Assessment of demand for natural gas from the electricity sector in India

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ABSTRACT

Electricity sector is among the key users of natural gas. The sustained electricity deficit and environment policies have added to an already rising demand for gas. This paper tries to understand gas demand in future from electricity sector. This paper models the future demand for gas in India from the electricity sector under alternative scenarios for the period 2005–2025, using bottom-up ANSWER MARKAL model. The scenarios are differentiated by alternate economic growth projections and policies related to coal reforms, infrastructure choices and local environment. The results across scenarios show that gas competes with coal as a base-load option if price difference is below US $4 per MBtu. At higher price difference gas penetrates only the peak power market. Gas demand is lower in the high economic growth scenario, since electricity sector is more flexible in substitution of primary energy. Gas demand reduces also in cases when coal supply curve shifts rightwards such as under coal reforms and coal-by-wire scenarios. Local environmental (SO2 emissions) control promotes end of pipe solutions flue gas desulphurisation (FGD) initially, though in the longer term mitigation happens by fuel substitution (coal by gas) and introduction of clean coal technologies integrated gasification combined cycle (IGCC).

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1. Introduction

Electricity sector accounted for 35% of natural gas consumption in 2005. High share of electricity sector is on account of government policies which gave it priority in gas allocation. A spurt in gas supplies is in the offing as there have been major gas finds off the east coast1 and there are proposals for creating a nationwide gas transmission grid to link these supplies to the existing and new markets (Fig. 1).

There is, however, a different environment in which future growth of gas market is going to take place. The new supplies will be more expensive as majority of the gas would come from deep sea basin. The production sharing contracts for new supplies allow for market determined pricing. Spreads of gas infrastructures will make gas accessible to new consumer segments like transport, residential and small industrial consumers with different price sensitivities. At the same time, lack of reforms in coal and electricity markets could significantly affect fuel choices made by power producers. In fact, electricity sector has shown faster growth in gas demand during the post-1991 reforms period and the same has been attributed to failure of electricity and coal markets (Shukla et al., 2005). In this paper, we would therefore like to understand demand of gas for power generation under alternative growth and reform scenarios in coal and power sector and what will be the implications for climate and electricity prices.

The future fuel choices for power sector in India have been modelled using energy system models in the past with focus on climate change issues (Shukla, 2006, 1997; Garg et al., 2003). In the immediate past, there are two government reports, which have looked at future energy scenarios, (Gol, 2006; TERI, 2006) and both provide projections for gas in electricity sector for different GDP growth rates. The issue of reforms in power sector and the impacts on fuel choices has been studied (Shukla et al., 2004) but the same has not been projected for future. Therefore, a study which has looked at reforms in coal and electricity sector in India and its impact on fuel choices in power sector with consequent implications for power prices and externalities has not been studied and this paper is trying to address this gap.

Reforms in energy markets have been fairly difficult in the past and even in future creation of a competitive market would be difficult in coal and electricity markets (Gol, 2006). In this paper, we focus largely on reforms on the generation side and coal markets. Finally, we explore the impact on fuel choice under local environmental constraints (SOx) as more aggressive measures to
reduce local air pollution are expected in future (Garg et al., 2006). The expectations about future growth of the Indian economy show a wide range—the Planning Commission of India currently talks of 8% and 9% GDP growth rates through 2032 (GoI, 2006) whereas the International Energy Agency (IEA) has talked of a 6.1% GDP growth for period till 2030 (IEA, 2007). Therefore, five GDP growth rate scenarios were used in this study to explore the impact of this uncertainty on fuel requirements and demand.

The paper is organized as follows. The first section talks about evolution of electricity generation markets in India to give a background to a reader uninitiated to Indian energy sector. A section follows this on future growth scenarios where we analyze gas demand for electricity sector under alternative expectations of growth rates and another section on policy reforms in coal and electricity sector. In the end, we conclude with a discussion of the results.

2. Evolution of gas in Indian electricity market

Electricity generation in India till 1991 was done mainly by government-owned entities—State Electricity Boards (SEBs) owned by respective state governments and Central government-owned entities (Shukla et al., 2004). In line with the definition of a utility provided in the Electricity Act, 2003 all these above-mentioned entities are referred to as utilities. In 1991, as a part of overall economic liberalization of the Indian economy, power generation was opened for investment by private sector (Shukla et al., 2004). It was believed that reforms in generation are the best way to begin and distribution reforms could follow later (Godbole, 2002). The reforms were able to attract only few private players into generation (Shukla et al., 2004) and as a result the electricity shortages also persisted (Fig. 2).

The Indian electricity sector follows inverted tariffs—industrial customers cross subsidize the low or uncollected tariffs from residential and agricultural users. Persistent shortages, high tariffs and spill over benefits like waste heat made it attractive for industrial units to go for their own generation, which is referred as captive generation. The Electricity Act, 2003 has also introduced a provision of allowing captive plants to supply directly to consumers. The evolution of captive is discussed after discussion of utilities.

2.1. Fuel choices within utilities

Gas competes with coal for base load and hydro for peak load. Coal has been the mainstay fuel choice of the utilities and...
accounted for more than 50% of total installed capacity in 2006 (Fig. 3), however, the share has gone down over the last 15 years.

