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ORIGINAL PAPER

# Emission constrained power system planning: a pinch analysis based study of Indian electricity sector

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**Abstract** In the light of rising electricity demands and a need to curb carbon dioxide emissions, this article investigates the problem of power system planning with emission targeting. A pinch analysis based approach is utilised here. The key aspect of this study is investigating the parameters that decide the priority of one type of power plant over another. For this, a quantity called prioritised cost, a trade off between cost incurred and emission from a new power plant is identified. In addition to cost and emission factor of a power plant, a third parameter, the present state of the system, also plays a significant role in deciding a power plant's prioritised cost. The analysis done proves that new power plants can be added to the system in the order of their prioritised cost. This methodology is applied to Indian power sector as a case study. Two different problems, involving minimisation of investment and annualised cost, are considered. It is observed that renewables are slightly more favoured when the objective is to minimise overall cost and not just the capital investment. In both cases, the energy mix is still dominated by coal-based power generation. The share of renewables was seen to increase with more stringent emission targets when the objective was to minimise overall cost.

**Keywords** Emission targeting · Power system planning · Pinch analysis · Power generation optimisation · Prioritised cost

## List of symbols

| | |
|---|---|
| $C$ | Cost ($) |
| CF | Capacity factor |
| CRF | Capital recovery factor |
| $D$ | Energy (MWh) |
| $d$ | Discount rate |
| EF | Emission factor (t $CO_2$/MWh) |
| $E$ | Emission (t $CO_2$) |
| $F_s$ | Total energy flow from an existing power plant (MWh) |
| $F_r$ | Total flow from a new power plant (MWh) |
| $F_d$ | Total energy demand (MWh) |
| $F_{r\_Max}$ | Maximum potential capacity of a power plant (MWh) |
| $f_i$ | Energy flow from existing power plant $i$ to demand (MWh) |
| $f_{jw}$ | Unutilised energy of existing power plant $i$ (MWh) |
| $f_j$ | Energy flow from new power plant $j$ to demand (MWh) |
| $N$ | Total number |
| $n$ | Life time (years) |
| $P$ | Power plant Capacity (MW) |
| Pr .Cost | Prioritised cost |
| $Q$ | Quality load |
| $q$ | Quality |
| $R$ | Total energy required from new power plants |
| $t$ $CO_2$ | Tonnes of carbon dioxide |
| $W$ | Total unutilised energy from existing power plants |

## Subscripts

| | |
|---|---|
| D | Demand |
| Mw | Per megawatt |
| Max | Maximum |
| o&m | Operation and maintenance |
| ov | Overall |
| p | Pinch |
| T | Target |

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**Greek symbols**

Δ Difference

## Introduction

The world's energy needs are on a constant rise. Substantial economic growth is placing enormous demand on energy resources. Sustained economic growth, betterment of living standards, rapid industrialisation, spread of energy access, rise in per capita energy consumption, etc. are the important factors to substantially increase the total demand for energy in general and electricity, in particular. At the same time, global warming and associated destructive effects are making carbon dioxide ($CO_2$) reduction a pressing need. This poses a great concern as carbon intense fossil fuels are our major source for electricity generation. It is, therefore, necessary to balance electricity generation and emission reduction.

Carbon dioxide reduction in power generation sector can be achieved in a number of ways. The overall efficiency of power generation can be improved by good housekeeping, reduction of transmission and distribution losses, improved processing scheme, etc. For a conventional coal power plant, 1 % efficiency improvement decreases $CO_2$ emission by 2.5–3 % (Boulet Emmanuel et al. 2010). However, such changes have only a limited effect. Installation of renewable energy sources with low or zero carbon emission is another solution to the problem. While very low emissions are possible using renewable sources, these are, in general capital intensive and fluctuating in nature. Also, a sudden and complete departure from the fossil fuels is not practical. This disadvantage can be overcome with the help of carbon capture and sequestration (CCS) methods. These techniques allow the continued use of fossil fuels while reducing the $CO_2$ emissions drastically. However, CCS is capital intensive. CCS units also act as parasitic loads, effectively reducing the overall efficiency of power generation (Tan et al. 2009; Cormos et al. 2011).

