www.rericjournal.ait.ac.th

Dynamic Life-Cycle Analysis of India's Electricity System

P.R. Shukla* and D. Mahapatra+1

Abstract – *Energy production and consumption cause environmental and human health damages. Their exclusion by the market leads to inefficient resource allocations. Because of weak market regimes in developing countries, the conventional development pathways overlook these inefficiencies. A sustainable energy system would need to ameliorate this adverse trend while maintaining the equilibrium path that represents true life-cycle cost of energy resources. This paper considers life cycle analysis (LCA) for full accounting of externalities of energy use with specific focus on electricity sector. The LCA is carried out for major energy resources and technologies. The dynamic equilibrium analysis is carried out, spanning period up to year 2050 using an energy system model, ANSWER-MARKAL. The results show that the shift to an efficient frontier can be made at a very low cost by introduction of technologies that mitigate local air pollutants like* SO_2*, NOx and SPM. Internalization of these local externalities too results in co-benefits including reduction in carbon intensity of energy. In addition, the inclusion of life carbon price in life cycle equilibrium leads to further reduction in carbon emissions, besides also delivering the local air quality co-benefits. Our results show that renaissance of domestic coal in India could last so far as national policymakers are concerned with local pollutants. However, mitigation of CO2 emissions to achieve low stabilization target would significantly shift the energy system equilibrium, notwithstanding the introduction of CCS technology. Finally, a generic lesson from our analysis is that the inclusion of all external cost of each energy technology and resource still leads to 'no silver bullet', i.e. a single dominant technology, which dominate future energy system. The energy-environment efficient frontier thus would evolve through a mix of choices from a portfolio of energy resources and technology options. The diversity of these options including their cost structures; multiple objectives of energy-environmental policies and the varied inter-linkages of energy and environmental policy dynamics call for a hybrid package of direct regulation and market based economic instruments to sustain energy-environment-economy frontier on the efficient path.*

Keywords – Electricity generation technology, energy modeling and scenario analysis, fuel cycle, monetization of externalities, pollution capture technology.

1. INTRODUCTION

India faces three major energy challenges: energy access, energy security and energy related environmental impacts. Besides, India's energy system demonstrates unsustainable patterns of development characterized by growing dependence on imported fossil fuels, rising energy demand and growing CO_2 emissions. With the exclusion of the unintended impacts resulting from the energy production and consumption by the market forces, resource gets allocated suboptimally [2], [8], and [17]. This incentivizes market forces to generate too much of an activity where diseconomies prevail and too little where economies hold. As a result, damage to air, soil, and water backfires on the rapid economic growth in the form of health impacts. Further, developing countries like India cannot adopt an exclusive climate-centric development pathway as it might prove very expensive and create large mitigation and adaptation burden as compared to sustainable development pathway [51].

Hence, the challenge is to alleviate and reverse these adverse trends to achieve a truly sustainable energy system, while preserving the equilibrium of ecosystems and encouraging economic development. Two recent instructions from the Prime Minister's Office (PMO) in 2008 summarize the current concerns in the India's energy system: first, to work out a system for computing the country's green GDP and second, to make appropriate energy pricing a key component of energy policy. In order to understand if India's current energy system is sustainable or not, life cycle analysis (LCA) is deployed in this paper for full accounting of externalities of energy use for electricity production [15], [16] and [17]. The assessed impacts are then monetized providing an estimate of corresponding welfare losses. The estimated impacts are considered robust and, if needed, can be used as the basis for decision-making independently of the monetary values. A "bottom-up" partial equilibrium modeling framework ANSWER-MARKAL is then used to internalize the external costs from the static life cycle analysis to generate dynamic energy system equilibrium and to make comparative policy assessment for India's energy system [32].

---

*Public Systems Group, Indian Institute of Management Ahmedabad, India

+ (on leave) Adani Institute of Infrastructure Management Ahmedabad, India.

[1] Corresponding author;
E-mail: diptiranjan@iimahd.ernet.in;
mahapatra.diptiranjan@gmail.com.

This paper is organized as follows. In Section 2, the context and the associated literature is described in brief. In Section 3, externality monetization is shown. In Section 4, the modeling framework and results are discussed. Finally in Section 5, broad recommendation and conclusion is derived.

2. CONTEXT AND LITERATURE REVIEW

Since Pigou [38], concept of "external cost" came into the domain of the debate as to why market mechanisms often fail in many of the provisioning of goods and services and eventually results in suboptimal solutions. The usual assumption of market based solution in providing a welfare maximizing outcomes relies on a fundamental prerequisite such as price should reflect the social cost which is the sum of private and external cost [2]. In the energy sector, the prerequisite for an efficient and sustainable market is to get the price right so as to reflect the marginal social cost so that scarce resources are efficiently allocated. This helps consumers and producers decide about the fuel mix, future investments and initiatives in research and development. Without the correct price signals, the market remains distorted and even if the market is competitive it remains far from the socially optimum one. This would eventually lead to a market clearing price which is lower than the marginal social cost. Since the environmental damage costs or benefits are not getting internalized in the market cost, neither the producer nor the ultimate consumers of this product have to bear the full cost of this service. In other words, certain inefficient energy technologies even though having high social costs would get implemented because of its low private production cost.

Hall [22] goes on to argue that even if the full cost estimate may not be accurate, a mere examination of this aspect helps decipher the divergence between private and social cost thereby enabling greater economic welfare. Exploring the full cost energy pricing will throw open issues that are relevant not only to climate change policy but also to the debate over national energy strategy. One of the policy instruments for internalization could possibly be to introduce additional charges into the production cost of electricity reflecting the cost of the associated negative environmental and health impacts from local pollutants and climate change, impacts on terrestrial ecosystems, effects of water use and pollution, quantification of ozone damages, noise and amenity, visual amenity etc. Incorporating these externalities shall be helpful while assessing different energy options in terms of the damage – benefits associated with each one of them and then ranking them according to trade-offs. In the Indian context, the energy policy formulation is gradually evolving and issues like pricing, externalities, sustainability, and climate change are becoming prominent [11], [20]. In the coal sector, opencast mining for many years has led to land degradation, environmental pollution and reduced quality of coal putting a burden on the society. The cost of electricity does not represent the complete costs borne by the society such as costs of adverse human health impacts along the value chain *i.e.* fuel mining or exploration and drilling, transport by road, rail or pipeline, power generation and finally waste disposal. Both the power producers and the consumers reflect their preference for polluting fuels say, coal since it comes cheap as they do not have to pay for the externalities created on the society which are hitherto not getting incorporated in the cost-calculations.

The framework as suggested above in Figure 1 above identifies how life cycle costing helps formulate sustainable energy policy. It invokes both demand and supply side adjustment in terms pricing, technology adaptations and regulatory or policy interventions. The demand and supply side adjustments are made with respect to external environment such as climate regime, oil price shocks, terrorist attacks and geopolitics and internal environment such as local green lobbies, gas and oil discoveries, GDP projections and policy impetus to various sectors etc.

