60th Holland Memorial Lecture

at

Biswa Bangla Convention Centre

Newtown, Kolkata

on

29th September 2018

by

Dr Kirit Shantilal Parikh

Chairman, Integrated Research and Action for Development (IRADe)

The Mining, Geological & Metallurgical Institute of India (MGMI)
GM - 38/4, Salt Lake, Sector V, Kolkata 700 091, INDIA
Phone : +91 33 2357 3482 / 3987 / 6518 | Fax : +91 33 2357 3482
E-mail : mgmisecretary@gmail.com / mgmihonysecretary@gmail.com
Website : www.mgmiindia.in

60th Holland Memorial Lecture

Speaker

Dr Kirit Shantilal Parikh
FNASc, ScD (MIT), MS (MIT)
MTech (IIT Kharagpur)

Future of Coal in Power Generation

Coal faces severe challenges from environmental considerations. Local air pollution, emissions of CO_2 and even land degradation due to mining, all call for reduced use of coal. Major use of coal in India is for power plants. Dramatic reduction in cost of solar power and battery technology, expected by many, might make coal power generation economically less attractive. In this talk these issues will be explored and some scenarios for future use of coal in power generation will be presented.

Dr Kirit Shantilal Parikh is one of the most eminent experts on energy policy and economics in India and internationally. Currently, he is the Chairman of the Integrated Research and Action for Development (IRADe), an organization he founded with Dr Manmohan Singh, Dr R A Mashelkar, Mr Adi Godrej and other distinguished Indian leaders.

He holds a Doctoral degree in Civil Engineering and a Masters' degree in Economics from the Massachusetts Institute of Technology (MIT), USA.

Dr Parikh was Member of the Planning Commission, Government of India and the Chairman of its Integrated Energy Policy Committee. He was a Member of the Economic Advisory Council (EAC) of the Prime Ministers of India, S/Shri Atal Behari Vajpayee, P V Narasimha Rao, Chandra Shekhar, V P Singh and Rajiv Gandhi. He also founded the Indira Gandhi Institute of Development Research as the Director. Other key positions on which he has served include:

- Member of the Board of Directors, State Bank of India, LIC, IDBI and IPCL
- Senior Economic Adviser to the Administrator, UNDP, New York
- Programme Leader of the Food and Agricultural Programme, and later Chairman of the Indian National Committee at the International Institute for Applied Systems Analysis (IIASA), Austria
- Director of Programme Analysis Group (PAG), Department of Atomic Energy, Government of India
- Professor and Head of the Department of Economics, Indian Statistical Institute
- Member of the National Committee for Environmental Planning and Coordination
- Member of the National Committee on Science and Technology
- Member of the Fuel Policy Committee

He has been awarded the Padma Bhushan, the third highest civilian honours conferred by the President of India. Dr. Parikh has been the President of the Indian Econometric Society and Gujarat Economic Association. He was felicitated as one of the engineering personalities by Indian Engineering Congress, December 2006. He was honoured as the most distinguished and illustrious alumni of the decade from India by the Massachusetts Institute of Technology (MIT), USA in September, 2007. He was conferred the Distinguished Alumnus Award by Indian Institute of Technology (IIT), Kharagpur in September, 2007. Dr Parikh is also an elected Fellow of the National Academy of Sciences, India.

Dr Parikh has authored and edited 29 books, including editorship of the India Development Report, which provides a non-governmental assessment of India's development and policy options. He has also been Review Editor to the most-recent 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).

Future of Coal in Power Generation*

Dr Kirit Shantilal Parikh

I am honoured to have been invited to give Holland Memorial Lecture and join the ranks of many illustrious persons who have given this lecture before.

Indians have an ambivalent attitude about the legacy of British rule in India. The railways and the steel frame helped unite India, though many feel that the steel frame is too rigid and has kept us backward. They created many research and development institutions, which helped India in its industrial and technical growth. Among these is the one created by Sir T H Holland, Mining, Geological and Metallurgical Institute of India (MGMI).

