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Power Planning Under Carbon Budgets

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Introduction

Climate change mitigation in any country would require significant levels investment in low carbon technologies. Developing countries have to also the added responsibility of poverty eradication and raising the level of material well-being of the bulk of their populations. In the context of climate change mitigation, the developing countries argue against taking immediate action because of their need for energy. The strength of these arguments depends critically on estimating (a) the energy needs of the developing countries into the future and (b) on estimating the appropriate fuel-mix to satisfy these needs and the resultant financial impacts. The TISS Power Sector model provides a framework for evaluating the fuel options for each country using a carbon budget as the environmental constraint.

In this paper, we evaluate the fuel options in the power sector, assuming that a specific proportion of the national carbon budget is available for power generation. Thus we are able to study the impact of specific carbon budgets on fuel options as well as compare the costs incurred for electricity generation under different budgets. We can also apply the same technique to different countries and compare differential impacts on developed and developing countries under a common mitigation regime. This paper presents preliminary results for the power sectors in India and USA[1]. For the sake of completeness and a self-contained presentation we have discussed the carbon budgets approach in the first section of the paper in some detail. The carbon budgets for each country/region discussed in this section are used in the TISS Power sector model to evaluate fuel options for each country.

I . Global Carbon Budgets and Maximum Temperature Increase

Climate science is now clear that human activity, particularly the emission of GHG gases, is causing global warming. There is of course debate over how much of a temperature increase above pre-industrial levels is acceptable. Many small island states desire the recognition of a 1.5 deg. C temperature increase as the limit in view of the threat that they face from rising sea-levels. Many other countries have indicated their preference for 2 deg C as the acceptable limit for maximum temperature increase. The Cancun Declaration recognizes 2 deg. C as the limit while also allowing for a scientific review that will evaluate whether this limit should be lowered to 1.5 deg C. . This limit of 2 deg. C imposes a carbon budget on the world. For example, a carbon budget of 1440 Gt of carbon dioxide (392 Gt of Carbon) for the world[2] implies a 50% probability of keeping temperature rise below 2 deg. C . A greater probability of limiting temperature rise to 2 deg. C would imply a smaller budget. Even though the limit of 2 deg C. has been accepted by a majority of the countries, its realization through a global climate agreement on the required levels of mitigation is the subject of ongoing multilateral negotiations. The actual implied mitigation burden or carbon budget (depending on the choice of methodology to determine the mitigation effort) and the share of each country in contributing to this required effort is being currently debated.

Although developing countries have always emphasized the importance of historical responsibility, which implies a focus on cumulative emissions, in practice the debate has revolved around the “flow of emissions” instead of the “stock of emissions”. The first commitment period of the Kyoto Protocol, recommendations of the fourth assessment report (AR4) of the IPCC, the pledges from

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[1] The electricity data for USA has been collated from various sources by Mario D’Souza

[2] Meinshausen, M. et al, ‘Greenhouse-gas emission targets for limiting global warming to 2 deg C’

developed countries all tend to strengthen this emphasis further by prescribing emission reductions based on flows with respect to a base year (1990 is most often used). However, an approach based on cumulative emissions is a more suitable operationalization of the principle of historical responsibility. A clear distinction between flows and stock and a firm emphasis on the latter is necessary for two reasons – a) to determine the responsibility of the world as a whole to limit cumulative emissions under a certain level so that there is a reasonable probability of preventing temperature increase of more than 2 deg. C. and b) to determine the share of responsibility or cumulative emission limits for each country within the global goal, based on a principle of equity and the implications of such a distribution of responsibility.

II. The Carbon Budgets Approach

The concept of cumulative emissions naturally leads us to allocate to the world a carbon budget. To limit temperature increase the world must restrict emissions below this level. We have already emitted 332 gigatons of carbon (GtC) between 1850 and 2009, and we have to live within a carbon space of about 326 GtC between 2010 to 2050 for at least a 50% chance that temperature increase will not be more than 2 deg. C. This means that of the total carbon space of 658 GtC between 1850 and 2010, the world has already used up (occupied) more than half. However, of the total historical emissions, 245 GtC (74%) have been contributed by the developed countries (Annex-I countries), i.e. by only 20% of the total global population.

How is the entitlement to carbon space of different countries to be determined? The most notable candidate for an allocation rule for the carbon budget has been the distribution of the total carbon space available (from the pre-industrial era to the future specified target date) on the basis of an equal per capita principle. The standard procedure that advocates of this approach have followed is to consider the population with respect to a single base year, usually from the recent period, though varying population could also be used in the criteria. Any base year for population can be chosen; eariler years (before 1950) favour the developed countries whereas base years after 1950 favour developing countries. However for some large developing countries such as the BASIC countries the difference is not very significant.

Assuming 2000 as the base year, the Annex-I countries are entitled to approximately 20% of the 658 GtC available between 1850 and 2050, i.e. 133 GtC and the non-Annex-I countries are entitled to approximately 80% of the total 658 GtC, i.e. 525 GtC. However, the Annex-I countries have already emitted 245 GtC between 1850 and 2010. Thus they have occupied much more than their fair share of the carbon budget and they now owe carbon space to the other countries.

However, it is not possible to scrub carbon-dioxide from the atmosphere and certainly not at a rate which will be significant enough to impact climate change mitigation. Negative entitlements can therefore provide a basis to assign rights to every nation, but cannot be extended further to determine the actual amount of emissions that will be physically available to the developing countries. This is where the difference between entitlements and physical carbon space becomes important. An argument based simply on entitlements tends to focus on the repayment of the carbon debt mostly in terms of financial transfers and misses the importance of physical carbon space which is the indicator of the constraints that will actually be placed on the country's energy infrastructure, access to modern energy services and level of material well-being of its population.

Even if we assume that all the countries that have over-drawn their carbon budget (Annex-I countries), reduce their emissions to zero immediately, the carbon space available to the non-Annex-I countries from 2010 to 2050 is 326 GtC, significantly less than their entitlement, which is 438 GtC.

The emissions model discussed by Kanitkar, Jayaraman et al (2010)[3] gives a range of potential carbon budgets for various countries and regions. The results of the model provide various scenarios for potential physical carbon space that might be available to countries which have not yet exhausted their fair share of carbon space, given the mitigation action taken by Annex-I countries. Some of the results are shown in Table 1.

Table 1. Entitlements and Potential Physical Carbon Space for Annex-I and Non-Annex-I countries

1850 Basis, Non-LUCF, Based on 2000 Population	Entitlements - 1850-2050 (GtC)	Contribution to Stock – 1850-2009 (GtC)	Future Entitlements - 2010-2050 (GtC)	Potential Actual Share-2010-2050 (TISS-DSF Model)
Annex-I	133.13	245.15	-112.02	50.18
Non-Annex-I	524.60	86.32	438.27	271.13
Total	658	265	326	321

The last column in Table 1 shows the potential carbon share for Annex-I and Non-Annex-I countries between 2010 and 2050 in a scenario where the countries that have over occupied carbon space historically are required to reduce emissions at the rate recommended in the IPCC AR4 (Intergovernmental Panel on Climate Change, Fourth Assessment Report), i.e. 40% of 1990 levels by 2020 and 95% of 1990 levels by 2050. In this scenario, the carbon space available to non-Annex-I countries is 271 GtC. For most developing countries, this global emissions constraint (a budget of 326 GtC between 2010 and 2050) will mean that they will never be able to get their fair share of carbon space. For example, India is entitled to 103 GtC between 2010 and 2050, but in order to ensure sustainability, i.e. to restrict global temperature increase below 2 deg. C, India might potentially have access to only about 55-68 GtC, only about half of its entitlement.