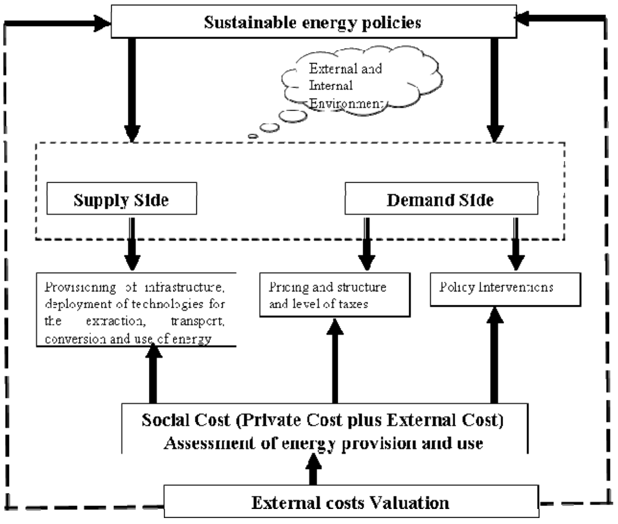

Fig. 1. Framework of context.

To put these factors in an Indian perspective, it is suffice to say that India is caught between a huge demand side pressure on energy needs on one side and issues like energy security, climate change, sustainable usage of energy resource and societal welfare on the other. One of the ways to resolve this conundrum is to get the price of energy right so that it reflects not only the impacts on environment but also the stress on local ecosystem and in this context life cycle cost becomes a linking thread. This study tries to reach out to these themes not in a vertical fashion by exploring each of these units *i.e.* energy security, climate change and sustainable development in depth but by a horizontal way through life cycle costing and energy market modeling.

Within India's energy sector, literatures covering complete fuel cycles are non-existent, but few are available covering the details either at the mining stage or at the power generation stage. Besides, literatures on the monetization of environmental impacts in the Indian context are sparse. One of the seminal papers within the gambit of monetization has been Brandon and Homman [4] in which the authors estimate the economic costs of environmental degradation in India. Subsequent to this few more came out, especially within the urban air domain (see for example [46], [10], [53], and [28]). Of late, Government of India has initiated actions that might help monetize environmental impacts in a scientific and robust manner; notable among them are source apportionment study and CSO [11].

Within the domain of externality studies in India, Bhattacharyya [3] and Kumar and Rao [30] deserve a mention in which the authors attempt to estimate and monetize the environmental costs of coal-based power plants. Bhattacharyya [3], Chatterjee, Dhavala and Murty [6], and Maria [33] also monetize the impacts albeit only at one stage of the fuel cycle. Chaulya [7], Ghose [18], Ghose and Majee [19], and Jain and Saxena [27] investigate only air pollution due to mining and other activities.

Coming to the energy-economy-environment modeling, Rafaj and Kypreos [41] uses the Global MARKAL-Model (GMM), a multi-regional ''bottom-up'' partial equilibrium model of the global energy system to address externalities from power production. These external costs include the costs of environmental and health damages from local pollutants (SO_2, NOx) and climate change, wastes, occupational health, risk of accidents, noise and other burdens. Rapid introduction of carbon abatement technologies, Structural changes and fuel switching in the electricity sector and enhancement of competitiveness of non-fossil generation are some of the outcomes of this study. The Indian modeling exercises with the inclusion of externalities costs are limited in the sense that most of these have carbon price as the only internalization cost in the model (see for example [29], [31], [47], and [48]).

On the basis of literature survey, the research gap is presented below:

Table 1. Summary of research gaps.

Focus	Issues Already Addressed	Research Gaps
Fuel Cycle	Research in the past have looked at the fuel cycle in stages, for example, in coal cycle studies have focused either on mining or power generation or ash disposal.	India specific fuel cycle study even for coal is missing.
Monetization	The available literatures on monetization of energy related impacts are none except one study that is at the coal power plant stage.	Monetization for the complete cycle is missing.
Modeling	Existing modeling literatures have articulated the environmental impacts either through Carbon or Sulphur tax or to the best of my knowledge there is only one published article that has dealt externality cost in the model.	India specific modeling exercise incorporating externality has not yet been done.
Investment and Policy Aid	Existing literatures on investment and policy aid draws from static analysis such as levelised cost calculations. Levelised cost analysis often misses out the upstream and downstream activities and focuses mainly on the power plant.	An investment and policy decision arising out of a holistic and integrated analysis is missing.

3. EXTERNALITY EVALUATION AND RESULTS

Externality Evaluation: The Approach

The external cost as defined in this work exclusively addresses impacts of outdoor emission related health impacts. Impacts such as noise and visual amenity, ecosystem, GDP were not analyzed in the present work. Reason being, in relative terms and considering the technologies of interest, the cost of health impacts far outweighs damage from all other categories [15], [16], [36], [45], [1], and [17]. The methodology developed within the ExternE Project of the European Union [17] has been essentially employed for the estimation of health and environmental external costs associated with air pollution from normal operation of the various energy chains. ExternE (External Costs of Energy) projects initiated by European Commission in 1991 primarily aimed at developing methodology and an accounting framework for externalities against each fuel cycle. The ExternE methodology starts from emissions generated at specific sources and follows their impact to receptors through atmospheric dispersion and dose-response functions. The criticality of the above seemingly straight-forward and simple approach lies with the dose-response (DRF). As the name suggests, DRF defines the relationship between the amount of pollutants that a receptor *i.e.* population receives to the impact on the receptor, say, in terms of incremental number of hospitalizations [17]. Hence in order that a particular damage needs to be quantified, there has to be a corresponding DRF. In other words,

Impact = Pollution x Stock at risk x Response function DRFs are estimated based on epidemiological studies that establish correlation between pollution and a health impact (known an end-point).

Coal, India's most important domestic energy resource, contributes 69 per cent of total electricity generation. Natural gas supplied by national Oil Companies (NOCs), private producers and imported Liquefied Natural Gas (LNG) supplies another 7 per cent of electricity. Nuclear electricity generated by the 15 pressurized heavy water reactors (PHWRs) and 2 light water reactors (LWRs) contributes 2.8 per cent to the total power generation [5]. The Indian nuclear fuel chain involves activities like mining, transport, fuel fabrication, electricity generation and waste repositories spread in the country. With the recent onshore gas discovery and the signing of Indo-US nuclear deal, share of natural gas and nuclear in power generation is likely to increase substantially in near future. Further, India is also one of world's largest producers of sugarcane and hence bagasse based electricity generation is also making inroad. Keeping these things in mind, the externality evaluation has been done in detail for coal, natural gas, nuclear and bagasse fuel chain ending with electricity generation. External costs for renewables like wind and solar has been extrapolated from ExternE country studies.

Table 2. Boundary setting of fuel cycles.

