007].

Table 2. Comparison of technical and performance characteristics of relevant technologies[1]

Technology	Subcritical PC	Supercritical PC (SC-PC)	Advanced/ ultra-supercritical PC (USC-PC)	Circulating FBC (CFBC)	Oxy-fuel PC/CFBC	IGCC – entrained-flow	IGCC – fluidized-bed
Use in India	Almost all Indian thermal powr stations (TPSs)	Sipat-I TPS (in construction); Barh TPS (order placed)		Surat lignite TPS, Akrimota lignite TPS		Might be useful for using refinery residues.	R&D, pilot scale plant. Plans for demonstration plant.
Worldwide[2]	Standard technology worldwide	Europe (Denmark, Netherlands, Germany), Japan, USA, China, Canada	Netherlands, Denmark, Japan	USA, Europe, Japan, China, Canada	Development and planned pilot plants in Europe, Australia, Canada. Useful mainly for CCS.	Demonstration/ commercial plants in USA, Europe, Japan, China	A 6 MW unit in Europe, 100 MW demo plant in USA, biomass IGCC in Brazil. Widespread use for chemicals production and polygeneration.
Level of maturity	Commercial	Commercial	Commercial/ demonstration	Commercial	R&D/pilot scale	Gasifier commercial; IGCC commercially proven	Gasifier commercial; IGCC demonstration
Output flexibility	Primarily electricity; however, process steam and heat can also be extracted.					Electricity, syn-gas, chemicals, FT liquids, H_2, steam, heat	
Fuel flexibility	Can be flexible, with loss in efficiency			Highly flexible. Use of high-ash coals supported.	Same as PC and CFBC	Very flexible, but limited to coals with low ash content and low ash fusion temperature	Very flexible, but limited to coals with high ash fusion temperature
Net efficiency (net HHV): India[3]	33 % (w/o FGD)[4]	35 %		33 %			40 %
Net efficiency: worldwide[5]	37-38 % (w/FGD)	39-41 %	40-44 %	34-40 %[6]	34 % (USC-PC); 25 % (CFB-subcritical)[7]	35-40 %	44-48 %
Capital cost (TPC; $/kW): India[8]	610 (w/o FGD); 750 (w/FGD)			770			1290[9]
Capital cost: worldwide	1080-1280 (w/FGD)	1090-1290	960-1300	1070-1340	1860 (USC-PC); 2370-2410 (CFB-subcritical)	1200-1610	1250-1270
Environmental performance							
Particulate matter	Electrostatic precipitators (ESP) required; baghouse filters with high ash is difficult.			ESP required; multiple cyclones and baghouse filters may be needed.	ESP required; baghouse filters with high ash is difficult. Multiple cyclones for oxy-CFBC.	Syn-gas clean-up with ceramic filters. Reliability is an issue.	Syngas clean-up with ceramic filters. Multiple cyclones may be needed.

Table 2. Comparison of technical and performance characteristics of relevant technologies[1] (continued)

Technology	Subcritical PC	Supercritical PC (SC-PC)	Advanced/ ultra supercritical PC (USC-PC)	Circulating FBC (CFBC)	Oxy-fuel PC/CFBC	IGCC – entrained-flow	IGCC – fluidized-bed
Fly ash/ solid waste	Depends on coal quality	Depends on coal quality; less fly ash than subcritical PC. Slagging is an option.		Depends on coal quality; gypsum by-product	Depends on coal quality; slagging is an option. Gypsum by-product for oxy-CFBC.	Less solid waste; slag by-product	
Nitrogen oxides	Low NO_x burner (LNB) and selective catalytic reducer (SCR) as needed			Low NO_x production	Very low NO_x production	Very low NO_x production. LNB for gas turbine.	
Mercury removal[11]	With ESP and baghouse filters, 60-70 % can be removed. ESP alone not effective. Activated carbon injection if needed.			With baghouse filter, 70 % can be removed. If needed, activated carbon can be injected.	With ESP and baghouse, 60-70 % removal. ESP alone not effective. If needed, activated carbon can be injected.	Removal by particle filters. Carbon bed filters if needed.	
Ease of carbon capture[12]	Monoethanolamine (MEA) scrubbers are limited by SO_x/NO_x content in flue gas. Can be very expensive. Retrofitting to oxy-fuel combustion is possible, but not attractive.			MEA scrubbers have less problems with SO_x contamination. Can be very expensive. Retrofitting to oxy-fuel combustion is possible, but not attractive.	Direct flue-gas sequestration is possible. Less expensive, if flue gas purification is not required.	CO_2 shift reactor and MDEA or Selexol® gas purification and capture[13]. Incremental cost of capture may be less than MEA scrubbing.	