The difference between the actual physical space and the entitlements can be compensated to the developing countries through technology and financial transfers. Since this is a debt that is owed to the developing world, this transfer cannot be seen as aid or offsets. The physical carbon space is the actual 'development space' that countries will have within which to make decisions regarding infrastructure, energy access for their populations. Hence its utilization should be under the sovereign jurisdiction of every country.

IV. Carbon Budgets and Energy Requirements

In the context of climate change mitigation, one of the key arguments of developing countries for why they cannot undertake any serious emission reductions immediately has been based on their need for energy. Any mitigation action would require significant levels of investment and this would make energy more expensive and thus unaffordable to a majority of the population in a developing country. Also the levels of capital investment required for low-carbon high-cost resources of energy could potentially lead to reduced spending on other welfare measures The strength of these arguments depends critically on estimating (a) the energy needs of the developing countries into the future and (b) on estimating the appropriate fuel-mix to satisfy these needs and the resultant financial impacts.

There is now a significant literature on both these issues. A large section of the literature that discusses optimum pathways for climate change mitigation is based on integrated assessment modeling. These models typically maximize welfare or utility or minimize costs on an economy-

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[3] Kanitkar, T. et al, 'Conference on global carbon budgets and equity in climate change, Discussion Paper, Supplementary Notes and Discussion Report'

wide basis. In the context of equity in climate change, a key weakness of these models is that little attention is paid to the physical availability of energy. These models generally estimate costs based on a large number of assumptions and therefore are susceptible to large uncertainties, which together with the uncertainties of climate models can be quite significant. Another class of models that appears more useful essentially focuses on a bottom-up assessment of the energy demands of specific countries taking into account their current national circumstances in terms of the economy, while projecting future energy demands based on extrapolation from current trends. Although the bottom-up energy assessment models present a more thorough picture of the energy sector and the energy-emissions relations, the economic parameters input in the model are obtained from econometric models of the CGE (computable general equilibrium) variety. Also, both these classes of models provide no insights for situations of structural change in the economy, which is not a completely unlikely scenario in a developing country. Such models also suffer from the danger that they underestimate future energy requirements, especially in allowing for periods of much greater accelerated growth, for developing countries. Table 2 shows a comparison of some models that have allocated carbon space to India under various scenarios.

Table 2. Comparison of Budgets allocated by Various Economic Models

Model	**Budget between 2010-2030 [GtCe]**	**GHGs considered**
NCAER-CGE (2030-31)	14.86	CO2 & N2O
TERI-MoEF (2031-32)	14.27	CO2
IRADe AA (2030-31)	15.20	CO2
TERI Poznan (2030-31)	19.97	CO2
McKinsey India (2030)	19.75	all GHGs
TISS-DSF Model - 1850 Scenario (2030)	18.11	CO2
IEA-450 Scenario	10.61	CO2

Over and above these concerns are two further issues that are of particular relevance for this study. Many of these models do not consider an emissions constraint at all, but merely calculate the resultant emissions in a situation where in the global economy some welfare function is maximized or costs are minimized. So the objective function is not constrained by the environment; the resultant emissions are what the world 'has to live with'. Some models consider only a global constraint on emissions - a “global 2 deg. C pathway”. The world as a whole has to stay within the limits defined by this pathway and the differential responsibility of each country is calculated based on the cost implications of emissions reduction. Very few models explicitly incorporate equity as criteria to decide the mitigation effort required by various countries.

V. TISS Power Sector Model

The TISS Power Sector model is based on the recognition of the difference between entitlements and the actual carbon space that might be available to countries given a global carbon budget. The model uses the latter as the environmental constraint for each country under which its fuel options are evaluated. In this paper, we restrict our attention to the power sector and evaluate the fuel options in the power sector, assuming that a specific proportion of the national carbon budget is available for power generation. Thus we are able to study the impact of specific budgets on fuel options as well as compare the costs incurred for electricity generation under different budgets for specific countries. We can also apply the same technique to different countries and compare for instance how a larger carbon budget for a developed country would lower the costs of its electricity generation but would at the same time raise the costs for a developing country whose carbon budget would be correspondingly lower.

This paper presents preliminary results for the power sectors in India and USA[4]. For both countries multiple scenarios are modeled; e.g. the fuel options and resultant costs for the power sector in the USA if it undertakes emission reductions pledged in the Copenhagen pledges as opposed to the recommendations of IPCC AR4. Similarly for India, various such scenarios are modeled and the results are presented in this paper.

(i) Energy Requirements

In most models, energy demand is calculated by regressing it against a dependent variable such as GDP per capita. A more comprehensive analysis would assess sector-wise demand and then aggregate it to arrive at the economy-wide demand for energy. Many bottom-up energy models do this by choosing one or more dependent variables for each sector and projecting past trends into the future using regression. However, if in a country past trajectories of sectoral growth have not been able to achieve their proposed target values, then just projecting past trajectories into the future will amount to underestimating the requirements, particularly for a developing country which has yet to build its stock of infrastructure, ensure that basic needs are met and that average well-being attains some reasonable levels.

In the model presented in this paper, the demand for electricity can be specified as input by the user, based on any of the above analysis. The specific results presented in this paper however use a different methodology to arrive at estimates of demand which will be discussed in this section. The Indian economy is currently a low consumption economy, with very low levels of per capita consumption as compared to other developed countries as well as some other emerging economies as shown in Table 3.

Table 3. Energy and Development Indicators for some countries[5]

Countries (2007)	Per Capita GNI at PPP ($)	Per Capita Energy Consumption (kgoe)	Per Capita Electricity Consumption (kWhr)	Per Capita Installed Capacity (kW/person)	Per Capita Emissions (tCO2)	HDI (2010)
India	2870	529	452	0.13	1.4	0.52
China	5640	1484	2332	0.48	5	0.66
South Africa	9660	2784	4944	0.85	9	0.59
UK	36270	3465	6123	1.31	8.8	0.85
US	46740	7759	13638	3.24	19	0.9
World	10203	1821	2875	0.61 (2006)	4.6	-

India has lower per capita energy consumption compared to developed economies as well as some developing economies and is also below the world average in energy/electricity consumption. India also has a low level of HDI as compared to other countries and although the growth in energy consumption levels reaches a plateau after a certain achievement in HDI (Martinez, Ebenhack 2008), India is also below the nominal requirement to reach the level which will allow a sustained improvement/high level in human development without a further increase in energy use. However, as seen from Table 6, USA has levels of energy consumption that are much higher as compared to other developed countries as well. Also, there are other developed countries that have achieved similar levels of HDI as that of the US with lower levels of energy consumption.

The energy demand used in this analysis is estimated based on the premise that the main objective of any nation should be to target a reasonable quality of life for its citizens. This depends on many

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[4] The electricity data for USA has been collated from various sources by Mario D’Souza

[5] Data for all indicators taken from the World Bank Country Database

factors but several studies have shown that there is strong correlation between levels of well-being (measured in terms of the factors contributing to the HDI index) to energy consumption[6][7].If India's target is to achieve a human development index that is comparable at least to the middle level developed countries (0.8-0.85), then it is necessary to determine the most efficient way to achieve this. The best that has been achieved amongst developed countries has been in Portugal (0.8 HDI) and Greece (0.85 HDI) with per capita energy consumption of 2.54 toe/person and 2.87 toe/person respectively. Some emerging economies such as South Korea (0.87 HDI) and Singapore (0.85 HDI) have achieved high levels of HDI albeit with higher energy consumptions of 4.6 toe/person and 5.83 toe/person respectively.