Fuel Cycle	Upstream Process	Transportation	Power Generation
Coal	Mining	Rail	Subcritical PC
Natural Gas	Exploration	LNG plus Pipe	CCGT
Nuclear	Mining	Truck	PHWR
Bagasse	Farming	Tractor	Cogeneration
Wind	Manufacturing		S-66 and S-70
Solar	Manufacturing		ISCC

External cost valuation for power generation is based on bottom-up damage cost methodology adopted by European Commission (EC) ExternE Project (for details see [17]), while external cost for mining operation abatement or control costs methodology is used.

Damage costs are a measure of benefit to society of environmental protection. The damage function employed in this approach tracks the pathway from activities to emissions to ambient concentrations to impacts to monetization. Impact estimate is done through the use of dose response functions.

Control costs represent the costs to society of environmental protection to achieve a given standard that restricts the extent of the impact to an acceptable level. Control costs are often used as a surrogate for damage costs as they are a relatively straightforward concept, are relatively easy to derive, and can be applied to most environmental impacts. Essentially, unit control costs can be calculated simply by dividing the cost of mandated controls by the emissions reduction achieved by the controls. The implicit assumption in control costing is that society controls pollution until the benefit of additional controls would be outweighed by the cost of their imposition.

The control cost methodology has been adopted with the assumption that regulators has the perfect foresight to choose optimal control technologies *i.e.* those equating abatement costs and benefits at the margin, rather than on a political, health, or distributional basis [36]. The control-cost approach ideal where there is an urgent need to establish some back-of-the-envelop calculations. For some fuel cycles where neither control-cost nor damage-cost methodology could be applied, results of ExternE have been adjusted to reflect India's situation by considering the proportion of population density and GDP between India and the respective EU country [55], [56].

The method framework adopted for various stages of fuel cycle is as follows:

Table 3. Control and damage cost application.

Fuel Cycles	Methodology Adopted	Remarks
Upstream (Mining)	Control Cost	
Transport	Control Cost	
Power Generation	Damage Cost	For nuclear and renewables, other country study has been adapted after suitable calibration

Extensive data collection was done from the coal and nuclear mines, LNG terminals; coal, nuclear, natural gas, bagasse power plants; pollution control boards, census office, health authorities and websites of various ministries. Expert opinions have also been sought to reconfirm and calibrate data.

Dose Response Function and Value of Statistical Life

Within literatures, no dose-response functions (DRF) specific to India are available. Usage of DRFs from [37] has support from previous Indian studies [4] and [46] and hence has been used while evaluating health impacts from power generation. For India, no consensual value of statistical life (VSL) could be obtained from literature. To be on a conservative side, it is decided to rely on the lower bound results of [25]. Further, this value has also support from the recent government report [11] and hence a VSL of US$ 17734 (equivalent Rupees 798000 at 1US$ = Rs 45) at 2005 price is used in this analysis. The DRF gives additional mortality, additional Respiratory Hospital Admissions (RHA), additional Emergency Room Visits (ERV), additional Restricted Activity Days (RAD), additional Lower respiratory illness in children (<17yrs), additional daily Asthma attacks per asthmatic person, Respiratory symptoms days per person, and Chronic bronchitis cases with respect to unit increase in SO2 and NOx level beyond the acceptable limit. Multiplying this with the health cost [46], gives the monetized health impacts from power generation.

The radiological and non-radiological health effects resulting from the routine operation of the nuclear fuel cycle are directly proportional to the total collective doses and the expected number of health effects has been taken from ExternE study of French nuclear cycle assuming no lower threshold for radiological impacts [13]. To make the results of French cycle consistent with India’s demographic and economic conditions, it was suitably adjusted by calibrating it with respect to GDP and population

Results -Static

By adopting control costs and damage cost methodologies as described earlier, external costs with respect to various fuel cycles are calculated and the summary is shown in below table.

Table 4. Summary of external costs.

Type	External Cost (cent/kWh)	Cost of Generation (cent/kWh)		External cost as % of Cost of Generation
		Min	Max	
Coal Pithead		1.94	6.03	
Coal Non-Pithead	4.43	4.76	10.73	93%
Gas	0.81	2.35	12.31	34%
Nuclear	0.25	3.09	4.62	8%
Wind	0.13	4.44	5.56	3%
Solar	0.28	17.78	35.56	2%
Bagasse	0.31	4.44	6.22	7%

A comparison with the market cost *i.e.* the cost of generation in our case, is then done to show the forgone amount that is not getting captured in the existing market pricing mechanism. The above table represents data for a specific site and technology and hence should not be construed to be representative of all the sites and technologies existing in India.

Results -Dynamic

The result in Table 2 gives a static impression and in order to bring in dynamic analysis to it, simulation was carried out for generating levelised cost with and without the external costs. Input parameters such as capital cost, fuel cost and external cost are assigned triangular distribution, while heat rate, plant load factor (PLF), auxiliary consumption, discount rate and interest rate are assumed to be having uniform distribution. However, the simulation was done only for non-pithead subcritical coal power plant so as to demonstrate the impact of external costs. As shown in Figure 2, external cost addition shifted the levelised cost of electricity (COE) regime completely out of its earlier periphery to a new efficient frontier. The figure also reveals that even the highest cost of electricity without the external cost is still less than the lowest one with external cost.

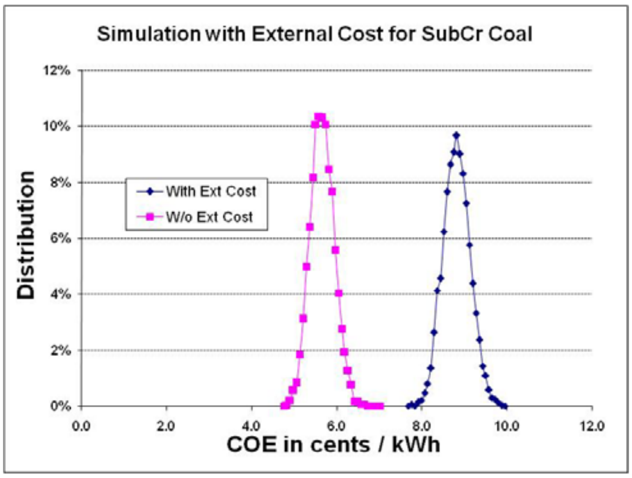

Fig. 2. Simulation result of sub-critical coal technology with external cost.

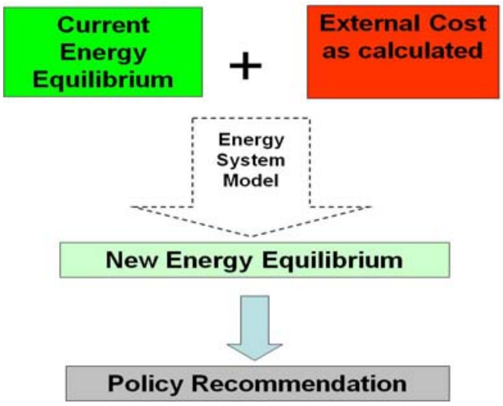

Fig. 3. Framework for analysis: LCA and energy market equilibrium.