On the other hand, India was one of the richest countries of the world when Robert Clive landed in India and one of the poorest when India became independent. The worst part was that the British rule created among Indians a sense of diffidence. However, there were many Britishers who nurtured a sense of inquiry and scientific attitude among Indians and we must be grateful Britishers like Sir T H Holland for their contribution to India's scientific development.

Coal in India's Economy

Coal has been the major energy resource of India. India is short of oil and gas but coal reserves are relatively abundant. Coal has been the mainstay of our energy use. Table 1 shows the energy resources of India.

Table 1: India's Hydrocarbon Reserves

Resources	Unit	Proved	Inferred	Indicated	Production in 2016-17	Net Imports in 2016-17	Reserve/ Production Ratio	
		(P)	(I)		(Q)	(M)	P/Q	(P+I) / Q
Coal (as on 31.03.2017)	Mtoe	58655	13440	57113				
Extractable Coal**	Mtoe	20882	6860-12685		271.7	77.6	77	102-123
Lignite (as on 31.3.2017)	Mtoe	1874	3478	7452				
Extractable Lignite	Mtoe	1874			13.0		145	
Oil (2005)	Mt	604.1			36.01	214	17	17
Gas (2005)	Mtoe	1161			29	17	40	40
Coal Bed Methane	Mtoe	96			0.52			

* Balance Recoverable Reserves

1 Indicated Gas resource includes 320 Mtoe claimed by Reliance Energy. In addition, GSPC has indicated about 360 Mtoe of reserves, which have not yet been certified by DGH.

2 From deep seated coal (not included in extractable coal reserves)

** Extractable coal from proved reserves has been calculated by considering 90% of geological reserve as mineable and dividing mineable reserve by Reserve to Production ratio (2.543 has been used in 'Coal Vision 2025' for CIL blocks); and range for extractable coal from prognosticated reserves has been arrived at by taking 70% of indicated and 40% of Inferred reserve as mineable and dividing mineable reserve by R:P ratios (2.543 for CIL blocks and 4.7 for non-CIL blocks as per 'Coal Vision 2025').

Sources :

http://petroleum.nic.in/sites/default/files/ipngs1718.pdf

Energy Statistics 2018

"Indian Petroleum & Natural Gas Statistics 2016-17"

**This is largely based on the final report of the study by IRADe for the Global Technology Watch Group set up by the Department of Science and Technology, Coal Road Map for India (2018)*

Note:

Conversion factors: 1 Million Tonne of Coal = 0.41 Mtoe

1 Million Tonne of Lignite = 0.2865 Mtoe

1 Billion Cubic Meter of Gas = 0.9 Mtoe

1 Million Tonnes of LNG = 1.23 Mtoe

Extractable coal can last for 77 years at the rate of production of 2017-18. However, if the coal production keeps growing at 5 % per year, then we can run out of coal including that from indicated and inferred reserves in less than 40 years.

Coal use in different sectors is given in Table 2.

Table 2: Industry wise Consumption of Thermal /Non Coking Coal in India 2016-17 (Million Tonnes)

Industries	In Million Tonnes	Percentage share
Power	527.26	67%
Industry	16.96	2%
Others	246.83	31%
Total	**791.05**	**100%**

Source: http://mospi.nic.in/sites/default/files/publication_reports/Energy_Statistics_2018.pdf

We see that power sector is the major user of coal consuming 67% of thermal coal used in the country. I will therefore look at the power sector.

Projection of requirement of coal in the power sector without any consideration of environmental concerns give us an upper bound of how much coal power sector would need in the future. Table 3 shows projection we have made with a multi-sectoral inter-temporal activity analysis optimizing model. In this coal efficiency improvement has been assumed at 1% per year. Also all new coal plants are to be super critical.