Portugal is a viable example that demonstrates the case for low use of energy per capita for levels of HDI that are comparable to other developed countries such as neighboring Spain. Since HDI has an inherently exponential character, we use indicators such as life expectancy and infant mortality for this analysis. However, the characteristics of the trend remain the same[8].

For India, we make a reasonable assumption that it should target levels of human development that are comparable at least to those of mid-level developed countries. Since Portugal demonstrates the use of the least amount of energy per capita (electricity per capita used here as a proxy) to achieve reasonably high levels of life expectancy and low levels of infant mortality, we assume that given the current levels of technology, this is the best that can be achieved by a country. An assumption of continuously declining levels of energy or emissions intensity would involve speculation that cannot be justified against the goals of achieving high levels of human development at this stage. The energy requirements to achieve high levels of development may of course change in the future, but since there is no reasonable way in which to predict these changes, we believe that policy decisions should be based on real, proven and achievable targets. Thus, by choosing a benchmark for the achievable best, we arrive at a target for energy consumption to be achieved in a given time period in the future.

The per capita electricity consumption of Portugal is 4860 kWh/person/year. The results presented in this paper use an electricity demand target of 4500 kwh/person/year by 2035 for India. For the USA, it is assumed that they keep their per capita electricity consumption constant at 13,638 kWh/person/year. Since their population is increasing, this would mean a marginal increase in the total electricity requirement in the country. Figure 1 shows the per capita and total electricity consumption for both countries in 2009, 2020 and 2035.

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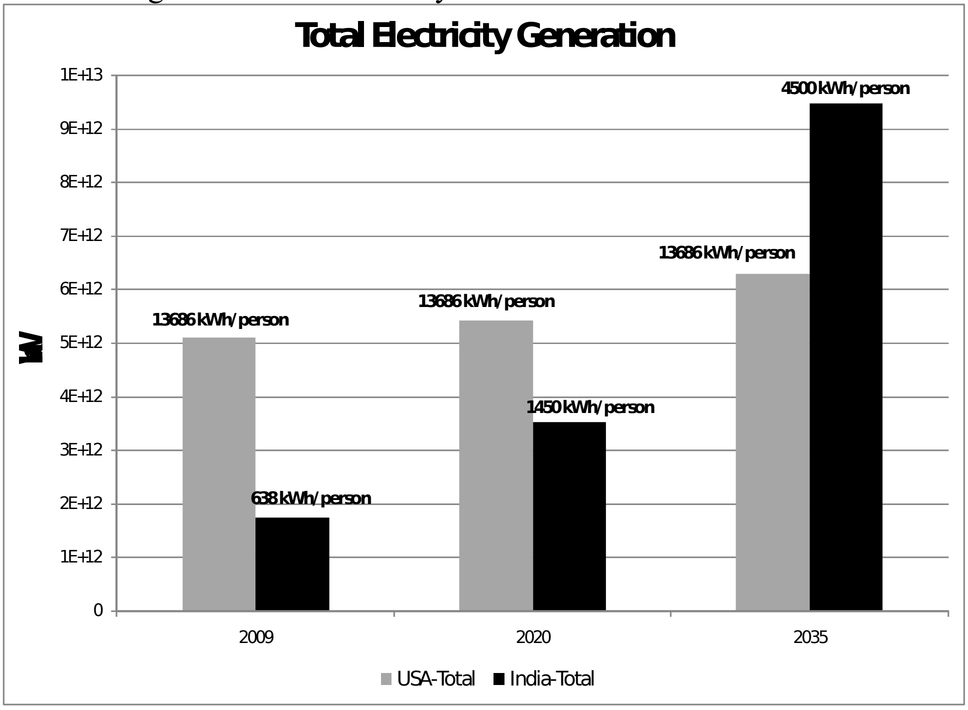
[6] Prabir Purkayastha, Tirthankar Mandal,A Note on Carbon Space as Development Space, Conference on Global Carbon Budgets and Equity in Climate Change, 28-29 June 2010, Organised jointly by Tata Institute of Social Sciences, Mumbai and the Ministry of Environment and Forests, Govt. of India

[7] Indian Energy and Emission Trends, Prayas Energy Group, Pune

[8] This analysis of energy requirement has been contributed by Prabir Purkayastha and Tirthankar Mandal

Figure 1. Total Electricity Generation for India and USA



As seen from the figure, India's total electricity generation would need to be higher than US if India is to achieve a per capita electricity consumption which is at least 30% of the US's current per capita electricity consumption or 70% of UK's current per capita electricity consumption by 2035.

(ii) Power Supply

Both countries studied in this paper are relatively diverse in terms of the fuel sources that supply the power demand. However, in both countries the share of coal based power generation is the highest. In India, more than 60% of all electricity is generated by coal based power plants. Large hydroelectric power plants contribute approximately 15% to the total electricity generation. A break-up of total fuel-wise installed capacity as well as contribution to actual electricity by generation from each fuel source for India and the US is shown in Figures 2 and 3.

Figure 2. Fuel-Wise Installed Capacity and Electricity Generation in India (2009)

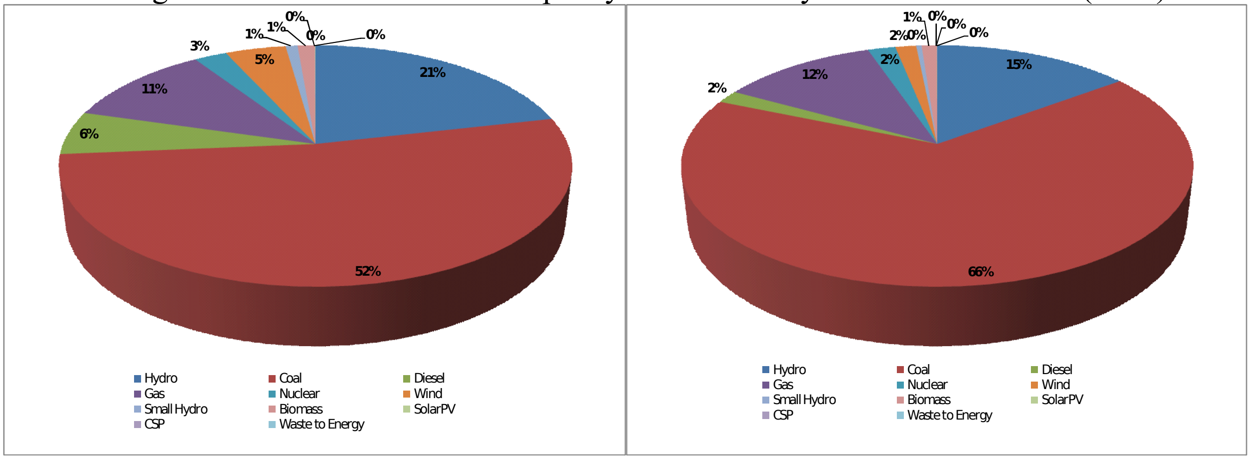
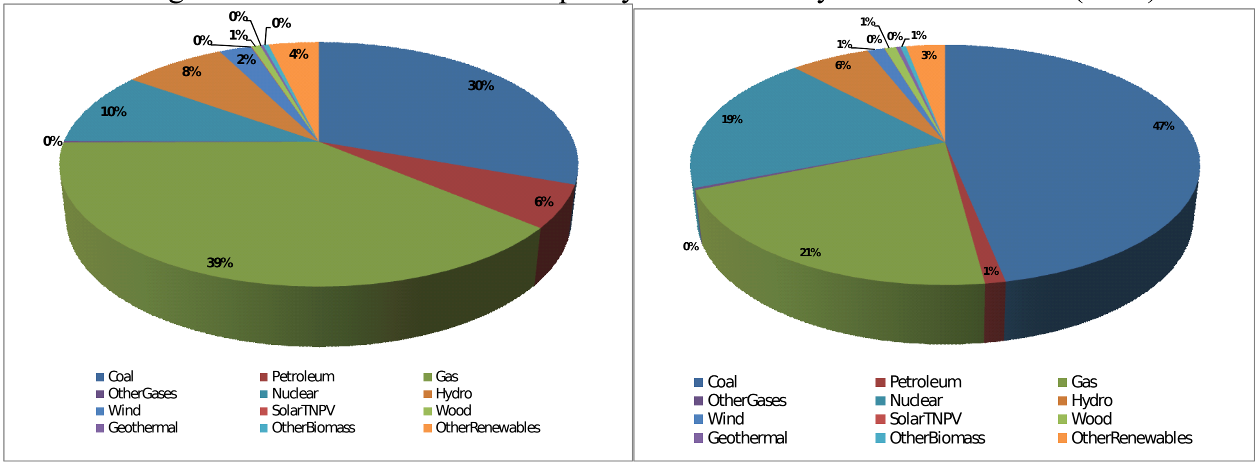