4. MODELING FRAMEWORK

Once the external costs for various power generation technologies have been derived, we then propose to carry out further modeling analysis as depicted in Figure 3.

The current energy equilibrium exists without the external costs. Now with its availability, external costs get inputted to the current dynamic modeling framework to generate new energy equilibrium. The new equilibrium by virtue of its characteristics is then become the Pareto one which then finally helps generate policy prescriptions.

MARKAL is a dynamic optimization model for evaluating the energy system of one or several regions. MARKAL provides technology, fuel mix and investment decisions at detailed end-use level while maintaining consistency with system constraints such as energy supply, demand, investment, emissions etc. A detailed discussion of the model concept and theory is provided at the ETSAP website [32]. To calculate the end-use demands, it is assumed that Indian economy is presently on a high growth path; demand for goods in the end-use sectors is witnessing high growth rates. The experience from developed countries has shown that these growth rates are going to saturate as the economy modernizes. The approach used in the past is to model the demands using a logistic regression. First the long term GDP projections are made using the past data available. Logistic regression using past data is then used to estimate the sector specific shares from industry, transport, commercial and agriculture. These sectoral shares on multiplication with GDP projections give us gross valued added (GVA) for each sector. The last step involves estimation of elasticity of each sub-sector (*e.g.*, industry is divided into eleven sub sectors like steel, cement, etc.) with the sector specific GVA. The elasticity is then used for estimating the future demand from each sector. The methodology described helps in capturing past trends and ensuring consistency with macroeconomic growth [50].

Scenario Definitions and Drivers

In this analysis, we have followed Scenario Analysis [40], [49], and [52] that entails developing a Business As Usual (BAU) scenario and then generating alternate scenarios around BAU [29], [41]. The embedded story-line for our BAU is same as B2 scenario reported by the Special Report on Emission Scenarios by IPCC [26]. Some of the salient features of this scenario are as follows:

- High economic growth so as to reduce the disparities across regions
- Environmental concerns and sustainability approach remain high on agenda

The BAU case assesses a projection of the evolution of the Indian energy system from 2000 through 2050 while GDP grows at the rate of 8 per cent. Five-year periods are considered and a discount rate of 8 per cent is applied. The BAU case has been generated using best estimates for the values of model inputs, such as the characteristics of existing and future technologies, energy service demands, and regulations on criteria pollutant emissions.

Scenario Descriptions

Around the BAU, four scenarios are created for this analysis, namely, the Local-Damage Scenario (LDS), Global-Damage Scenario (GDS), Nuclear Cooperation Scenario (NUCC) and High Carbon Scenario (HIGHCARB).The key drivers of the these scenarios and their parameterizations are given in the below chart.

All these scenarios are created keeping in mind the research questions that we posed at the beginning. Primarily, it revolves around the BAU with additional imposition of local pollution and then global pollution. Once they are internalized, in order to examine its implication on climate change, energy access and energy security NUCC and HIGHCARB are created. Besides, two recent events and debates on Indo-US nuclear deal and strong climate regime in future motivated us to look at the NUCC and HIGHCARB scenario in detail.

Scenario Drivers

i. Macro Economic

GDP for period 2005-2032 is 8 per cent which is similar to Planning Commission's GDP Scenario [20]. Population projections are based on UN Population Medium Scenario, Version 2004 for India since population projections given by Census of India are only available till 2026 [9]. The complete population and GDP assumptions are given in Table 5.

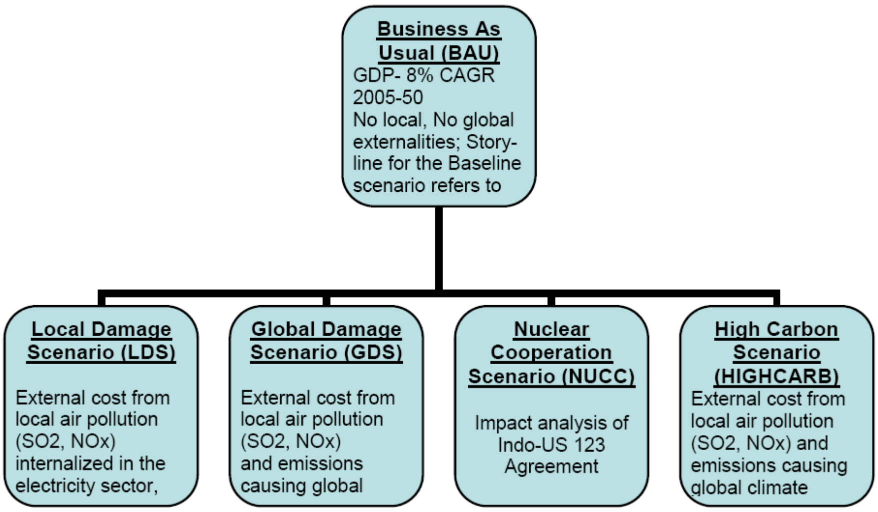

Fig. 4. Scenario architecture.

Table 5. BAU scenario drivers.

Year	GDP (2005 prices Bill. Rs.)*	Population (Million)	Period	Growth rate	
				GDP	Population
2005	32833	1103	2005-30	8.10%	1.10%
2030	229573	1449	2030-50	5.90%	0.50%
2050	774673	1593	2005-50	7.10%	0.80%

*1 USD = 45 Indian Rupees

ii. Energy Prices

A variety of prices are observed in the Indian energy markets especially for coal and gas. The regulatory regime tries to keep prices aligned to the cost of production. Pricing data on various fuels available in public domain[1] has been used to generate supply curves by approximating step-wise linear structure [32]. The price assumptions for imported fuels are based on price projections given by IEA [24].

iii. Carbon Prices

Carbon price trajectory for BAU scenario and HIGHCARB scenario are linked to CO_2e stabilization targets of 650 ppmv CO_2e concentration target and 550 ppmv CO_2e respectively. The price trajectories are obtained from outputs from global Second Generation Model (SGM) results [14].

Internalization of External Costs in MARKAL

MARKAL has a very elaborate representation of the fuel cycle starting from the mining to power generation. This gives the opportunity to assign the externalities at each stage. External costs are implemented in the model by assigning it as an additional variable operation and management cost from each power plant during each

---

[1] Information related to coal prices can be obtained from website of ministry of coal whereas information on oil and gas prices was taken from Infraline database (www.infraline.com)

time period *i.e.* VAROM input in MARKAL. In this way, it is assured that the external costs are directly charged to every unit of generation from each power plant. An alternative approach that could be used to internalize the damage costs for different pollutants is to levy an environmental tax per unit of pollutant (*e.g.*, Indian Rupees 1000/tNOx) on the entire energy system [41]. Since our analysis is explicitly focused on the externality impacts on the power generation sector, the externalities are normalized by generation output *i.e.* kilowatt hour (kWh).