Coal is the most economical fuel for power generation in India (Chikkatur et al., 2007) and its share in generation has remained more than 70% since 1996 (Fig. 4). When we assume variability in values of capital costs, fuel costs, efficiencies and other parameters then gas can become economical in certain cases (Shukla et al., 2004). At locations far from coalfields and close to gas infrastructures, the relative price difference between coal and gas will be lower. Large hydro is the cheapest source of power in India (Shukla et al., 2004), and is mainly used for meeting the peaking demand. Hydro has maintained its share of capacity, however, due to low availability lost its share of generation (Figs. 3 and 4).

A closer look at gas-based generation in the utilities shows that SEBs, centrally owned generators and the private sector had almost equal generation capacity in 2006 (Fig. 5). SEB plants had smaller unit sizes (average unit size 42 MW (CEA, 2006)), at many...
places without steam cycle, making them suitable for peaking purposes. The plants added in the last five years, however, have larger unit sizes (average unit size 60 MW). Central utility plants had larger unit sizes (average unit size 95 MW) and mostly with steam cycle (CEA, 2006). The central plants were given priority allocation of cheaper gas supplies through the administered pricing mechanism (APM), which helped them to run as base-load plants. Decline in supply of APM gas has been compensated by using re-gasified LNG, which, being more expensive, has increased their costs of generation. The weighted average tariffs for six gas-based plants of NTPC having a combined generating capacity of 3.6 GW increased from Rs 2.06 per kWh in 2001 to Rs 2.86 per kWh in 2006 (Infraline, 2007a). Private plants have large unit sizes (average unit size 101 MW) and mostly with steam cycle. These plants came up as a part of government efforts to attract foreign investment into the power sector in the post-reforms period and many of these power plants had a dual firing capability of running on naphtha and natural gas. This was necessary as many large plants (e.g., Enron power project at Dabhol (740 MW)), Gujarat Paguthan Energy at Bharuch (655 MW) did not receive priority allocations of gas and therefore started operations with Naphtha as fuel. However, increase in oil price around 2000 drove up naphtha prices making it unviable to run them. This contributed to very low plant load factor (PLF) for these plants in 2000. However, the PLFs for private plants have improved in last five years, (Fig. 5) mainly due to improved availability of private gas and imported gas.

2.2. Fuel choices within captive generation

Captive power plant capacity more than doubled between 1991 and 2006 and within this gas-based capacity rapidly increased its share (Fig. 6). The gas-based capacity has contributed to generation at a rate faster than coal and other fuels (Fig. 7), because coal as a fuel is not widely and easily available, and gas-based power is often cheaper as compared to tariffs charged by SEB’s to the industries (Shukla et al., 2004).

2.3. Regulation

The Indian electricity sector is characterized by peak shortages (Fig. 2) and sometimes over production in off-peak periods (Chikkatur et al., 2007) despite overall electricity shortages (Fig. 2). The government started giving incentives for high PLF since 1992 (Chikkatur et al., 2007) to improve availability of plants and thereby improve the utilization of capacities. The PLF for thermal plants showed improvement and in 2005 average PLF for India was 73.71%, up from 46% in 1991 (CEA, 2006). This incentive, however, did create a problem during off-peak periods as the
power plants continued generation even when the demand was low. Oversupply results in high frequency and demand more than supply results in low frequency (Bhushan, 2005). To correct the problem of frequency disturbances government introduced a mechanism called availability-based tariff (ABT) in 2002. ABT gives incentives (penalties) to power producers and the distributors (SEB’s) to maintain the system frequency. Power producers get a higher tariff if they supply beyond the scheduled generation when the system frequency is low and are penalised if they supply beyond their scheduled generation when system frequency is high. This mechanism has succeeded in reducing the grid frequency disturbances (GoI, 2006). ABT forces SEBs to commit their demand for grid power for the next day and arrange for the matching supplies. The demand for grid power is satisfied by central utilities, private producers, and surplus SEBs or imports. Power deficit states normally have long-term contracts with central utilities, but the quantity left out is met by having short-term contracts. The market for short-term contracts has developed with the clear articulation of power trading in the Electricity Act, 2003. In the market for short-term contracts, on account of prevalent shortages in electricity, high rates are being paid (e.g., in February 2006 different states were paying prices ranging from 201 to 585 paisa per kWh (Infraline, 2007a)). High rates for power make it economically viable to run plants even on costlier gas available from private gas producers and gas imports which improve their PLF (e.g., in the state of Gujarat, aggregate PLF for private producers increased from 31% in 2001 to 83% in 2006 (CEA, 2007a)). High PLF mean gas-based plants are running as base-load plants. The long-term viability of the gas for base load against coal is discussed under future scenarios.

3. Future scenarios

Energy scenarios are useful tools to understand the impact of a range of market drivers on the future energy system. Each scenario is one alternative image of how the future can unfold based on a range of assumed input; they are neither predictions nor forecasts. They represent the playing out of certain economic, social, technological and environmental and policy paradigms (IPCC, 2000). The most prominent exercises on scenarios-based analysis have been done by the IPCC (Houghton et al., 1990; Alcamo, 2001; IPCC, 2000). The scenario methodology has also been widely used for India (TERI, 2006; Shukla, 2006; Garg et al., 2001; Rana and Morita, 2000; Shukla et al., 1999).