Figure 3. Fuel-Wise Installed Capacity and Electricity Generation in US (2009)



This distribution of electricity sources in India is accounted for by two reasons; i) cost of electricity generation and ii) resource availability. India has high amounts of coal reserves. Gas has recently started to acquire greater significance in power generation; however demand for natural gas from other sectors (fertilizer production for example) is likely to limit the role that it can play in the power sector in the future. However, most studies of the power sector project an increase in the share of gas-based generation in the medium-term. According to the IEP (Integrated Energy Policy), a large portion of the hydro reserves are yet to be tapped; India has a total potential of about 1,50,000 MW of which only about 36,000 MW has been tapped so far. However, the capacity factors of hydro-electric plants are low compared to coal plants and a large part of the new hydro capacity is expected to be of the "run-of-the-river" variety, with lower capacity factors. Electricity generation from renewable energy sources in the country has increased considerably in the last few years. Wind based power generation for example has increased substantially in some states (Tamil Nadu, Maharashtra, Gujarat, and Karnataka). However, capacity factors of wind plants are also low, with the highest being around 20% achieved only in Tamil Nadu. The average plant capacity factors (2009 values) for India are shown in Table 4.

Table 4. 2009 Average Plant Capacity Factors in India[9]

Hydro	38%
Coal	70%
Diesel	16%
Gas	58%
Nuclear	47%
Wind	19%
SHP	25%
Biomass	49%
Solar PV	15%
CSP (assumed)[10]	20%
MSW	31%

In the US, gas-based power generation plays a very important role in supplying electricity at times of peak load. The US also has a large number of combined co-generation plants which use natural gas as the primary fuel to provide electricity as well as central heating. The renewable-source based installed capacity in the US is currently about 7.5% only slightly higher than India's 6.8%. These estimates exclude large hydro plants. Nuclear energy also plays a much larger role in the US,

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[9] CSP - Concentrated Solar Power; SHP – Small Hydro Power; MSW – Municipal Solid Waste

[10] Plant Capacity Factor for CSP Plants is assumed as there is no plant in operation as yet

contributing around 10% to the installed capacity and around 19% to the electricity generation vs. India's 2% contribution to both installed capacity and electricity generation. The average capacity factors for plants in the US are given in Table 5.

Table 5. 2009 Average Plant Capacity Factors in USA

Coal	72%
Petroleum	9%
Gas	25%
Other Gases	67%
Nuclear	91%
Hydro	37%
Wind	26%
Solar Thermal and Photovoltaic	18%
Wood	62%
Geothermal	76%
Other Biomass	48%
Other Renewable Sources	37%

The average plant load factor for gas plants is low (at 25%) in the US. The probable reason for this might be the differential use of these plants in the winter and summer months. In this model it is assumed that the plant load factors for gas plants in the US can go up to 50% by 2035, if needed. For both India and the US, it is assumed in the model that the load factors for coal based power plants can go up to 85%. In India the PLF for nuclear plants is assumed to increase to 75% (this would be contingent on smoother supplies of fuel). The plant capacity factors for 2009 are based on current average values for plants across each country. The changes however are input by the user. Therefore these can be changed in the model in lieu of breakthrough's or improvements in available technology.

Electricity utilities have to make sure that the demand at the consumer end is met at all times. Therefore, the actual amount of generation and installed capacity need to be higher than the consumption to account for losses in the transmission and distribution network (T&D losses), as well as auxiliary consumption by the plants. The T&D losses in India are high (25% of total electricity generated is lost in transmission and distribution) partly because India has the highest length of low tension distribution lines with very low density of domestic consumers at the tail-end especially in rural areas as well as low usage of electricity by domestic consumers. This would result in higher technical T&D losses than countries such as the UK for example that have a higher density of power consumption. However, the USA, having to face similar problems of large T&D networks has nevertheless managed to keep T&D losses at 6%. A part of what is categorized as "transmission and distribution" loss in India is actually un-metered consumption; however, even after accounting for these reasons, the T&D losses in India can be reduced significantly in the future. The model assumes a reduction of T&D losses from 25% in 2009 to 15% in 2035 in India. For the US, the loss is assumed to neither increase nor decrease till 2035. Apart from the T&D losses and auxiliary consumption, a spinning reserve of 10% is assumed to be kept on standby in case of un-planned failures in power plants.

(iii) Constraints on supply of electricity

The sources of electricity that will meet the energy demand are constrained by many factors viz. resource constraints (e.g. availability of coal, gas, uranium), constraints on factors such as water, land etc. The second category of constraints is not considered in this model. The resource constraints estimated by various agencies can vary quite widely and have a significant impact on the outcomes of the kind of fuel mixes that may be possible in the future. In the model, this input can also be changed by the user as better estimates become available. The estimates of potential resource availability for India (shown in Table 6) are obtained from the Integrated Energy Policy (IEP) and for the US the numbers (shown in Table 7) are approximated from data given in the World Energy Outlook 2010.