External costs as derived in Section 3.3 based on the [17] methodology reflects characterization of a site-specific technology of different value chains of a particular fuel. Factors such as population density in regions, fuel quality expressed as the content of the sulphur in coal and oil, technology specification with respect to installation of the emissions control systems, and finally, the possible improvement in conversion efficiency over time horizon must get embedded in the static cost so as to reflect the evolution of myriad of technologies that get evolved over the time horizon [41]. However, given the limited data availability, it becomes imperative to limit the analysis and yet make it result-oriented. Furthermore, one of the objectives of this research is also to demonstrate the application of external cost methodology in Indian context and then to internalize it in the MARKAL model rather than to come out with precise number. Given this background, changes in the population density over time are not considered and whatever improvement in externality going to happen in future is assumed to be coming through efficiency improvements in generation. This assumption makes the future external cost EC_t as inversely related to efficiency of generation *i.e.* with improvement in efficiency we are going to see less of environmental impacts. Mathematically, it can be expressed as

$EC_t = EC_0 \times Eff_0 / Eff_t$, where 0 and t represents the time period

External costs for various generation technologies in fossil as well as non-fossil domain have been calibrated using the above equation as well as [41]. Externality for various generation technologies, fossil as well as non-fossil as an input to MARKAL are shown in Figures 6, 7 and 8.

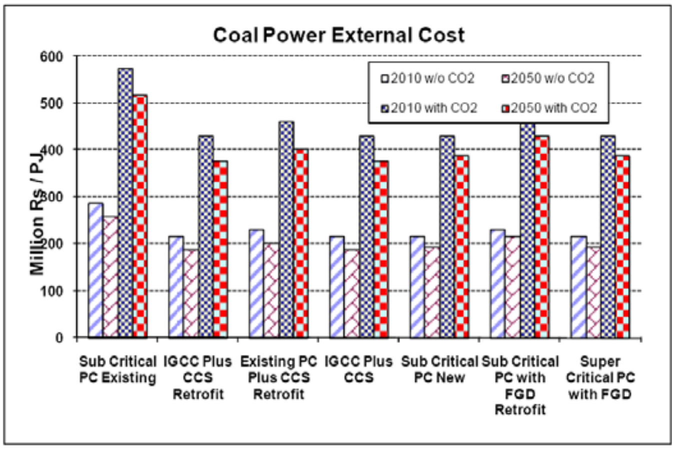

Fig. 5. Coal external cost.

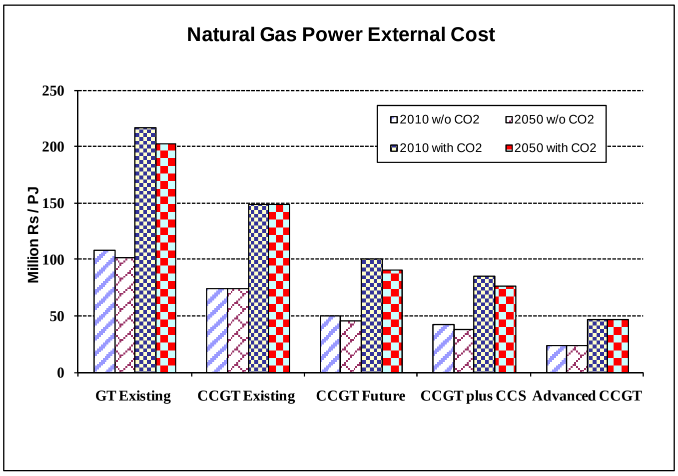

Fig. 6. Natural gas external cost.

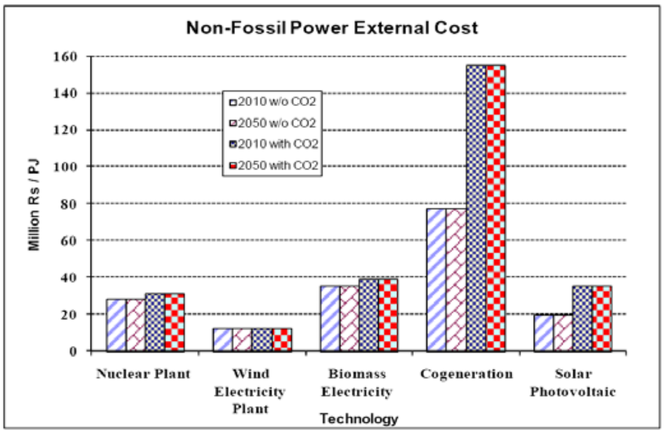

Fig. 7. Non-fossil external cost.

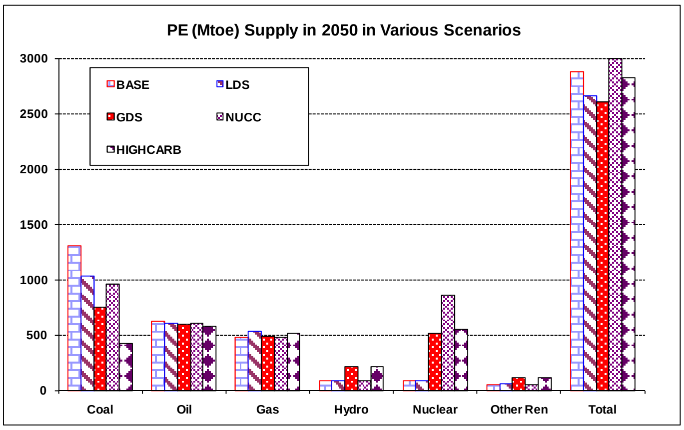

Fig. 8. Comparison of PE supply.

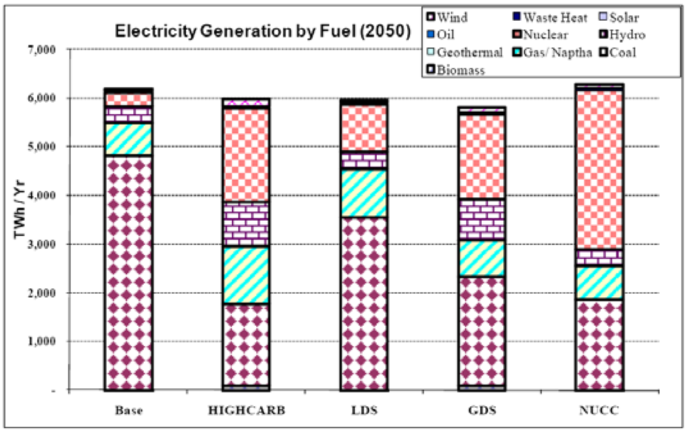

Fig. 9. Electricity generation by fuel in various scenarios.