Table 3: Coal Requirement for Power Sector (MT)

Year	Capacity (GW)	Generation (Billion Kwh)	Coal Requirement (MT)
2015	143	999	680
2020	216	1511	1022
2030	440	3081	2071
2040	836	5862	3930
2050	1398	9799	6557

The projected requirement is huge and would involve substantial import of coal. Can we absorb this level of coal use?

Coal faces severe challenges from environmental considerations. Local air pollution due to emissions of particulates and SOx, emissions of CO_2, displacement of people and land degradation due to mining are growing concerns. What role can clean coal technologies play here?

Major use of coal in India is for power plants. What are the implications for coal of dramatic reduction in cost of solar power and battery technology that is expected by many? Would it make coal power generation economically less attractive?

Role of Clean Coal Technologies in Controlling Local Air Pollution

The government already requires that coal plants have modern electro-static precipitators. One needs to make sure that these trap particulates of 2.5 micron size. This should involve some retrofitting of old plants and additional investment in new plants.

Controlling SOx NOx emissions requires FGD, flue gas desulfurization. Also selective catalytic reduction (SCR) can clean up the plant further. This is somewhat more expensive. Yet, coal power may still remain competitive with other alternatives. We have explored the role that FGD can play in a multi-sectoral inter-temporal optimizing model that considers various alternative power technologies and optimizes power production with a 40 year horizon. It considers the investment required as well as the operating costs of different types of plants. Table 4 shows the characteristics of different plants considered.

Table 4: Characteristics of Different Coal Based Power Plants

Technology	Sub critical PC Boiler with ESP	Super-critical PC Boiler with ESP	Ultra-Super Critical PC Boiler with ESP	Sub-critical PC Boiler with ESP, FGD, SCR	Super-critical PC Boiler with ESP, FGD, SCR	Ultra Super-critical PC Boiler with ESP, FGD, SCR
Net Plant efficiency (%)	34.38%	35.92%	37.19%	33.18%	34.73%	35.96%
Auxiliary power (%)	7.27%	7.18%	9.92%	10.50%	10.27%	12.88%
S.F.C. (Kg/ kWh) coal GCV 2800 Kcal/kg	0.89	0.85	0.83	0.93	0.88	0.85
Capital Cost# INR Cr/MW	5.90	6.30	7.01	9.28	9.69	9.96
O&M# INR Lakh/MW	97	96	104	121	122	125
LCOE (INR/kWh)	2.35	2.4	2.62	3.23	3.28	3.38
CO_2 emission (kg/MWh)	1015	971	938	1059	1010	977
SO_2 emission (kg/MWh)	10.1	9.6	9.3	0.3	0.3	0.3
NOx emission (kg/MWh)	4.5	4.2	4.1	0.5	0.5	0.5
Particulate emission (kg/MWh)	1	1	0.9	0.1	0.1	0.1

Source: GTWG Report (2018)

Cost in 2016 prices Source: IRADe Analysis, and Chapter 5 prepared by IIT-B and IIT-M

It is seen that plants with ESP, FGD and SCR have higher initial capital cost over plants with only ESP. The costs are 57%, 54% and 42% higher for sub-critical, super-critical and ultra-super-critical plants respectively. However, the CO_2 emissions are higher per kWh. The emissions of particulates, SOx and NOx are 85 to 95% lower.

What is of interest is to see what it would cost in terms of foregone growth in GDP or consumer income. Also what is the economically justifiable level of use of these technologies?

We generate two scenarios, one with all plants have ESP and another in which all plants have ESP, FGD and SCR. We call the scenarios as follows:

- **DAUPM:** Dynamics as usual with ESP that controls Particulate Matter emissions. Economical choice of technology no restrictions except as per government policy no new subcritical plants.
- **PMSOxNOx:** Only new plants with all pollution control technologies (ESP,FGD+SCR) are permitted

The results are summarized for 2030 and 2050 in table 5.