Notes

1. Detailed technical information about these technologies is available in [Chikkatur and Sagar, 2007] and references therein.
2. Sources: NETL, 2004; PowerClean, 2004
3. Based on [Nexant, 2003] analysis using run-of-mine coal
4. Flue gas desulfurizer (FGD) is the standard pollution control equipment for limiting sulfur dioxide emissions from power plants.
5. Sources: IEA, 1998; David and Herzog, 2000; EPRI and Parsons, 2000; NETL, 2000; Marion et al., 2003; Dillon et al., 2004; Palkes et al., 2004; Ghosh, 2005
6. This includes both supercritical and subcritical CFBC plants.
7. This includes the efficiency and cost penalties of CO_2 capture.
8. The total plant cost (TPC) is given in 2004 $. Cost information from various studies was adjusted to 2004 $ using the consumer price index. Note that the capital cost of all technologies has increased dramatically over the last few years because of rising steel prices and labor costs. Hence, all of these numbers will have to be scaled up significantly to arrive at today's costs.
9. Cost based on [Nexant, 2003] analysis of IGCC based on a General Electric F-class turbine
10. Removal of H_2S can be done using several different types of processes, including the use of methyl diethanolamine (MDEA), Claus sulfur removal process (Claus), and Shell Claus Off-gas Treating process (SCOT).
11. Highly dependent on input coal quality. Sources: PowerClean, 2004; Winfield et al., 2004.
12. Sources: Marion et al., 2003; PowerClean, 2004
13. The Selexol® process uses a physical solvent (mixtures of dimethyl ethers of polyethylene glycol) to remove acid gas from streams of synthetic or natural gas. See http://www.uop.com/objects/97%20Selexol.pdf.

advanced direct combustion pathways. Furthermore, if India increases coal imports for power generation, then this widens the range of technologies that may be usable in the Indian context, although it will clearly add complexity to the technology policy decision-making.

Given this, it would be useful to consider several different steps to help strengthen technology policy-making in the Indian coal–power sector.

- First and foremost, it is critical to buy time for decision-making by reducing inefficiencies in the transmission and distribution (T&D) system, increasing end-use efficiency, and improving demand-side management. For example, current losses in the Indian T&D system are very high and reducing these losses to a more manageable (though still high) 10 % will release power equivalent to about 10,000-12,000 MW of capacity [CEA, 2007]. Saving a kW on the end-use side is equivalent to almost 1.8 kW in generation (once auxiliary consumption at the power plant and T&D losses are taken into account). It is also estimated that the deployment of energy-efficient lighting, more efficient refrigerators in households, and more efficient motors in industry could save as much as 10 % of total national power generation [Shrestha et al., 1998].
- At the same time, the wide variation in efficiency in power generation from the existing stock of power plants [Chikkatur et al., 2007] offers the potential of significant gains through measures enhancing plant efficiency. It is estimated that nearly all existing power plants can improve their efficiency by 1-2 percentage points, and efficiency improvement by one percentage point would reduce coal use (and other environmental impacts) by about 3 % [Deo Sharma, 2004].
- Tightening the pollution control regimes for air pollutants (particulates, SO_x and NO_x) would not only yield direct benefits by mitigating the local air pollution from coal-power plants, but also provide an incentive for deploying cleaner technologies. It is not enough to have tighter regulations; their strict enforcement (which is often absent in India) is critical for realizing any actual gains from these regulations. India might also want to explore other economic instruments (such as pollution taxes and tradable permits) in this context.
- In the short-to-medium time-frame (10 years), only higher efficiency combustion technologies (such as supercritical PC and CFBC) should be deployed. While there is already some movement towards deploying supercritical PC technology in the central sector and the private sector (through the Ultra-Mega Power Plant scheme[11]), we believe that suitable incentives and mechanisms are needed to accelerate the rate of deployment, particularly in the state sector.
- For the medium-to-long-term future, it is essential to assess and plan for emerging technologies that may become relevant as the contours of India's coal availability and GHG mitigation responsibility become clearer. Furthermore, the menu of technological options will also continue to evolve as industrialized countries invest in their own programs of RD^3. Therefore, it is important for India to study and learn from these activities, and leverage global innovation to its benefit. Hence, India should establish a program to (1) monitor evolving and emerging pre-commercial technologies, and (2) conduct techno-economic feasibility assessments for existing advanced commercial and near-commercial technologies.
- Specific elements of particularly relevant technologies (such as ultra-supercritical PC and IGCC based on fluidized-bed gasifiers) must be advanced through a strategic RD^3 program to better position the sector for deployment of these technologies as their feasibility becomes clearer. At the same time, a program of domestic policy research is needed to couple and coordinate technical efforts with suitable implementation pathways.
- While the timing and nature of India's greenhouse gas commitments are as yet unclear, it is inevitable that the coal-power sector will play a key role in the eventual mitigation of India's CO_2 emissions. Currently, CCS from power plants is considered the key enabling technology for deep reductions of CO_2 emissions[12]. While it should be possible to adapt CO_2 capture technologies for Indian power plants (although with technical and economic challenges)[13], the feasibility of CCS strategies hinges on the availability of suitable storage options.