Scenario Results Summary

Primary Energy Supply

This decrease in primary energy (PE) is observed in LD scenario and this could be because of the switch to other fuels than electricity in the final energy demand such as combined heat and biomass. Further, the efficiency gains from electricity to others could be higher resulting in lower primary energy supply. Local pollution resulting from transport and residential sectors are also arrested because of measures and hence results in PE decrease. As seen from the Figure 8 below, the HIGHCARB scenario consumes more primary energy compared to LDS and GDS. Reason being, since this scenario depicts a strong carbon regime, energy system as a whole has to pay energy penalty to generate same output as other scenarios.

Electricity Generation by Fuel Type

Overall, the coal share in the generation mix is getting reduced (Figure 6) and substituted with natural gas and renewables. The resulting enlarged energy portfolio calls for lesser reliance on coal and would therefore pose higher energy security risks. The energy security risks are further exacerbated if India undertakes carbon emissions constraints *i.e.* in the HIGHCARB scenario. Due to high coal content in India's business-as-usual scenario and highest carbon content per energy unit for coal, the carbon constraint has most severe impact on coal use compared to any other fuel.

Coal Technology Transition Across Scenarios

In all the scenarios, coal-based installed capacity is getting reduced as compared to BAU. Polluting technologies like the sub critical pulverized coal is getting substituted by advanced generating technologies like Integrated Gasification Combined Cycle (IGCC) with Carbon dioxide capture and Storage (CCS) and Super Critical with Desulphurization (DeSOx) and Denitrification (DeNox). Installed capacity of IGCC remains highest at 170 GW in HIGHCARB scenario.

One thing that came clear of this research is that cheaper electricity options (Figure 10) without environmental impacts are difficult propositions for India, at least in the near term. By adding externality cost into the generations it is shown that energy mix portfolio is going be diversified as opposed to a pure coal dominated one.

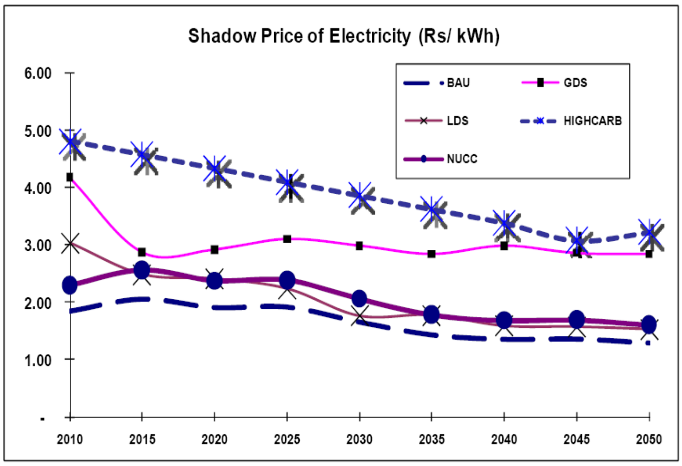

Fig. 10. Shadow price of electricity under various scenarios.

Table 6. Coal technology transitions across various scenarios in 2050.

Installed Cap (GW)	BAU	LDS	GDS	NUCC	HIGHCARB
Adv Sub Cr+DeSOxDeNOx		68			5
Ultra/Super Cr PC		475.72			
SC with FGD Retrofit		10			
SC with FGD New		10			
Adv Sub Cr+DeSOxDeNOx			8.58		
Adv Coal with CCS			272.7		
IGCC+CCS			69.5		170.02
IGCC	105.6			98.35	
Super Cr	676.13			441.28	

5. FINDING, POLICY RECOMMENDATIONS AND CONCLUSIONS

Key findings of this research are highlighted below.

First, the lack of internalization of life-cycle externalities in India is resulting in significant distortions in energy prices. This is contributing to inefficient use of energy resources, higher demand and suboptimal investments on supply side.

Second, the internalization of life-cycle environmental costs have highest implications for coal based power generation system, leading to early introduction of advanced coal burning and clean-coal technologies.

Third, the shift from the current inefficient equilibrium to an efficient frontier is made at very low cost by introduction of technologies which mitigate emissions of local air pollutants like SO2, NOx and SPM. Besides, the efficient equilibrium also includes substitution of coal by natural gas and to a lesser extent also by the renewable energy and nuclear technologies. Evidently, India's environmental policy therefore should include mandatory use of FGD, ESP and SCR technologies in the coal-based electricity generation units.

Fourth, the long-run marginal cost of electricity is significantly altered if life-cycle external costs are internalized. The resulting enlarged energy portfolio calls for lesser reliance on coal and would pose higher energy security risks.

Fifth, the energy security risks are further exacerbated if India undertakes carbon emissions constraints. Due to high coal content in India's business-as-usual scenario and highest carbon content per energy unit for coal, the carbon constraint has most severe impact on coal use compared to any other fuel.

Sixth, in case of carbon constraints, CCS (carbon capture and storage) technology is an alternative to advanced coal generation. However, this research shows that due to low potential of depleted oil and gas fields in India, the initial benefits from sale of oil and gas through enhanced oil / gas recovery (EOR/EGR) soon gets overwhelmed by the cost of capture. Hence, deployment of CCS in India would require very high international carbon price or explicit incentives for deployment of CCS.

Policy options for internalizing externalities

If policymaker had known the exact shape of the marginal cost and benefit curves of pollution emissions, it would have hardly mattered if the policy instrument is the quantity of emissions (through a cap) or the setting of the price (through a tax). The debate over the price versus quantity owes its origin to the seminal paper by Weitzman [57]. An alternative to these above two instruments is something called hybrid system initially suggested by Roberts and Spence [44] and later developed by Weitzman [57]; McKibbin and Wilcoxen [34]; and Pizer [39].

From a pure neoclassical view point, the policy prescription would be to put a tax to reduce the external costs on society. However, in developing countries like India such tax can potentially conflict with other social objectives, such as access to affordable energy for the marginalized section of the society and industrial competitiveness. Further, earlier research suggests that a pure tax regime to stabilize emission would be costly for India [21]. As mentioned earlier, alternative to the tax instrument is to go for cap-and-trade schemes. Two of the biggest trading schemes in existence today *i.e.* Europe's Emissions-Trading Scheme for carbon and America's market for trading sulphur-dioxide permits are cap-and-trade schemes. Indian policy makers have the options to experiment either with cap and trade or look at the hybrid system having a “safety valve” in which the price of pollution has floors and ceilings [44]. Nonetheless, sound policy design must be able to maneuver the price or quantity uncertainties associated with each of these instruments and resolve the trade-off so that burden to the society is minimized [35].

Conclusions

A robust result across the scenarios is that the inclusion of life-cycle costs in energy and technology prices would decrease the share of coal in the primary energy mix. However, since coal-based projects would increasingly have associated technologies that mitigate or capture the local pollutants and carbon dioxide, coal will likely to play a significant role in India’s future energy mix. Therefore, the policies to promote DeSOx, DeNox and CCS technologies acquire urgency in coal sector. This would result in resolving an important conundrum for India by enhancing usage of abundant domestic coal leading to secured energy supply and access and at the same time by adopting pollutant capture technologies would result in environmental security.