Table 5: Generation in bkWh by Different Technologies

Scenario	DAUPM		PMSOxNOx	
Technologies	2030	2050	2030	2050
Coal				
Sub Critical	700	453	703	694
Super Critical	2363	9337	48	58
Sub Critical FGD	3	1	356	196
Super Critical FGD	3	1	1972	8865
Total Coal	**3081**	**9799**	**3079**	**9813**
Gas	47	5	54	10
Diesel	0	0	0	0
Nuclear	15	7	15	7
Hydro	54	19	54	19
Renewable	27	14	27	14
Total Generation	**3224**	**9844**	**3229**	**9863**
Share of Coal Generation (Per Cent)	**96**	**100**	**95**	**99**

Source: Chapter 6, GTWG report

What is interesting to see is that the share of generation from coal based plants exceeds 95 % in both the scenarios. The emissions under the two scenarios are summarized in table 6:

Table 6: Emissions under the Two Scenarios

Scenario	DAUPM			PMSOxNOx		
Year	SOx	NOx	CO_2	SOx	NOx	CO_2
2010	7	3	673	7	3	673
2020	15	6	1493	8	4	1547
2030	30	13	3017	8	4	3135
2040	57	25	5716	9	6	5940
2050	94	41	9530	10	8	9932
2010-50 (MT)	1534	672	155042	346	197	161034
2010-50 from the whole economy (GT CO_2)			298			303

The reductions in SOx and NOx emissions inPMSOxNOx scenario are substantial but seem much less than what one would have expected from the emission coefficients in table 4. This is because the existing sub-critical coal plants in 2017, after which no sub-critical plants are built, continue to operate for many years and have not been retrofitted with SOx NOx control devices. In fact from the cumulated emissions over 2010-50 of these sub-critical plants are 289 MT of SOx out of total 346 MT and 129 MT of NOx out of total 197 Mt.

With the PMSOxNOx scenario the emissions of SOx and NOx come down substantially. This suggests that if we want to control local air pollution, end of the pipe measures should be adequate. The question is how much do they cost?

We measure this in terms of the impact on Gross Domestic Product and on private consumption, which is an important element of consumer welfare. Table 7 shows these.

Table 7: Macro Impact of SOx and NOx Control

Year	GDP Trillion 2007-08 Rs		Per capita consumption '000 2007-08 Rs/year	
	DAUPM	PMSOxNOx	DAUPM	PMSOxNOx
2010	53	53	21	21
2020	110	110	30	29
2030	242	240	69	68
2040	546	542	164	162
2050	1078	1068	399	394
CAGR 2010-30	7.91	7.88	6.17	6.09
CAGR 2010-50	7.83	7.81	7.67	7.63

Table 7 shows that there is very little difference in the growth rates of GDP and per capita consumption. Thus SOx, NOx and particulate emissions control does not involve any significant cost to the economy.

However, if you look at CO_2 emissions in table 6, there is no reduction in it, if anything there is a small increase. For this we need to explore carbon capture and storage (CCS).

Role of CCS in Controlling CO_2 Emissions

We consider two alternative technologies of CCS.

- Supercritical Pulverized Coal (PC) boiler with MEA-based CCS
- Supercritical PC boiler with oxy-fuel combustion (OFC)-based CCS

"Post-combustion technology means that the CO_2 is captured after the combustion of the coal (or other fossil fuel) has taken place. This can be done using various processes such as adsorption, absorption and membrane separation. Generally, in absorption, CO_2 is absorbed over a solvent such as Mono-ethanolamine (MEA) (Johnsson, 2011) and is then exposed to higher temperatures where CO_2 is stripped off from the solvent. Other solvents such as ammonia may also be used for such a process. Post-combustion processes are the most matured ones at this point of time. However, solvent regeneration is an energy-intensive process and leads to significant losses in the energy output of the plant. The energy penalty here is thus, mainly due to the solvent generation (Johnsson, 2011). …

Oxy-fuel combustion systems use pure oxygen or a nitrogen-free gas mixture instead of air for the combustion of a hydrocarbon fuel to produce a flue gas that consists primarily of water vapor and CO_2. This produces a flue gas stream with CO_2 concentrations greater than 80% by volume. The water vapor is then removed by cooling and compressing the flue gas stream. Oxy-fuel combustion requires an upstream air separation unit (ASU) to produce oxygen stream with a purity of 95–99%. Further treatment of the flue gas may be needed to remove air pollutants and non-condensed gases (such as argon and nitrogen) from the flue gas before the CO_2 is sent to storage." (Sreenivas Jayanti et al, 2018)

Table 8 gives the technological and cost details of the two technologies.