3.1. Scenario storylines

Storylines provide consistent narration of complex interplay among various driving forces for alternative scenarios (Shukla, 2006). Storylines are a way of moving from the qualitative narratives about key drivers to quantitative assessments for the model parameters. The key drivers for the current scenarios are similar to IPCC scenarios, namely economic growth, demographic profile, technological change, energy resources, institutions and policies (IPCC, 2000). The quantification of key drivers is a judgmental process done using a two-stage process (Shukla, 2006)—first the range of numerical values for key drivers from known data sources is collected and then using the qualitative storyline, we decide a specific driver trajectory. We will first discuss about drivers that are common across scenarios and then discuss the storylines of the three reform scenarios which we have developed around this reference scenario.

3.1.1. Macro-economy

The expectations about GDP growth rate of India vary considerably (Table 1). GDP is one of the key drivers; therefore we developed scenarios (Table 2) to explore the expected impact of GDP growth on energy use. In this paper, we report scenarios for the 5%, 6%, 7%, 8% and 9% GDP CAGR for year 2005–2025 period. At the higher end, we matched the growth rate with the planning commission 9% growth rate (Gol, 2006), and at the lower end we took a flat 5% growth rate which is lower than DOE

Table 1
GDP growth rate future—key agencies.

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<tbody>
<tr>
<td>DOE</td>
<td>5.9</td>
<td>5.4</td>
<td>5</td>
<td>5.6</td>
<td>International Energy Outlook, 2007 (DOE/EIA, 2007)</td>
</tr>
<tr>
<td>IEA</td>
<td>7.2</td>
<td>6.4</td>
<td>5.8</td>
<td>6.1</td>
<td>World Energy Outlook 2007 (IEA, 2007)</td>
</tr>
<tr>
<td>Planning commission</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8.0</td>
<td>Integrated Energy Policy (Gol, 2006)</td>
</tr>
</tbody>
</table>

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Fig. 7. Electricity Generation—captive. % Figures indicate CAGR in the intervening period. Source: data from CMIE and CEA (2006), year 2006 author estimates.
scenarios (DOE/EIA, 2007). The five growth rate scenarios differ in terms of their assumptions about economic reforms, regional cooperation, globalization and structure of economy. Economic reforms, regional cooperation and globalization are assumed to show a positive movement with economic growth. The structure of economy with increasing growth becomes increasingly service sector dominated. The population projections as well as the urbanization are as per medium scenario of United Nations Population Projections to 2030 available from United Nations World Population Statistics (UNPD, 2006).

3.1.2. Energy supply and prices

India is a large country with geographically separated energy resources and demand centres. Different fuels become competitive at different locations and at different times depending upon the availability of the resource, extraction costs and transportation costs. This results in competition among energy sources at multiple points that result in their partial penetration. This is represented in the model through multiple-grade specifications for each energy form. Coal and gas are the two most important sources of thermal energy in India and the competition between the two will depend to a large extent on the relative prices of these two fuels.

3.1.2.1. Coal. Coal mining for selling into the broader market is restricted to centrally owned Coal India Limited (CIL) and Singareni Coal Company Limited (SCCL), however, captive mining by power producers was allowed in 1993. The coal companies supply coal to users, decided by a coal linkages committee, composed by government representatives from the state-owned coal companies, railways and major consuming industries. In March 1996, the government granted CIL & SCCL the freedom to set prices for Grade A, B & C coal. The move allowed producers to charge differentially based on coal quality and transportation costs. The prices were progressively decontrolled and as per the Colliery Control Order, 2000 CIL & SCCL are now free to price all grades of coal. The prices increased post-decontrol (see Fig. 8) and the gap between domestic coal prices and international coal prices was rationalized to some extent but the recent spike in international coal prices has again left domestic coal prices out of sync with international coal prices. The mine mouth coal price varies with grade (with higher grades commanding a higher price) and also the between different coalfields (e.g., Grade A coal prices varied from Rs 1160 to Rs 2060 per tonne) (Ministry of Coal, 2007).

The domestic reserves of coal and hence production is not evenly spread and located mainly in eastern and central parts of India, whereas power plants are scattered rather evenly across country (Fig. 9).

The average distance over which coal was transported to power plants was 641 km in 2005 (Ministry of Railway, 2006). The average transportation cost of coal by rail in 2005 for one tonne of coal was Rs 853 (US $ 19.4) per 1000 km (Ministry of Railway, 2006), which is around the price of Grades C and D coal used for power generation. Therefore, the coal cost for domestic coal show a wide variation firstly due to widely varying mine mouth costs and secondly due to different transportation costs. This wide variation in prices is modelled by having around seventeen grades of coal with total annual mining capacity projected to increase from about 400 million tonnes in 2005 to about 820 million tonnes per annum in 2025.