Table 6. Constraints on Electricity Generation in India due to resource availability[11]

Coal	7 times current capacity
Nuclear	63,000 MW
Gas	3 times current capacity
Large Hydro	1,50,000 MW
Diesel*	5 times current capacity
Wind[12]	800,000 MW
SHP	15000 MW
CSP*	Inf
Solar PV*	Inf
Biomass*	15 times current capacity
MSW*	8 times current capacity

Table 7. Constraints on Electricity Generation in USA due to resource availability

Resource	**Current Capacity (GW)**	**Maximum Availability by 2035 (GW)**
Coal	313	600
Petroleum	57	100
Gas	397	600
Other Gases	2	5000
Nuclear	101	200
Hydro	78	150
Wind[13]	25	100
SolarTNPV	1	-
Wood	7	75
Geothermal	2	20
OtherBiomass	4	20
OtherRenewables	38	50

These numbers are rough estimates. User can input more robust numbers that can provide results with lower uncertainties

(iv) Cost of Electricity

The aim of the model is to provide a potential 'least-cost' fuel mix that will ensure that the carbon budget constraint for each country will not be violated. Therefore the cost of electricity generation and potential trajectories of this cost for each fuel source is an important input. Currently the methodologies that are used to predict behavior of energy cost in the future involve many

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[11] Values for coal, large hydro, wind, gas, SHP and nuclear are approximated from the Integrated Energy Policy. Values for CSP, Solar PV, Biomass and MSW are assumed and can be changed when reliable projections are available

[12] Wind potential assessed by LBNL is about 800-1000 GW (at 100 metres). The assessment done by CWET is much lower at 48,000 MW. To avoid overestimating costs of total electricity generation, LBNL's assessment is used in this analysis

[13]

assumptions. For example coal costs might be linked to cost of carbon to be determined in the international carbon market depending on implicit emission caps allocated to various countries in the future. The cost of uranium is also estimated by linking it to an artificial constraint on coal.

In this analysis, the current costs of electricity are extrapolated based on historical trends to arrive at future costs. These are then discounted to 2009 the model minimizes the discounted cost of electricity. The trends of electricity costs might well change in the future, and can be modified accordingly in the model. The current cost of electricity generated with different technologies is however known and is shown in the Table 8 for Indian and Table 9 for USA.

Table 8. Cost of Electricity from various fuel sources in India

	Cost of Generation/Tariff (whichever is available and more reliable) – Rs./kWh
Large Hydro[14]	2.5
Coal (Domestic)[15]	1.6
Coal (Imported)[11]	2.25
Gas[16]	3
Nuclear (Domestic)[12]	3.65
Nuclear (Imported)[17]	6.59
Wind[18]	4.51
SHP[19]	3.35
Biomass[20]	3.96
SolarPV[21]	15.67
CSP[22]	12.85
Waste to Energy[23]	3.902
Diesel[24]	7.10

Table 9. Cost of Electricity from various fuel sources in USA[25]

Plant Type	**2009 $/kWh**
Coal	
Conventional Coal	0.0948
Advanced Coal - Supercritical	0.1094
Advanced Coal with CCS	0.1362
Natural Gas-fired	
Conventional Combined Cycle	0.0661
Advanced Combined Cycle	0.0631
Advanced CC with CCS	0.0893
Conventional Combustion Turbine	0.1245
Advanced Combustion Turbine	0.1035

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14 Ministry of Power

15 Prayas Energy Group, Nuclear Energy in the Context of India's Energy Policy

16 Prabir Purkayastha, Uncle Sam's Nuclear Cabin

17 Tejal Kanitkar, Cost Analysis of the Jaitpur Nuclear Power Plant

18 Based on average cost of generation in 7 Indian states

19 Based on average cost of generation in 7 Indian states

20 Based on average cost of generation in 13 Indian states

21 Based on average cost of generation in 11 Indian states

22 Based on average cost of generation in 8 Indian states

23 Based on average cost of generation in 5 Indian states

24 Based on average cost of generation in 2 Indian states

25 U.S. Energy Information Administration

Advanced Nuclear	0.1139
Wind	
Onshore	0.097
Offshore	0.2432
Solar	
Solar PV	0.2107
Solar Thermal	0.3118
Geothermal	0.1017
Biomass	0.1125
Hydro	0.0864

The cost of energy for India and the US are input in the currencies of the respective country for ease of calculation. In this paper the pooled cost of electricity is later converted to USD at current exchange rates as well as in purchasing power parity (PPP) terms, to ensure comparability.

There is a difference between cost of generation and regulated tariff (which might also include subsidies and incentives provided by the Government), but in India for renewable energy sources, these are the best estimates due the low amounts of generation currently. After a certain level of experience is gained about the actual generation levels of these plants, the cost estimates can be fine-tuned and improved. As is evident from the figure, coal is currently the cheapest source of electricity. Electricity from solar photovoltaic is almost 7 times more expensive than electricity from imported coal. The costs however will change over a period of time.

The cost projections for the future also incorporate current estimates of new technology such as carbon capture and sequestration (CCS) or Integrated Gasification Combined Cycle (IGCC) for gas and coal based generation. The costs of coal, hydro, nuclear and gas based generation are assumed to increase by 2035 whereas cost of electricity from renewable energy sources is assumed to reduce. To calculate the discounted costs to 2009 values, a discount rate of 6% is used. Multiple scenarios based on different discount rates can be built.

(v) <u>The Budget Constraint</u>

In addition to resource and cost constraints the power sector will now also have to adhere to a budget constraint derived from an equity based emissions allocation model. This emissions model is discussed in detail by Kanitkar, Jayaraman et. al. (2010) and briefly described in the first section of this paper. The budget for each country is the actual physical carbon space that may potentially be available to each country. The results presented here use a global budget of 1440 GtCO2 (392 GtC) between 2000-2050. These results are compared against scenarios wherein allocation of carbon budgets is not on the basis of equity, but according to a pledge and review system which nonetheless has to obey the global environmental constraint. For example, options for potential fuel mix and their resultant cost impacts in the US are compared for two scenarios – a) if they stay within the budget of 18 Gt of carbon between 2010 and 2050 allocated to them based on a principle of equitable access to sustainable development and b) if they actually use the carbon space implied by certain proposals/pledges by country experts, i.e. Copenhagen pledges, the reports of the National Academy of Sciences etc. A similar analysis is done for India. Table 10 shows the various budgets for which scenarios have been modeled in this analysis.

Table 10. Carbon Budgets for 4 Scenarios

	USA	India

	Total Budget (GtC) - 2010-2050	Budget for Power Sector (GtC)	Total Budget (GtC) - 2010-2050	Budget for Power Sector (GtC)
Scenario - I: No restrictions on emissions for India and USA between 2010 and 2035	--	--	--	--
Scenario -II: Equitable Allocation of Carbon Space within the global budget	18	6	68	24
Scenario-III: Annex-I reduce emissions according to their Copenhagen Pledges, Non-Annex-I have to bridge the gap	35	12	30	11
Scenario - IV: Budget for USA proposed by National Academy of Sciences, USA; Highly curtailed Budget for Non-Annex-I	54	19	21	7

About 40% of the non-LUCF CO_2 emissions in India can be attributed to the power sector. The number is lower (at about 25-30%) in developed countries such USA. The total emissions from power sector in India may reduce vis-à-vis other sectors as the economy develops and a certain level of infrastructure is built.

(vi) *Details of the Model*

The power sector model presented in this paper provides a least-cost fuel mix for a resource and emissions constrained energy sector. It is basically a linear optimization problem wherein the total pooled cost of electricity for the time-period 2010 to 2035 is minimized subject to constraints on total available input resources (e.g. coal, gas, oil, wind potential etc.) and output resources viz. carbon space. The mix of fuels has to supply energy requirements that have been input based on a demand-side analysis discussed in an earlier section in the paper.