  Currently, underground storage in geological structures (particularly saline aquifers) is the most promising option for storing large quantities of CO_2. Therefore, it is important for India to invest in detailed mapping of specific storage locations and capacity within these locations. Currently, only broad first-of-a-kind estimates of storage capacity are available in the country, and there is a strong need for detailed site-specific assessment of storage mechanism and capacity in potential onshore and offshore locations.

5. Conclusion

A well-thought-out and robust technology policy based on empirical data and analysis is critical to ensure that India makes the appropriate technology choices as it strives to add substantial coal-power generation capacity in the coming decades. Our preliminary analysis indicates the country should not make rigid technology choices at this point, given the evolving nature of challenges and of the coal-power generation options. Thus, the short-term focus should be on buying time to make the right choices by enhancing the overall efficiency of the existing power system (generation units, T&D systems, and end-use devices) and by deploying available high-efficiency combustion technologies. At the same time, a strategic RD^3 program must be targeted to advance key technology options and keep them open while new and emerging technologies worldwide must be monitored and assessed continuously. The analysis presented here is a first step, and can be thought of as a foundation for a more comprehensive assessment process that is needed to build consensus among decision-makers and stakeholders on a robust technology policy and a suitable domestic innovation strategy to help

the Indian coal-power sector to meet the country's energy needs in a sustainable manner. ■

Acknowledgements

Financial support for this work was provided through the Kennedy School of Government's Energy Technology Innovation Project, from the David and Lucile Packard Foundation, a gift from Shell Exploration and Production, and general support grants from BP Alternative Energy and Carbon Mitigation Initiative.

Notes

1. This is not to say that higher energy consumption necessarily adds to human development but rather that the availability of energy services can enable and advance many aspects of human development.
2. See Page 1-1 of [PCAST, 1997].
3. See [Goldemberg et al., 1988] for a discussion on energy for meeting basic needs.
4. On the other hand, if a particular technology is already well-developed and commercialized, private players will readily adopt them as long as the economics are favorable. For example, although the development of gas turbines for power generation took a long time, their current deployment is rather fast as they are commercially viable.
5. A full consideration of all elements of the technology innovation process (i.e., research, development, demonstration, and deployment (RD^3)) is necessary for a successful and holistic technology policy. While setting R&D priorities and future directions for the energy sector is important, and often receives most of the attention, issues such as the effectiveness of R&D programs and coupling them to demonstration and deployment efforts must also receive adequate consideration. In addition, energy innovation policies must take into account the specificities of the national context (i.e., relevant economic, social, and environmental issues).
6. Even in industrialized countries, where the private sector dominates the energy area, the government plays a key role in shaping the energy sector by setting societal goals and uses incentives and regulation to generally guide the sector. Theoretically, the market then determines the allocation of resources, technology choices, and pathways to meet the required goals [Chikkatur and Sagar, 2007].
7. While economic growth by itself does not lead to wider human and social development, it can facilitate such development through the provision of additional resources and infrastructure.
8. Community development blocks are administrative units, consisting of about 100 villages, for development activities in India.
9. See http://cea.nic.in/thermal/Shelf_of_Thermal_Power_Projects_11th%20Plan.pdf.
10. Engineering assessments of a few coal-power technologies (pulverized coal combustion) have been performed in the Indian context. See, for example, [Suresh et al., 2006].
11. See, for example, [CEA, 2007].
12. Deep reductions of global CO_2 emissions are increasingly being seen as necessary for avoiding "dangerous" climate change.
13. It should be noted that higher-efficiency power plants and cleaner flue gases are more amenable to economic carbon capture [see Chikkatur and Sagar (2007]).

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