Coal imports have increased from 5.93 to 34.88 million tonnes in 2005 (CMIE) and a large percentage is for power generation. Plants both near coast and inland are consuming this coal. Imported coal is modelled as three grades to account for variation in leads of inland transportation costs. The import coal price assumptions are based on price assumptions given by IEA (IEA, 2007)

3.1.2.2. Natural gas. There are currently multiple prices prevailing in the Indian gas market, which are dependent on the suppliers. Broadly the Indian gas prices can be classified into three grades—administered government prices, market-priced domestic gas and market-priced imported gas. The current gas prices for these three categories shows a very wide variation in prices (Table 3). However, reforms of the markets in the long term are necessary for achieving the economic growth targets and hence assumed. Reforms of gas markets will help to get the market integrated with global gas markets (Siliverstovs et al., 2005) and converge towards an efficient equilibrium. The wellhead price information (Infraline, 2007b) is, however, useful because we make the regulated prices equal to the marginal costs for different gas basins and combine it with the expansion plans for different basins to create supply curves for future years. To understand expansion plans for future, we met key persons in the firms who

Table 2
GDP growth rate—future scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>2007–2012 (%)</th>
<th>2012–2017 (%)</th>
<th>2017–2025 (%)</th>
<th>Overall CAGR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9%</td>
<td>9.0</td>
<td>9.0</td>
<td>9.0</td>
<td>9.0</td>
</tr>
<tr>
<td>8%</td>
<td>8.0</td>
<td>8.0</td>
<td>8.0</td>
<td>8.0</td>
</tr>
<tr>
<td>7%</td>
<td>7.0</td>
<td>7.0</td>
<td>7.0</td>
<td>7.0</td>
</tr>
<tr>
<td>Reference</td>
<td>7.0</td>
<td>6.0</td>
<td>5.0</td>
<td>6.0</td>
</tr>
<tr>
<td>5% (RS) G</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
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</tbody>
</table>

Fig. 8. Coal price trend: northern coal fields. Source: data from Indiastat (2006) and CMIE for January-05.
are into development of gas basins. An upper cap was put based on gas reserves available from Directorate General of Hydrocarbons.

Gas imports can come through LNG and pipelines. The two modes for imports not only have different investment costs but also different risks. International pipelines are generally considered riskier than LNG due to the high sunk costs, involvement of transit countries, and supplier inflexibility, but pipelines are generally cheaper over shorter distances than LNG (Jensen, 2004). India is close to several gas-rich countries in Central Asia and Middle East, therefore pipeline can be a cheaper option. However, discussions with experts on geopolitics, and study of literature on cross-country pipelines (Victor et al., 2006) and pipelines from Middle East and Central Asia to India (Pandian, 2005; Tongia, 2005) show that international pipelines are a very low probability event and therefore not considered. However, to understand the implication of these pipelines, we introduced imported pipeline gas for 8% scenario. This case is referred as the 8%—IP scenario.

The international prices of LNG were based on price forecasts of IEA (IEA, 2007), however, given the uncertainty associated with

Table 3

<table>
<thead>
<tr>
<th>US $ per Mbtu</th>
<th>Lower</th>
<th>Upper</th>
<th>Remarks</th>
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</thead>
<tbody>
<tr>
<td>APM</td>
<td>1.67</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Market priced gas (pre-NELP &amp; NELP)</td>
<td>3.06</td>
<td>4.75</td>
<td>Lower : gas from Lakshmi and Gauri fields</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Upper : gas from PMT</td>
</tr>
<tr>
<td>LNG imports</td>
<td>2.53</td>
<td>10</td>
<td>Lower : petronet</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Upper : shell spot cargoes</td>
</tr>
</tbody>
</table>

Source: Prices based on (Infraline, 2007b).
these prices we also used a high oil gas price scenario where the oil prices are assumed to be at US $ 100 in 2030 (DOE/EIA, 2007). This high gas price scenario has been referred as 8%—HP scenario.

In addition to the wellhead costs there are pipeline transmission costs and city gas network costs, which have to be taken into the supply prices. The wellhead costs and transmission costs were combined and modelled by having sixteen grades of gas to develop a supply curve (Fig. 10). We provide for year 2010 both underlying grades (only nine grades active in 2010) and the linearization of the step-wise articulation. CGD network costs were separately provided by modeling CGD as a consumer of bulk gas and seller to retail customers.

3.1.3. Electricity generation technology

The electricity generation technologies differ from each other on the basis of type of fuel used, capital cost, operating and maintenance costs, conversion efficiencies, scale economies, suitability to meet peaking loads, and environmental characteristics. In addition, the same generation technology will have different costs at different places on account of land prices, labour costs and scale of production and utilization levels. The non-linear distribution in the costs of technologies across the country and the diversity in technological characteristics are represented in the model by different grades of technologies. The different technologies have been assumed to improve over time on account of autonomous efficiency improvements, which happen due to penetration of advanced technologies, retrofitting of existing technologies with improved ones, and retirement of old and inefficient technologies.

3.1.3.1. Peak and base-load technology representation. There are two peaks observed in the all India daily load curve, occurring for about 3 h each in the morning and evening (Bhushan, 2005; Banerjee, 1998). This changing hourly demand is represented in a stylized way by a two-step demand function having an off-peak and peak period (Loulou et al., 2004). To satisfy the demand generation capacities are designated as peak and off-peak. Hydro and gas technologies are more suitable for meeting peak load requirements than coal technologies due to inherent technology characteristics. Coal and nuclear technologies are suitable for meeting base-load requirements.