The carbon budget constraint can be input as a hard constraint that cannot be violated. Therefore, the country has to choose a fuel mix that ensures adherence to the carbon budget allocated to it. A solution has to be found within these constraints. Alternatively the carbon budget can also be input as a soft constraint, wherein it can be violated, but there is a progressive penalty on violation which would force changes in the fuel mix towards low carbon fuels in each consecutive year. The second approach can enable the modeler to differentiate between Annex-I and Non-Annex-I countries even further which can be useful as violation of the carbon budget would mean two different things in the case of Annex-I countries as compared to the bulk of non-Annex-I countries. A violation of the physical carbon budget by Annex-I countries would mean a further over-occupation of the atmospheric commons as opposed to violation by most of the non-Annex-I countries, which would only amount to getting a higher share of their entitlements. However, even the non-annex-I countries will have to be penalized albeit to a lesser degree as the global budget is inviolable.

The resource constraints are input as simple limits on the total generation or installed capacity for each fuel source. For each fuel source, there is a limit applied to how much new power generation capacity can be reasonably commissioned in each year and how much can be decommissioned. For example it is assumed that no more than 30% of current installed capacity can be commissioned anew in each year. The model also has to follow a constraint for base and peak load. It is assumed here that total base load capacity at any given time cannot be below 30% of the total.

Model Outputs

The model provides a potential fuel mix based on a minimization of the total pooled cost of electricity. The unit cost of electricity in 2035 as well as the total emissions is also estimated.

In Scenario-I the electricity costs are minimized based on only the resource constraints. There is no emissions constraint in this scenario for both India and USA. The shifts in fuel use are determined only by costs and the availability of fuel. The results for India and USA are shown in Figures 4 and 5 respectively.

Figure 4. Potential Fuel Mix for India – Scenario I: No restriction on Emissions

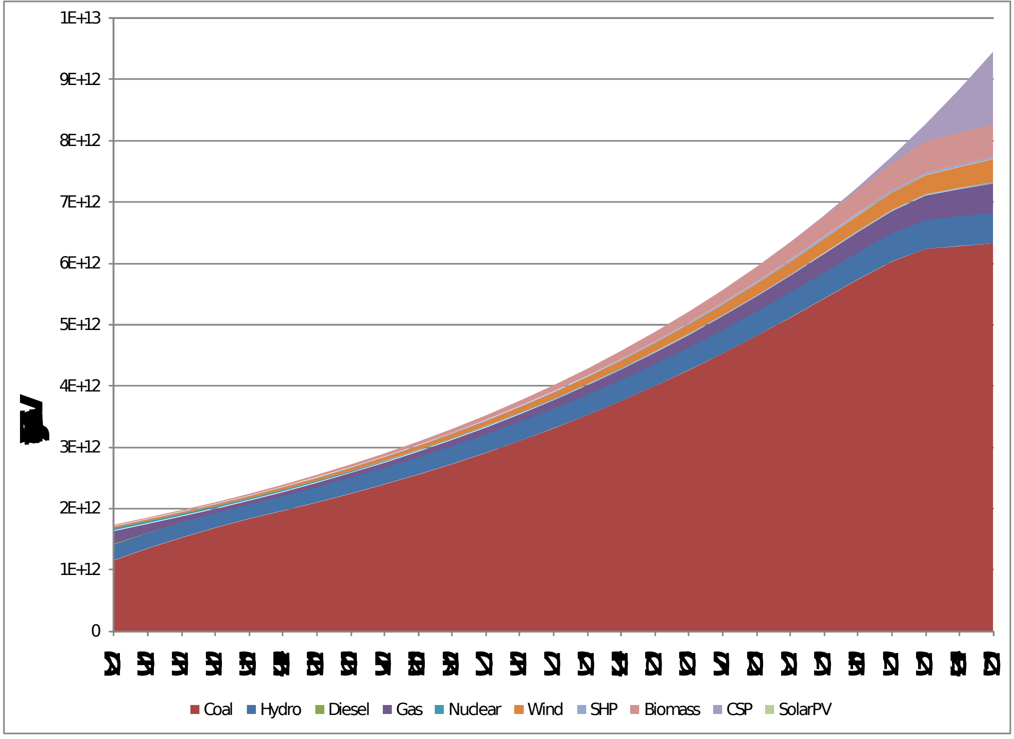
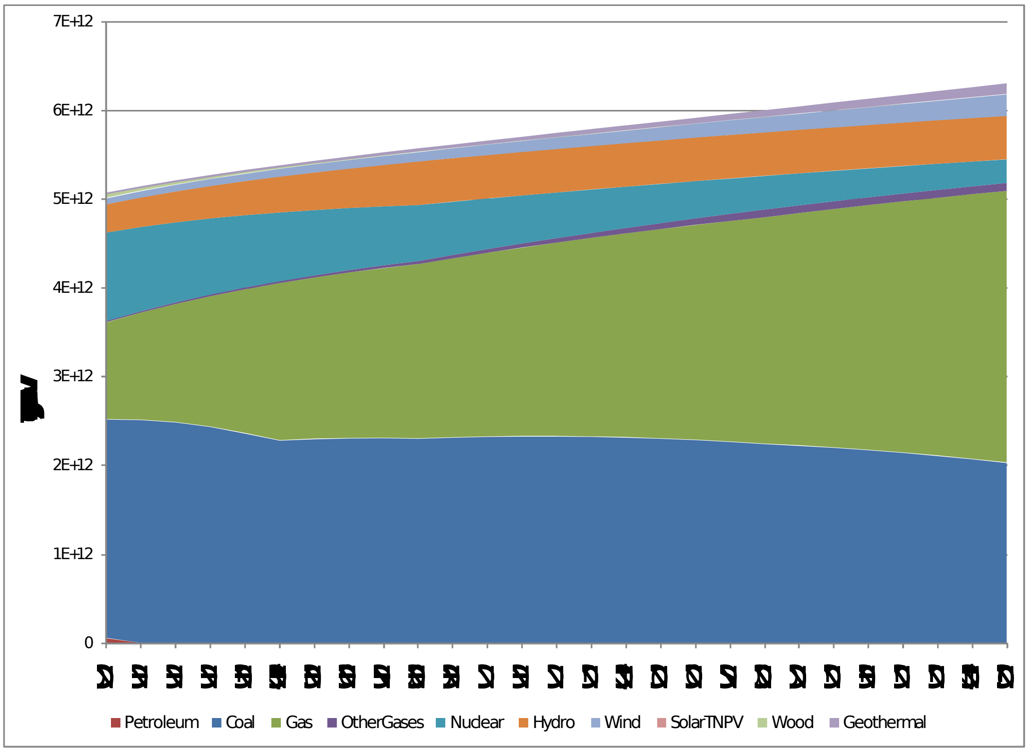


Figure 5. Potential Fuel Mix for USA – Scenario I: No restriction on Emissions



As can be seen from Figure 6, in a scenario where emissions from the power sector are not restricted, a least-cost emissions plan would call for rapid increase in coal-based electricity generation till the resource constraint for coal is reached. For the US, prices for gas based electricity generation are also low. Therefore the share of gas also increases till the resource constraint for gas is reached.

The discounted unit cost of electricity in India for Scenario-I in 2035 is Rs.10.23/kWh as compared to the current cost of Rs.3.63/kWh. For the US, this cost increases from $0.097/kWh in 2009 to $0.32/kWh in 2035.