Table 8: CCS technologies Costs and Emissions

Technology	Supercritical PC with MEA based CCS	Supercritical PC with CCS +OFC
Net Plant efficiency (%)	29.05%	26.44%
Auxiliary power (%)	24.93%	31.69%
S.F.C. (Kg/ kWh) coal GCV 2800 Kcal/kg	1.06	1.16
Capital Cost# INR Cr/MW	19	23
O&M# INR Lakh/MW	246	221
LCOE (INR/kWh)	6.61	6.76
CO_2 emission (kg/MWh)	121	132
SO_2 emission (kg/MWh)	0	0
NOx emission (kg/MWh)	0.6	0.7
Particulate emission (kg/MWh)	0.1	0
Net Plant efficiency (%)	29.05%	26.44%
Auxiliary power (%)	24.93%	31.69%
S.F.C. (Kg/ kWh) coal GCV 2800 Kcal/kg	1.06	1.16
Capital Cost# INR Cr/MW	19	23
O&M# INR Lakh/MW	246	221
LCOE (INR/kWh)	6.61	6.76
CO_2 emission (kg/MWh)	121	132
SO_2 emission (kg/MWh)	0	0
NOx emission (kg/MWh)	0.6	0.7
Particulate emission (kg/MWh)	0.1	0

We develop two scenarios, where the total CO_2 emissions over the period 2010 to 2050 that India can make are given by 133 GT and 156 GT. These limits are imposed in the scenarios. These are arrived at looking at the global carbon budget and allocating it to different countries giving each country the same per capita allocation based on their population in 1990 and 2010. The two scenarios with carbon budget (CB) are as follows:

- CB156: a carbon budget of 156 GT from 2010- 2050 imposed
- CB133: a carbon budget of 133 GT from 2010-2050 imposed

Table 9: shows power generation in the different scenarios

Scenario	DAUPM		CB156		CB133	
Technologies	2030	2050	2030	2050	2030	2050
Coal						
Sub Critical	700	453	446	54	96	12
Super Critical	2363	9337	34	4	5	1
Ultra Super Critical	3	4	2	0	0	0
Sub Critical FGD	3	1	2	0	0	0
Super Critical FGD	3	1	2	0	0	0
Ultra Super Critical FGD	3	1	2	0	0	0
Super Critical PC with MEA CCS	3	1	469	6120	154	1005
Super Critical CCS OFC	3	1	3	1	1	1
Total Coal	**3081**	**9799**	**960**	**6179**	**256**	**1019**
Gas	47	5	47	10	22	3
Diesel	0	0	0	0	0	0
Nuclear	15	7	1806	1968	1968	1968
Hydro	54	19	292	600	376	600
Renewable	27	14	73	724	382	5129
Total Generation	**3224**	**9844**	**3178**	**9481**	**3004**	**8719**
Share of coal (percent)	96	100	30	65	9	12

With a carbon budget of 156 GT, there is still 65 % generation is from coal in 2050. It may also be noted that MEA CCS is selected and not CCSOFC. However, with a tighter budget of 133 GT, coal power generation is only 12 %. It shows it is cheaper to go for nuclear, hydroelectricity and renewables.

The macro-economic impact carbon constraint on GDP and per capita consumption is shown in table 10. The impact is not very large on GDP but somewhat larger on private per capita consumption, which is 4 % lower in CB156 and 11 % lower in CB133 in 2050. The cumulative loss will be substantial as can be seen in table 11.