The actual peak demand can be higher than the peak demand representation through the two-step demand curve as there can be unscheduled shutdowns, demand peaks and uncertainty in the availability of solar, wind or hydro power (Loulou et al., 2004). To overcome this shortcoming and improve system reliability a peak reserve capacity factor is introduced which leads to creation of a reserve capacity. Higher levels of peak reserve capacity need to be built in the system to improve reliability of electricity supply.

3.1.3.2. Technology penetration. The penetration of technologies like hydro and nuclear, is restricted by social and political factors. Hydro-power development in South Asia is dependent on cooperation within the countries (Shukla et al., 2009) besides resolving issues related to rehabilitation. Nuclear power development would depend mainly on the unfolding of Indo US nuclear cooperation agreement. These constraints are modelled by specification of upper bounds on technology penetration. Starting points for assigning the upper bounds are the official government of India projections (Gol, 2006). These projections have been moderated for the growth rates assumed.

3.1.3.3. Transmission and distribution efficiency. The Indian electricity grid has historically faced very high transmission and distribution losses (Table 4). The transmission loss figures include commercial losses in addition to the technical losses, which are euphemistically referred to as “Electricity Unaccounted” (CEA, 2006). The technical losses should vary from 7% to 15.5% and in most developed countries these are even less than 7% (Bhalla,
2001). The auxiliary power consumption figures show variations which is due to variations in fuel mix.

T&D losses have shown a declining trend of late and the government is apprised of the need to reduce the same further and by employing technology options as well as community participation (Ministry of Power, 2006). Therefore, our future projections adopted the two pronged approach of the central government to improve T&D efficiency and reduce commercial losses (Table 5). The technical losses are put at 15.5% for 2005 which is the maximum possible (Bhalla, 2001) and then improved progressively over years. Commercial losses are also reduced rapidly to reflect the partial success of reforms in controlling thefts from industrial units and residential consumers in urban areas. Commercial losses from agricultural sector would be politically difficult and therefore not brought down to zero.

Commercial losses are nothing but a zero price demand for electricity but the model is passing on the marginal cost of generation to all consumers. Commercial losses were made a part of the technical losses and this raises the delivered price of electricity to all consumers. This method helped us to remain closer to reality because the utilities are using T&D losses to get higher tariffs on the grounds of remaining viable.

### 3.2. Analysis and results growth scenario

The future gas market analysis has been done using ANSWER MARKAL Model (Loulou et al., 2004). ANSWER MARKAL model that follows the bottom-up modeling paradigm enabling specification of technology details was initially setup for India by Shukla and Loulou (Loulou et al., 1997) and later, significant model development in an integrated framework have been done (Kanudia and Loulou, 1999; Garg et al., 2003; Shukla et al., 2003). The current exercise involved upgrading the model databases to reflect the changed expectations about the future of Indian economy and to create a more detailed representation for natural gas.

#### 3.2.1. Demand for gas in power generation

The general trend across the five growth scenarios is an increase in gas demand for power in future (Fig. 11). However, the future transitions reveal when economic growth is faster than RS growth of 6% as is in 7%, 8% and 9% scenario, gas demand is lower till 2020 after which the gas demand is higher than RS. The trend of gas in power sector can be explained by four main factors: demand for electricity, gas availability, relative prices of coal and natural gas and gas demand from other sectors.

#### 3.2.1.1. Demand for electricity

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#### 3.2.1.2. Gas supply

There is a rightward shift of the gas supply curve (see Fig. 10) on account of increasing availability of gas from domestic sources and imports post 2010. This enhanced availability of gas helps in removing constraints of gas supply. In 2025, however, we see a shift towards left on account of decline in cheaper domestic gas reserves and an increase in global gas prices. This shift means that gas prices will be higher for the same quantity and increase the price for power sector. However, if international pipelines happen as is the case in 8% IP scenario they will deliver gas directly into Northern parts of India (Fig. 1) which have a large market. This reduces the need for inland transportation and lowers delivered price relative to LNG and, therefore additional supplies are created at lower prices.

#### 3.2.1.3. Relative prices of fuels

Coal and natural gas are the two fossil fuels that compete with each other for a share of power generation. Their future share in the power sector will depend largely on the relative prices of these two fuels. Gas-based plants have lower capital costs and higher generation efficiencies (Shukla et al., 2004), which gives them a competitive advantage of around US $ 4 per Mbtu over coal-based plants. The coal prices in nearly all the scenarios are close to US $ 3 per Mbtu (Fig. 14) and this means that a market clearing price of gas till US $ 7 Mbtu will result in growth of gas-based generation. The tightening gas situation post-2015 results in an increase in the gas prices (Fig. 14) and these results in a fall in gas demand from base-load gas plants in 2025. In case, the expectations are of high oil and gas prices in future as in 8% HP scenario then the new capacity additions would...
become difficult and the existing gas-based capacities would be mainly used for meeting the peaking demand thereby severely reducing the demand for gas in electricity (Fig. 11).

In the 7%, 8% and 9% growth scenario the coal prices decline due to improved coal supply and therefore widen the relative price difference and this makes it difficult for the growth of gas in the power sector.