To remind the reader, in Scenario II an equitable distribution of carbon space is assumed. Therefore the total carbon budget for India is about 68 GtC of which if 35% is utilized by the power sector, it would mean a carbon constraint of 24 GtC for the sector. In this scenario, the US is allocated a constrained carbon budget of 18 GtC totally, of which 35% (6 GtC) is assumed to be allocated to the power sector. In Scenario III, it is assumed that the Annex-I countries follow reduces emissions according to the pledges that were announced at the COP-15 at Copenhagen. This gives a higher budget to the US (35 GtC totally of which 12 GtC may be consumed by the power sector). For India this scenario constrains the carbon budget further – 30 GtC of which 11 GtC will be used for the power sector. In Scenario IV, the carbon budget for the US is assumed to be 54 GtC[26], of which 19 GtC is allocated to the power sector. In this scenario, India gets a smaller share of carbon space – 21 GtC of which 7 GtC is allocated to the power sector. Figures 6, 7 and 8 show the potential fuel mix for each scenario for India.

Figure 6. Potential Fuel Mix for India
Scenario II: Carbon Budget of 24 GtC for the Power Sector

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[26] Proposal of the National Academy of Sciences, USA

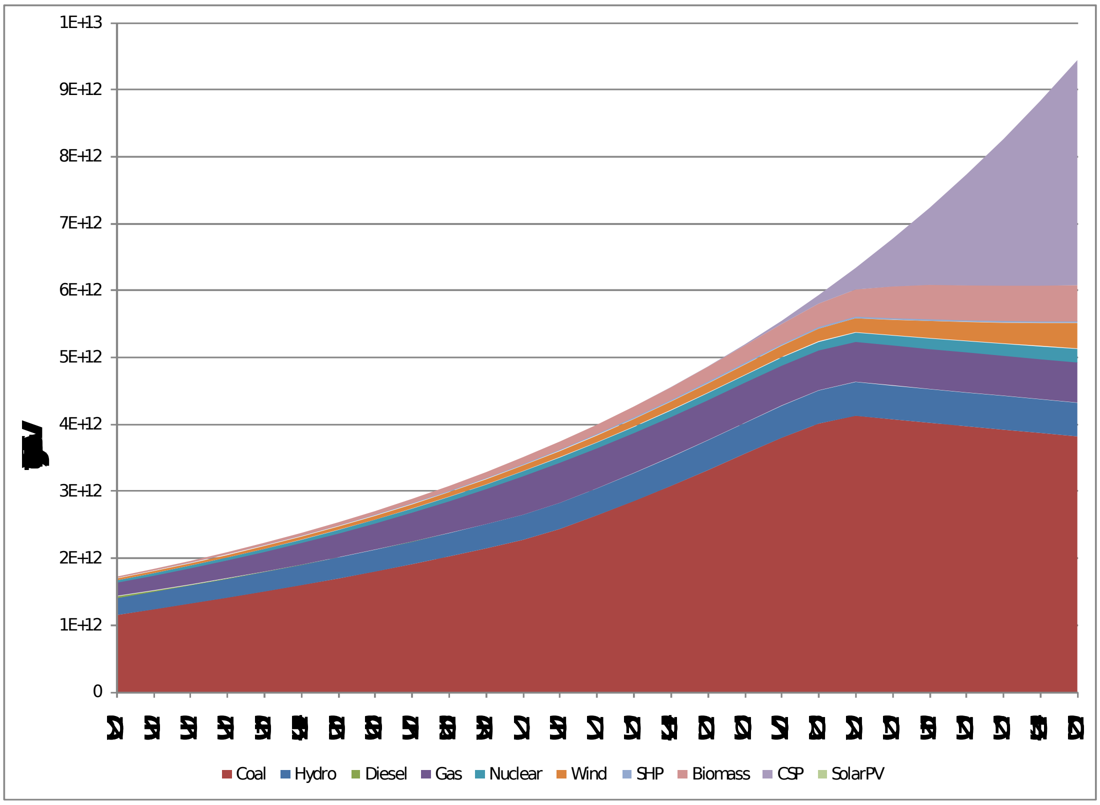


Figure 7. Potential Fuel Mix for India
Scenario III: Carbon Budget of 11 GtC for the Power Sector

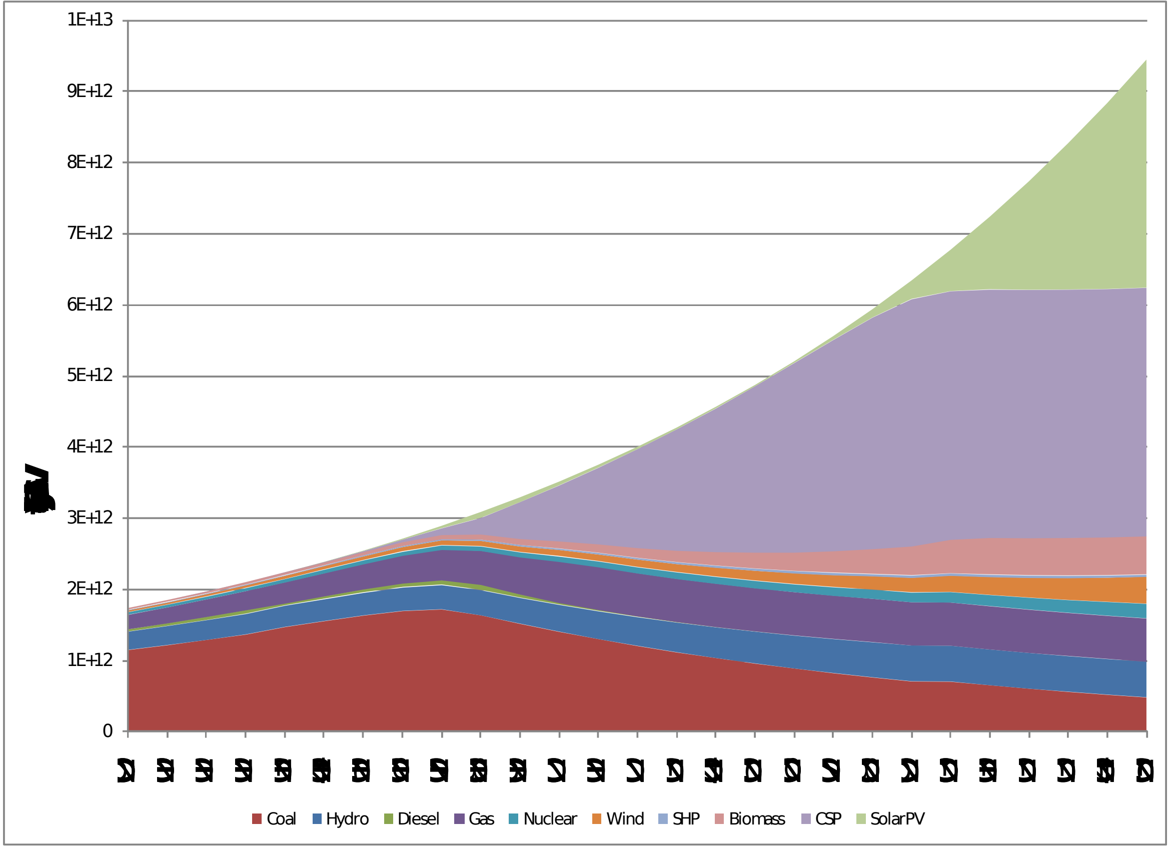
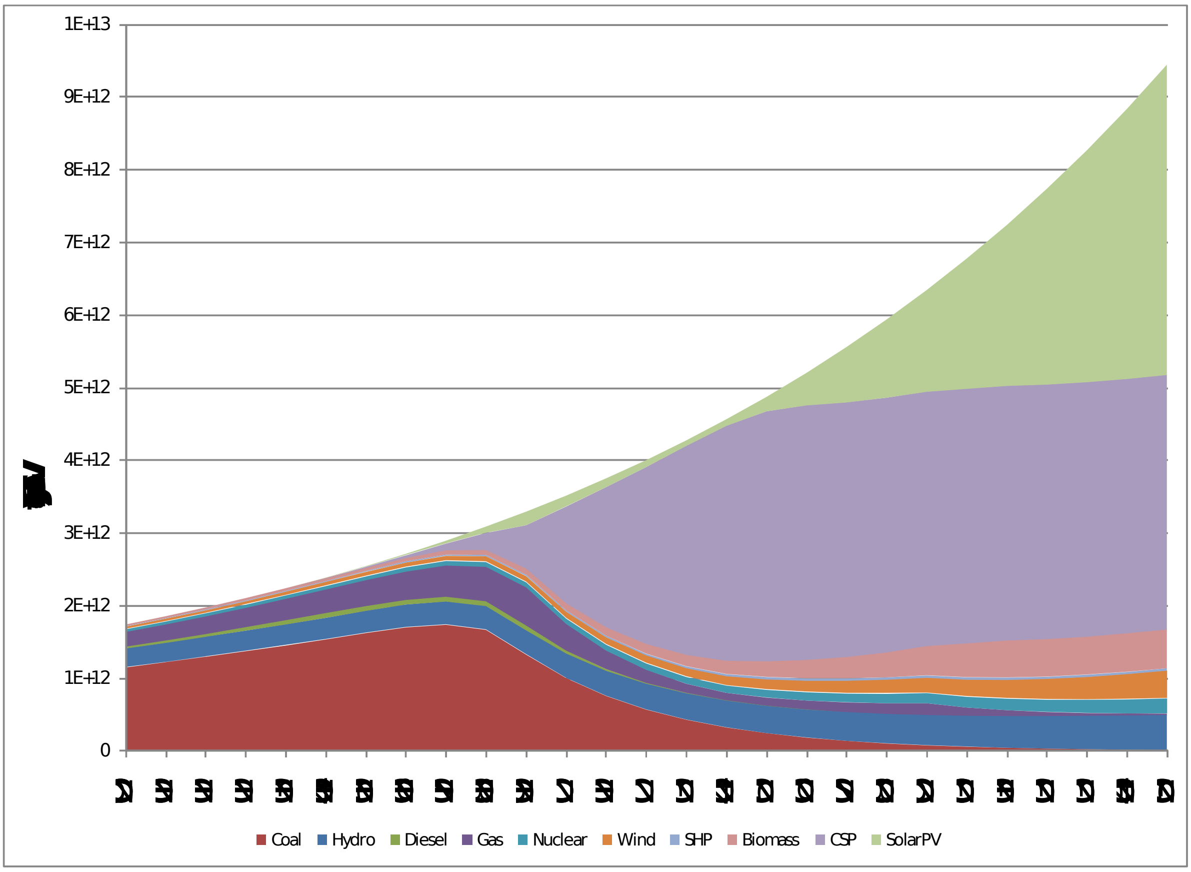