Table 10: Macro Impact of Carbon Constraint

	GDP Trillion 2007-08 Rs/year			Per capita consumption Thousand 2007-08 Rs/year		
Year	DAUPM	CB156	CB133	DAUPM	CB156	CB133
2010	53	53	53	21	21	21
2020	110	111	110	30	28	27
2030	242	239	233	69	66	62
2040	546	534	524	164	158	149
2050	1078	1058	1015	399	384	359
CAGR 2010-30 (%)	7.91	7.85	7.72	6.17	5.96	5.66
CAGR 2010-50 (%)	7.83	7.78	7.67	7.67	7.57	7.38

Table 11: Reduction in cumulated GDP and Consumption (Trillion 2007-08 Rs) Compared to DAUPM (DAUPM value – Scenario Value)

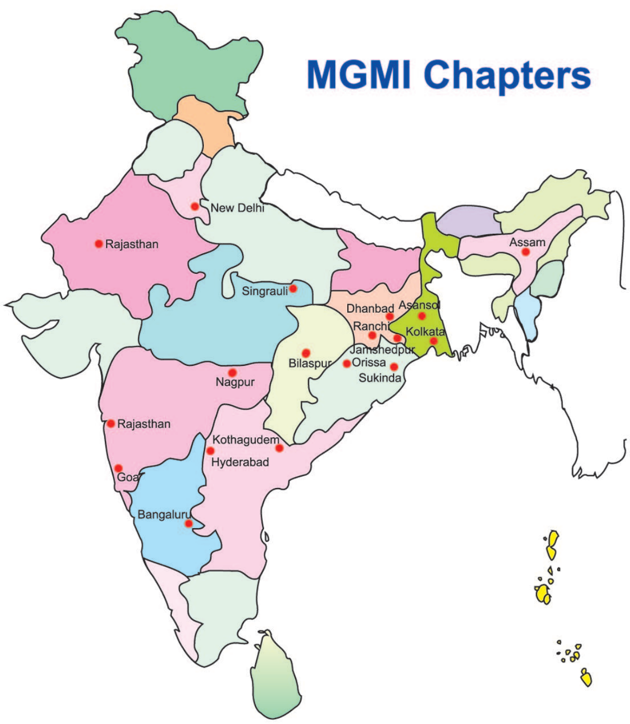
Year	GDP		Consumption	
	CB156	CB133	CB156	CB133
2010-20	-3	3	6	15
2010-30	10	50	33	80
2010-40	80	195	101	246
2010-50	212	554	277	684

Impact of Steeper Decline in Renewable Costs

The significant increase in renewable generation with the tighter carbon budget of 133 GT has assumed fall in renewable technologies costs is modest. There are many however, who expect a much steeper decline in renewable costs and rapid increase in their efficiency.

References

- *Sreenivas Jayanti, Anand B Rao, D K Sharma, Sreedevi Upadhyayula, Preeti Aghalayam, Munish Chandel, (2018), "Technologies for Coal-based Power Generation" in Global Technology Watch Group, Coal Road Map for India, final report*
- *Johnsson F, (2011), Perspectives on CO_2 capture and storage, Greenhouse Gases: Science and Technology, vol. 1, pp. 119–133, 2011*
- *GTWG (global Technology Watch group), (2018), Coal Road Map for India*
- *Probal Ghosh, Kirit Parikh, Vinay Kumar Saini, Jyoti Parikh, (2018), "Model-based Assessment of Technology Options: Sustainability Analysis" in GTWG final report*



The Mining, Geological & Metallurgical Institute of India (MGMI)
GM - 38/4, Salt Lake, Sector V, Kolkata 700 091, INDIA
Phone : +91 33 2357 3482 / 3987 / 6518 | Fax : +91 33 2357 3482
E-mail : mgmisecretary@gmail.com / mgmihonysecretary@gmail.com
Website : www.mgmiindia.in / www.asianmingcongress.com