3.2.1.4. Demand from other sectors. The demand from other sectors like industrial, residential, commercial and transport where gas is a substitute for liquid fuels like motor spirit, diesel, naphtha and furnace oil increases with increasing economic growth e.g., for the 8% scenario the demand from other sectors is around 100 bcm in 2025, for RS scenario it is around 90 bcm in 2025, and for the 5% scenario it is around 83 bcm in 2025. Higher demand from other sectors reduces the supply of cheaper gas for electricity sector. Costlier gas cannot compete for base load though it is competitive for peak load. This explains the lower gas demand in 7%, 8% and 9% growth scenarios relative to RS and 5% scenario till 2020. However, by 2020 gas prices increase and so does demand from other sectors confining gas mainly for peaking even in the RS and 5% growth scenario.

3.2.2. Electricity costs

Gas technology is the preferred option in the least-cost power plan in all scenarios for building lower utilization capacities such as for peaking generation and system reliability. Hydro is ideal for peaking generation, but growth is constrained by difficulty in installing new capacity (Shukla et al., 2009). Other renewable, like wind and solar are intermittent to provide for peaking power and reliability. Therefore, the price signals for peaking power arise from the long-run marginal cost (LRMC) of gas-based generation. The delivered LRMC of electricity for peaking demand shows greater variability over time and for different scenarios (Fig. 15) as compared to off peak.

The peak prices average between $0.08 per kWh to $0.12 per kWh and the off-peak tariffs remain between $0.06 per kWh and $0.04 per kWh. The peak period was defined for 6 h a day; therefore the weighted average tariff is around 6.25 cents per kWh. This tariff is lower than average tariffs charged for domestic consumers consuming more than 100 kwh in a month in most states, lower than tariffs charged for industrial and commercial customers in nearly all states but higher than agricultural tariffs (CEA, 2007b). Therefore, at an aggregate level, if agricultural subsidies are borne by the state government’s then there will be surpluses for SEBs without changing the tariffs.

The peak tariffs are nearly double the off-peak tariffs meaning that there is a merit in time of use pricing so that correct signals are passed on for bringing in generation capacities and reducing the peaking demand. ABT as a policy instrument for addressing the problem of peaking demand will translate into clear signals for peaking plants when the regulators make it mandatory for
SEBs to supply electricity to consumers at all times and in turn allow SEBs to charge as per the time of use.

3.2.3. Emissions

SO\textsubscript{2} emissions from electricity sector get decoupled from electricity demand across scenarios (Figs. 12 and 16) and in the 9% growth scenario this decoupling is complete and Kuznets phenomenon is clearly visible (Fig. 16). There are two reasons for this—mitigation by coal-based plants and substitution of coal by gas. Sulphur mitigation by coal-based plants happens due to coal washing and installation of flue gas de-sulphurisation (FGD) units. Power plants coming under the ultra-mega power plant policy have to provide space for FGD units and there is also local pressure on existing units to build FGD.\footnote{Reliance Energy Limited, has been forced to set up a FGD at their coal plant located at Dahanu Taluka in Maharashtra (REL, 2006).} After 2020 a leftward shift in gas supply curve (Fig. 10), results in lower gas demand from the power sector, and a rise in SO\textsubscript{2} emissions is seen (Fig. 16) due to a shift to coal. However, in 9% growth scenario with per capita GDP crossing US $ 3000 by 2020 the environmental concerns are stronger and, therefore, the coal-based capacities are lower than 8% growth scenario (Fig. 13).

4. Policy scenarios

4.1. Coal reforms

Coal reforms till 2005 were discussed in Section 3.1.2. Coal reforms in the future are defined as opening up of the coal mining to other players besides captive producers and the incumbent state-owned monopolies to bring an improvement in management practices. Improved management practices are expected to bring improvement in operational efficiencies, safety and local environment. Improvements in operational efficiencies mean a lowering of LRMC, however other measures may increase costs. The second function of a reformed market is availability at all locations freely and this means there will be adequate capacity for transporting coal by railways and ports. Additional transport sector investments will mean higher transportation costs. Investments in transport would also make it possible to reduce differences between domestic and international coal market which is currently high (Fig. 8). Overall the supply curve becomes flatter due to reforms (Fig. 17). The success of reforms will depend on the level of investments that are mobilised which will eventually increase the supply of domestic coal. However, it is hard to predict the level of investments and therefore we consider three states low, medium and high (Fig. 17) in the reform scenario.

4.2. Electricity reforms

India has faced a shortage of power consistently (Fig. 2) despite electricity reforms launched in many states. One solution currently being promoted by the central government would establish several 4000 MW coal-fired power plants. These “ultra-mega power plants (UMPP)” will be built on an expedited approval process through which the government identifies project location, contracts with long-term buyers for power, takes necessary clearances and then sells the special purpose vehicle to the private player who bids to generate power at the cheapest cost. The goal is to encourage jittery investors who have been reluctant to invest in the Indian power sector due to the bankrupt SEBs. The plants will be located at either pithead or along the coast, and will source their coal either from the local mine or via imports—eliminating need for railway transport, however, these plants will deliver electricity over a longer distance. This strategy has been referred to as “Coal by Wire”. The current policy paradigm to correct for market failures in generation will create a generation and transmission structure quite different from that followed in the past where generation was located close to demand centre (Fig. 18).