Figure 8. Potential Fuel Mix for India
Scenario IV: Carbon Budget of 7 GtC for the Power Sector



It is obvious from the three figures that a smaller budget would result in a higher reliance on low carbon, high cost energy resources. The resultant impacts of costs are presented in Table 11.

It is obvious from the three figures that a smaller budget would result in a higher reliance on low carbon, high cost energy resources. The resultant impacts on costs are presented in Table 11 and Table 12 for USA and India respectively.

Table 11. Impacts on Cost of Electricity for four Carbon Budgets

	USA		India		
	Carbon Budget for the Power Sector (35% of total between 2010-2035) [GtC]	Cost of Energy in 2035 [$/kWh]	Carbon Budget for the Power Sector (35% of total between 2010-2035) [GtC]	Cost of Energy in 2035 ($/kWh) -@ PPP	Cost of Energy in 2035 ($/kWh) - @ Current Prices
Scenario - I	--	0.322	--	0.509	0.181
Scenario -II	6	0.619	24	0.668	0.237
Scenario-III	12	0.547	11	0.978	0.348
Scenario - IV	19	0.367	7	1.063	0.378

For the US, emission reduction according to the IPCC AR4 recommendations increases the cost of energy by 15% as compared to emission reduction based on their Copenhagen pledges, whereas for India, for the same two scenarios, the increase in costs is about 46%. The total financial burden of climate change mitigation on both countries for the four scenarios is shown in Table 14.

Table 12. Total Financial Burden on India and US

USA	Total Cost of Electricity Generation between (2010-2035) [Trillion US$]	Additional Burden As Compared to Scenario-I
Scenario - I	29	--
Scenario -II	52	23
Scenario-III	42	13
Scenario - IV	30	1
India (@ Current Prices)	Total Cost of Generation between (2010-2035) [Trillion USD]	Additional Burden As Compared to Scenario-I
Scenario - I	13	--
Scenario -II	16	3
Scenario-III	28	15
Scenario - IV	33	20
India (@ PPP)	Total Cost of Generation between (2010-2035) [Trillion USD]	Additional Burden As Compared to Scenario-I
Scenario - I	38	--
Scenario -II	46	8
Scenario-III	79	41
Scenario - IV	92	54

For the US, with the most constrained carbon budget, the annual additional cost does not go above around 6% of their current annual GDP. However, for India, the annual additional costs amount to almost 40% of current annual GDP. Even if the unused entitlement of developing countries is compensated for by the developed countries at a price of say $50 per ton of carbon dioxide, it does not cover the complete additional costs that would have to be incurred by the developing countries for lost carbon space. Table 13 shows the total unused entitlements for India and the financial debt that this implies

Table 13. Total Carbon Debt owed to India between 2010-2035 (calculated at $50/tCO2)

	Carbon Debt Owed to India (For power sector 35% of total carbon budget entitlement - 36 GtC [GtC]	Transfers @ $10/tCO2 (Trillion USD)	Transfers @ $20/tCO2 (Trillion USD)	Transfers @ $50/tC)2 (Trillion USD)
Scenario - I	--	--		
Scenario -II	12	0.4	0.9	2.2
Scenario-III	25	0.9	1.8	4.6
Scenario - IV	29	1.1	2.1	5.3

Even in the Scenario where the budget is not very constrained (Scenario-II), the transfer at a rate of $50/tCO2, will amount to around 2 trillion USD over 25 years, which is less than the total avoided cost of carbon that India will have to bear (3 trillion USD over 25 years). The financial burden for scenarios where budgets are highly constrained is even higher.

VI. Conclusion

The carbon budget approach provides a simple and straightforward way of operationalising equity and estimating the impacts of not meeting equity. Developing countries share very little responsibility for the amount of stock already in the atmosphere. However, it is becoming increasingly obvious that in order to avoid catastrophic impacts of climate change, developing countries will have to contribute towards climate change mitigation efforts in the future. Even within a framework that recognizes equity as the basis on which mitigation efforts for each country should be estimated, there is likely to be significant financial impact on developing countries given the current level of proven technology available to the world. In a scenario where equity is violated, the impact is even higher and it is highly unlikely that developing countries will be able to bear the consequent financial burden. The result is likely to be a continued state of poverty in developing countries such as India. The energy options and costs discussed in this paper underscore the need for a multilateral agreement that is based on equitable access to carbon space. Such an agreement can be the only route towards achieving the goal of sustainable development, wherein environmental concerns as well as concerns of ensuring the material well-being of people from the developing countries will be addressed.