Our analysis shows that there is no single dominant energy resource or technology which can resolve these three challenges. If energy access is the priority, then even nuclear cooperation comes out to be a solution to generate lower cost electricity. However, if energy security and environment are the priorities, then India must invest in coal coupled with non-polluting technologies. Since mitigating local pollution is less expensive compared to mitigating carbon, as our analysis of local damage scenario (LDS) shows, Indian policy makers have option to deal first with local pollution alone. This also reconfirms earlier research results [49] which showed sequencing preference which decouples mitigation of local pollution from climate change mitigation policies. Thus, whereas emissions control initiatives such as ‘cap-and-trade’ programmes to control nitrogen oxides (NOx), sulphur dioxide (SO_2) and mercury would have immense local benefits but would not generate climate co-benefits unless national GHG policies evolve simultaneously.

Finally, given the diversity of future energy resources and technology options, there is no single or a few dominant options that internalize the external costs. The energy and environment policy regime thus remains rooted to a ‘portfolio’ of options. The energy-environment efficient frontier evolves amidst choices from a dynamic portfolio of energy resources and technologies. The diversity of these options, local conditions and inherent nexus between energy and environmental calls for a hybrid package of direct regulation and market based economic instruments for sustainable energy transition in India.

NOMENCLATURE

CCS: Carbon dioxide Capture and Storage; CO2, carbon dioxide; DeNOx, nitrogen oxides abatement, denitrification; DeSOx, sulphur oxides abatement, desulphurisation; EC, European Commission; ExternE, externalities of energy; FGD, flue gas desulphurisation; GHG, greenhouse gas; GDP, Gross domestic product; IGCC, integrated coal gasification combined cycle; IPCC, intergovernmental panel on climate change; PHWR, Pressurized Heavy Water Reactor; LWR, light water reactor; MARKAL, market allocation model; NGCC, natural gas combined cycle; NOx, nitrogen oxides; RES, reference energy system; SO2, sulphur dioxide; SRES, special report on emission scenarios;

Unless otherwise mentioned, all prices are of 2005 price level. One US Dollar ($) is assumed to be 45 Indian Rupees (Rs).

ACKNOWLEDGMENT

The authors are grateful to numerous researchers, policymakers and practitioners who spared their time to provide us valuable data and information relevant to carrying out the life-cycle analysis of various energy resources and technologies. The authors wish to thank modeling experts who shared their model and policy analysis relevant information. Our thanks are especially due to Asia-Pacific Integrated Model (AIM) team from NIES, Japan for sharing model database and insights from the Low Carbon Asia project. The authors wish to thank the two European Commission projects - CASES and TOCSIN - for supporting the work leading to this paper.

REFERENCES

[1] Abt Associates, Inc. 2000. The particulate-related health benefits of reducing power plant emissions. October. Prepared for EPA by Abt Associates Inc., Bethesda, MD.

[2] Baumol, W.G. and W.E. Oates, 1975. T*he Theory of Environmental Policy: Externalities Public Outlays, and the Quality of Life*. Prentice-Hall.

[3] Bhattacharyya, S.C., 1997. An estimation of environmental costs of coal-based thermal power generation in India. *International Journal of Energy Resources* 21, 289–298.

[4] Brandon, C. and K. Homman, 1995. The cost of inaction: valuing the economy-wide cost of environmental degradation in India. In Proceedings of the Symposium on Global Sustainability. Tokyo, Japan, October. United Nations University.

[5] CEA, 2009. *All India Electricity Statistics 2009.* Central Electricity Authority, New Delhi

[6] Chatterjee, S., Dhavala, K.K., and Murty, M.N., 2007. Estimating Cost of Air Pollution Abatement for Road Transport in India Case Studies of Andhra Pradesh and Himachal Pradesh. *Economic and Political Weekly*, September 8, 2007.

[7] Chaulya, K.S., 2005. Air Quality Status of an Open Pit Mining Area In India. *Environmental Monitoring and Assessment* 105: 369–389.

[8] Coase, R. 1960. The Problem of Social Cost. *Journal of Law and Economics* 3(October): 1–44.

[9] CoI, Census of India. 2006. Population Projections for India and States 2001-2026: Report of the Technical Group on Population Projections constituted by the National Commission on Population.

[10] Cropper, M.L., Simon, N.B., Alberini, A., and Sharma, P.K., 1997. The Health Effects of Air Pollution in Delhi, India. *The World Bank Policy Research Working Paper* Series 1860.

[11] CSO, 2006. *Study of post-clearance environmental impacts and cost-benefit analysis of power generation in India*. Central Statistical Organization, Government of India.

[12] Dahowski, R.T., Dooley, J.J., Davidson, C.L., Bachu, S., and Gupta, N., 2004. *A CO_2 Storage supply curve for North America*. Technical Report 2005/3. IEA Greenhouse Gas R&D Programme.

[13] Dreicer, M., Tort, V., and Margerie, H., 1995. Nuclear fuel cycle: implementation in France. Final report for ExternE Program, contract EC DG12 JOU2-CT92-0236. CEPN, F-92263 Fontenay-aux-Roses.

[14] Edmonds, J.A., 2007. Personal communication on global carbon price trajectories for various stabilization scenarios.

[15] ExternE. 1998. ExternE: Externalities of energy, vol. 7, Methodology 1998 update (EUR 19083); vol. 8, Global warming (EUR 18836); vol. 9, Fuel cycles for emerging and end-use technologies, transport and waste (EUR 18887); Vol. 10, National implementation (EUR 18528). Luxembourg: European Commission, Directorate-General XII, Science Research and Development. Office for Official Publications of the European Communities. Results are also available at http://ExternE.jrc.es/publica.html.

[16] ExternE. 2000. External costs of energy conversion—Improvement of the ExternE methodology and assessment of energy-related transport externalities. Final report for contract JOS3-CT97-0015, EC Directorate General for Research. P. Bickel et al., IER, Universität Stuttgart. Also published as Environmental external costs of transport, eds. R. Friedrich and P. Bickel. Berlin: Springer Verlag, 2001.

[17] ExternE, European Commission, 2005. *ExternE – Externalities of energy: Methodology 2005 update.*

[18] Ghose, K.M., 2007. Generation and quantification of hazardous dusts from coal mining in the indian context. *Environment Monitoring Assessment* 130: 35–45.

[19] Ghose, M.K. and Majee, S.R., 2000. Assessment of dust generation due to opencast coal mining – an Indian case study. *Environmental Monitoring and Assessment* 61: 255–263.

[20] GoI, Government of India. 2006. *Integrated Energy Policy: Report of the Expert Committee*. New Delhi: Planning Commission.

[21] Gupta, S., 2002. Incentive-based approaches for mitigating greenhouse gas emissions: issues and prospects for India. *Report no 86*, MIT Joint Program on the Science and Policy of Global Change.