This will happen because four eastern states (Fig. 9) Jharkhand, West Bengal, Orissa and Chattisgarh account for 77% of coal reserves and therefore a lot of coal-based power generation capacities will come here. The UMPP policy would require adequate inter-regional transmission capacities between power surplus regions and power deficit regions. Coal-by-wire scenario has higher availability of coal grades which have lower transportation costs and higher transmission costs.

4.3. Sulphur controls

The burning of fossil fuels causes damage to the atmosphere in terms of SO\textsubscript{2}, NO\textsubscript{x}, and particulate emissions. In India coal is the major fossil fuel used for power generation and as the emissions are conjoint we take SO\textsubscript{2} as the key pollutant around, which we have modelled the environmental reform scenarios.

SO\textsubscript{2} emissions increased from 2.85 Million tonnes in 1990 to 4.80 million tonnes in 2005 (Garg et al., 2006) and within this the contribution of power sector increased from 36.7% to 56.7% during the same period (Garg et al., 2006). In the hot spot districts (top 25 districts) for SO\textsubscript{2} emissions the contribution from power sector is very high (Table 6). It is also seen that most of these hot spot districts have high population-density, which means that the
impacts of pollution will be felt by a large number of people and lead to substantial social costs.

The power sector being a point source, sulphur can be easily monitored and controlled. The spatial spread (at district level) of emissions in 2025 in the reference scenario (Fig. 19) showed a rise in hot spot districts in the eastern part and coastal regions. Increasing concentration of SO$_2$ in districts which already had high levels would mean policy interventions beyond what have been taken in the RS scenario.

SO$_2$ emission problems can be solved by either technology performance standards or by using economic approaches (Baumol and Oates, 1998). Economic approaches have been found to be superior to technology performance standards (Kerr and Newell, 2003; Schmalensee et al., 1998; Stavins, 1998). We analyze a policy of having sulphur permits which limit the overall emissions followed by emissions trading to achieve the most efficient reduction. The policy objective is to reduce SO$_2$ emissions by 40% from Reference scenario in 2025.

4.4. Analysis and results policy scenarios

The policy analysis was done around the reference scenario which is our 6% growth scenario. This scenario is closer to the international scenarios of IEA and DOE for two reasons. The first is that this paper was developed as a part of an international study of gas markets in India and China, and therefore, there was a need to make the scenarios comparable and acceptable to the international audience. The second is that the Planning Commission scenario of 8% economic growth are likely only if a fair amount of reforms are carried out (GoI, 2006) and therefore a reforms scenario over and above these reforms would become useless. The results for all three policy cases have been consolidated so that a comparison between different cases can be done. The graphs, for the sake of clarity, have been abbreviated to CR L, M, H for coal reforms low, medium and high, CBW for coal-by-wire, and SC for the sulphur controls scenario.
4.4.1. Demand for gas in power generation

CR L, CR M, CR H and CBW scenarios show lower gas demand, whereas the SC scenario shows demand for gas rising post-2015 (Fig. 20). The trend in gas demand that emerge for three policy cases has been explained by—relative prices of fuel, environmental constraints and infrastructure availability.

4.4.1.1. Relative prices of fuels. The three coal reforms and CBW scenario have lower coal prices (Fig. 21). In the three CR scenarios coal prices go down due to a rightward shift of coal supply curve (Fig. 17) whereas in CBW it is due to the flexibility of infrastructure. The difference in gas demand from the RS scenario reduces as the difference in relative prices is reduced.

4.4.1.2. Sulphur constraint. The sulphur constraint results in a shadow price of SO2 which changes the relative price of coal and gas. Coal has the highest sulphur concentration in the fossil fuels, whereas gas is free from sulphur. In the initial years, when constraints are mild, it is cheaper to install FGD units which partially mitigate SO2 emissions from coal plants at a low cost, for

Table 6
Hot spot districts (top 25) for SO2 emissions in 2005.

<table>
<thead>
<tr>
<th>Rank</th>
<th>District</th>
<th>Emission per unit area (ton/sq. km)</th>
<th>% Contribution of power</th>
<th>Population density</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Central Delhi</td>
<td>457.91</td>
<td>85</td>
<td>29,098</td>
</tr>
<tr>
<td>2</td>
<td>Kolkata</td>
<td>261.98</td>
<td>77</td>
<td>24,430</td>
</tr>
<tr>
<td>3</td>
<td>Chennai</td>
<td>233.47</td>
<td>66</td>
<td>26,420</td>
</tr>
<tr>
<td>4</td>
<td>Mumbai</td>
<td>188.58</td>
<td>72</td>
<td>22,315</td>
</tr>
<tr>
<td>5</td>
<td>South Delhi</td>
<td>181.14</td>
<td>87</td>
<td>10,204</td>
</tr>
<tr>
<td>6</td>
<td>New Delhi</td>
<td>162.92</td>
<td>92</td>
<td>5545</td>
</tr>
<tr>
<td>7</td>
<td>North East Delhi</td>
<td>77.76</td>
<td>33,204</td>
<td>33,204</td>
</tr>
<tr>
<td>8</td>
<td>East Delhi</td>
<td>59.88</td>
<td>25,570</td>
<td>25,570</td>
</tr>
<tr>
<td>9</td>
<td>Panipat</td>
<td>52.42</td>
<td>91</td>
<td>784</td>
</tr>
<tr>
<td>10</td>
<td>Mumbai (suburban)</td>
<td>47.48</td>
<td>20,277</td>
<td>20,277</td>
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<tr>
<td>11</td>
<td>Sonbhadra</td>
<td>47.30</td>
<td>99</td>
<td>243</td>
</tr>
<tr>
<td>12</td>
<td>Bokaro</td>
<td>47.18</td>
<td>75</td>
<td>745</td>
</tr>
<tr>
<td>13</td>
<td>West Delhi</td>
<td>43.46</td>
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<tr>
<td>14</td>
<td>Hyderabad</td>
<td>41.72</td>
<td>17,814</td>
<td>17,814</td>
</tr>
<tr>
<td>15</td>
<td>Gautam Buddha Nagar</td>
<td>37.81</td>
<td>1089</td>
<td>1089</td>
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<tr>
<td>16</td>
<td>Rupnagar</td>
<td>36.09</td>
<td>594</td>
<td>594</td>
</tr>
<tr>
<td>17</td>
<td>North Delhi</td>
<td>34.38</td>
<td>14,681</td>
<td>14,681</td>
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<tr>
<td>18</td>
<td>Cuddalore</td>
<td>32.70</td>
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<td>19</td>
<td>Korba</td>
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<td>Anugal</td>
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<td>21</td>
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<td>1002</td>
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<tr>
<td>22</td>
<td>Chandigarh</td>
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<td>9211</td>
<td>9211</td>
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<tr>
<td>23</td>
<td>Murshidabad</td>
<td>21.27</td>
<td>1185</td>
<td>1185</td>
</tr>
<tr>
<td>24</td>
<td>Gandhinagar</td>
<td>20.50</td>
<td>720</td>
<td>720</td>
</tr>
<tr>
<td>25</td>
<td>Purbi Singhbhum</td>
<td>19.75</td>
<td>596</td>
<td>596</td>
</tr>
</tbody>
</table>

Source: author estimates.

Fig. 19. District wise SO2 emissions from coal-based power generation.
both the existing and future plants. In the longer term, the constraint becomes stringent, and choice for power producers is between gas, costlier FGD (with high sulphur removal), and technologies like integrated gasification combined cycle (IGCC). The FGD continues as the first choice for mitigation but the second most economical solution is substitution to gas. IGCC also gets a minor push because of sulphur controls (Fig. 22).

4.4.1.3. Infrastructure. Electricity uses different infrastructure to transport the raw materials (coal and natural gas via pipelines and rail) and the final product (electricity over the grid). In the CBW scenario, we modelled this flexibility for coal plants and it turns out that power producers find it cheaper to set up plants at the mine mouth. This flexibility helps coal-based power plants to overcome shortages in rail capacities and therefore install additional coal-fired capacity.

5. Conclusions

The current capacity of gas-based plants is mainly for base load because there are shortages for electricity. Gas has played an increasing role in power generation within utilities and even more in the case of captive power plants. Power shortages have resulted in high prices for electricity and these have helped the gas-based power plants which have improved PLF even when gas prices have increased in the Indian market. In the future, gas competes with coal for base-load capacity in scenarios where domestic coal supply remains constrained or when there is not adequate demand elsewhere in the economy. Base-load gas power plants are competitive vis-à-vis coal plants when relative difference between gas and coal prices is below US $ 4 per MBtu. At higher than $ 4 per MBtu price difference, gas is competitive only for peak power supply. The US $ 4 price advantage for gas and ability to play an equal part in peak and base-load market gives a lot of flexibility to power producers. This flexibility results in a high elasticity of substitution between the coal and gas. In the higher growth scenarios as a result though the overall demand for gas is higher the demand for gas from power sector is lower owing to higher demand from other sectors. In the coal reforms scenarios the flexibility allows power producers to shift faster to coal when there is a rightward shift of coal supply curve. The flexibility of transporting coal or transporting power to demand centre’s is used by power producers to overcome the rail infrastructure bottlenecks and substitute gas from base-load power generation. High gas prices like those witnessed when oil crossed US $ 100 level make gas costly even for peak load market and restrict any capacity additions of gas-based power plants.

The flexibilities available in the electricity sector due to gas effectively lead to higher coal power capacities that add to environmental problems, like higher SO2 emissions from coal burning. Our results show imposing a cap on SO2 emissions, results in end of pipe solutions like FGD as most cost-effective solution. However, in a longer term, gas technologies are also contributing to sulphur mitigation. Clean coal technologies like IGCC get a minor push in the longer term. Gas also benefits from international gas pipelines which help in making gas competitive with respect to coal in northern gas markets which are far from coal deposits.

Gas technology is the preferred option in the least-cost power plan in all scenarios for building lower utilization capacities such as for peaking and system reliability. The increase in gas price thus has higher implications for the peak electricity price. In the early years though, improvements in generation and T&D efficiency, including reduction in commercial losses from pilferage and metering deficiencies, can compensate for higher gas price. However, as the electricity system becomes competitive and converges to an efficient equilibrium in the long-run, the peak electricity price gets increasingly aligned to the gas price.