[22] Hall, D.C., 1990. Preliminary estimates of cumulative private and external costs of energy. *Contemporary Policy Issues* VII: 282–307.

[23] Holloway, S., Garg, A., Kapshe, M., Deshpande, A., Pracha, A.S., Khan, S., Mahmood, M., Singh, T., and Kirk, K., 2008. An assessment of the potential for CO_2 storage in the Indian subcontinent. *IEA Greenhouse Issues* - March 2008.

[24] IEA. 2006b. *World Energy Outlook 2006*. Paris: OECD/IEA.

[25] IGIDR project report, 1994. *Economic valuation of air quality degradation in Chembur, Bombay, India*. PP-018.

[26] IPCC, 2000. *Emission Scenarios.* Cambridge: Cambridge Universities Press.

[27] Jain, M.K. and N.C. Saxena, 2002. Air quality assessment along Dhanbad – Jharia Road. *Environmental Monitoring and Assessment* 79: 239–250.

[28] Kandlikar, M. and R. Gurumurthy, 2000. The causes and consequences of particulate air pollution in urban India: a synthesis of the science. *Annual Review Energy Environment*: 629–684.

[29] Kanudia, A., 1996. *Energy-Environment Policy and Technology Selection: Modelling and Analysis for India.* Doctoral Thesis, Indian Institute of Management, Ahmedabad, India.

[30] Kumar, S. and D.N. Rao, 2001. Valuing the benefits of air pollution abatement using a health production function: a case study of Panipat

Thermal Power Station, India. *Environmental and Resource Economics* 20: 91–102, 2001.

[31] Loulou R, Shukla, P.R., and Kanudia, A., 1997. *Energy and Environment Strategies for a Sustainable Future: Analysis with the Indian MARKAL Model*. New Delhi: Allied Publishers Ltd.

[32] Loulou, R., Goldstein, G., and Noble, K., 2004. *Documentation for the MARKAL Family of Models, October 2004*. Vol. 2007: Data downloaded on 26th June 2007 from http://www.etsap.org/documentation.asp

[33] Maria, A., 2003. The costs of water pollution in India. In *Proceedings of the Conference on Market Development of Water and Waste Technologies through Environmental Economics*. 30-31 October 2003, Delhi.

[34] McKibbin, W.J. and P.J Wilcoxen, 1997. *A better way to slow global climate change*. Brookings Policy Brief No. 17, the Brookings Institution.

[35] Murray, B., Newell, C., Richard, G., and Pizer, William, A., 2008. Balancing cost and emissions certainty: an allowance reserve for cap-and-trade. RFF Discussion Paper 08-24.

[36] Oak Ridge National Laboratory (ORNL), Resources for the Future [RfF], 1994–1998. External Costs and Benefits of Fuel Cycles (Reports 2–8). McGraw-Hill Utility Data Institute, Washington.

[37] Ostro, B., 1994. Estimating the health effects of air pollutants: a method with an application to Jakarta. World Bank Policy Research Working Paper 1301.

[38] Pigou, A.C., 1920. The Economics of welfare, Macmillan, London.

[39] Pizer, William A., 2002. Combining Price and Quantity Controls to Mitigate Global Climate Change. *Journal of Public Economics* 85(3): 409–434.

[40] Placet, M., Humphreys, K.K., and Mahasenan, N.M., 2004. *Climate Change Technology Scenarios: Energy, Emissions and Economic Implications*. Pacific Northwest National Laboratory, August 2004.

[41] Rafaj, P. and S. Kypreos, 2007. Internalisation of external cost in the power generation sector: analysis with global multi-regional MARKAL model. *Energy Policy* 35(2): 828-843.

[42] Riahi, K., Rubin, E.S., and Schrattenholzer, L., 2004. Prospects for carbon capture and sequestration technologies assuming their technological learning. *Energy* 29(9-10): 1309-1318.

[43] Riahi, K., Rubin, E.S., Taylor, M.R., Schrattenholzer, L., Hounshell, D., 2004. Technological learning for carbon capture and sequestration technologies. *Energy Economics* 26(4): 539-564.

[44] Roberts, M.J. and M. Spence, 1976. Effluent Charges and Licenses under Uncertainty. *Journal of Public Economics* 5(3–4): 193–208.

[45] Rowe, R.D., Lang, C.M., Chestnut, L.G., Latimer, D., Rae, D., Bernow, S.M., and White, D., 1995. *The New York electricity externality study*. Dobbs Ferry, NY: Oceana.

[46] Shah, J.J. and T. Nagpal, 1997. *Urban air quality management strategy in Asia: greater Mumbai report*. World Bank technical paper no. WTP 381.

[47] Shukla, P.R., 1998. Technology Strategy for India: Modeling and Analysis of Energy and Carbon Mitigation. In the *Steering Group Meeting for Technology Strategy Project*. Battelle, Pacific Northwest National Laboratory, Washington D.C., USA, 16 October 1998.

[48] Shukla, P.R., 2000. AIM ENDUSE Model Application for India: Sectoral Energy and Emissions Analysis. In the *Fifth AIM International Workshop*. NIES, Tsukuba, Japan, 24-25 March.

[49] Shukla, P. R., 2006. India's GHG emission scenarios: aligning development and stabilization paths. *Current Science*, 90(3).

[50] Shukla, P.R., Rana, A., Garg, A., Kapshe, M., and Nair, R., 2004. *Climate Policy Assessment for India: Applications of Asia Pacific Integrated Model (AIM)*. New Delhi: Universities Press.

[51] Shukla, P.R., Dhar, S., and Mahapatra, D., 2008. Low-carbon society scenarios for India. *Climate Policy* 8: S156-S176.

[52] Siddiqui, A. and C. Marnay, 2006. Addressing an uncertain future using scenario analysis. LBNL-62313, December.

[53] Simon, N.B., Cropper, M.L., Alberini, A. and Arora, S., 1999. Valuing mortality reductions in India: a study of compensating wage differentials", *World Bank Policy Research Paper*, WPS-2078.

[54] Singh, A., Mendhe, V., and Garg, A., 2006. CO_2 Sequestration potential of geologic formations in India. In Eight International Conference on Greenhouse Gas Control Technologies, GHGT-8. Trondheim, Norway, 19-22 June.

[55] Wong, C., Vichit-Vadakan, N., Kan, H., Qian, Z., 2008. Public Health and Air Pollution in Asia (PAPA): a multicity study of short-term effects of air pollution on mortality. *Environmental Health Perspectives* Vol. 116, Number 9.

[56] Wang, H., and T. Nakata, 2009. Analysis of the market penetration of clean coal technologies and its impacts in China's electricity sector. *Energy Policy* Volume 37, Issue 1.

[57] Weitzman, M.L., 1974. Prices vs. Quantities. *Review of Economic Studies* 41(4): 477–491.

[58] Weitzman, M.L., 1978. Optimal rewards for economic regulation. *American Economic Review* 68(4), 683–69.