To address the problem of electricity generation at lower emission rates, it is necessary to combine various methods of power generation and emission reduction to obtain an economically viable solution. This gives rise to the problem of power system planning with emission targeting. The objective of power system planning with emission targeting is to identify an optimum mix of power plants that will meet the energy requirements and emission constraints of a nation.

Mixed integer linear programming (MILP) is the most common technique used in emission targeting as some of the variables have discrete values. Muis et al. (2010) carried out a study on Malaysian energy sector with emission targeting constraint. The objective was to minimise operating cost of all existing power plants, retrofit cost of existing power plants, annualised capital cost and operation and maintenance (O&M) cost of new power plants. The new power plants considered are renewable or fossil fuel based with integrated gasification combined cycle (IGCC) technology. The constraints considered were those imposed by demand, availability of fuel, and power plant availability. It was observed that IGCC, biomass and nuclear power plants dominate the energy mix for 30 % emission reduction. At 50 % emission reduction, landfill gas became competitive. However, solar energy was found to be unsuitable due to high capital cost and low-conversion efficiency. A similar study was done on the Chinese power sector by Han Na et al. (2011). An MILP model was proposed to study the power sector in 2020 with 2005 as base year. It was concluded that a 40–45 % reduction in emission intensity is possible by shifting from carbon intense fuels to renewable based power generation. Shammakh Ba and Mohammed (2011) proposed an MILP model for sulphur dioxide ($SO_2$) targeting in power sector and applied to Ontario power generation, Canada. Three options were considered for reducing $SO_2$ emission; namely, fuel switching, fuel substitution, and conventional flue gas desulphurisation. Various MILP based models have also been developed to study emission constrained energy sector planning, e.g. market allocation model (Watcharejyothin and Shrestha 2009; Shrestha and Rajbhandari 2010; Mondal et al. 2010), integrated resource planning model (Shrestha and Marpaung 2002; Shrestha and Marpaung 2005; Srivastava et al. 2003), etc.

Pinch analysis based methodologies have been developed for power system planning with emission constraint. Emission targeting in a chemical process plant, applying pinch analysis, was developed by Linnhoff and Dhole (1993). Pinch analysis was first extended to the carbon constrained energy sector planning by Tan and Foo (2007). Carbon emission pinch analysis (CEPA) methodology was applied to the Irish electricity sector (Crilly and Zhelev 2008; Crilly and Zhelev 2010) and to the New Zealand's energy sector (Atkins Martin et al. 2010). Lee et al. (2009) extended the CEPA to target the amount of low-carbon resources, as low-carbon energy resources are often less expensive than zero carbon resources, needed to meet a given energy demand and emission limit. The limitation of graphical pinch analysis, as the accuracy of the solution depends on visual resolution, has been overcome by a tabular and algebraic approach, called cascade technique, by Foo et al. (2008).

CCS units with various technologies like oxy-fuel combustion, pre-combustion capture, post-combustion capture, chemical looping combustion, etc. are available.

However, CCS imposes an energy penalty on the generation process as a certain amount of energy is needed to meet the needs of a CCS plant. The CCS process acts like a parasitic load on the power system (Tan et al. 2009; Cormos et al. 2011). An improved discrete mathematical formulation of the same problem has been proposed by Tan et al. (2010) and Pekala et al. (2010). These works detailed which power plants should be retrofitted with which type of CCS unit. The characteristics of CCS sinks like availability, maximum injection rate possible and capacity are not accounted for. These were addressed by Tan et al. (2012a) and Tan et al. (2012b).

In this article, the Indian electricity sector is studied and the implications of limiting carbon emission are analysed. For this, 2007 is considered as base year and the target year is 2020. An optimum energy mix that meets both energy and emission targets at the minimum cost is determined. A concept called prioritised cost in introduced to allow a trade off between cost and emission for various types of power plants. The expression for prioritised cost varies with objectives and here, two possibilities, namely the minimum capital investment and the minimum annualised cost (including capital investment and operating cost) have been considered. After identifying the optimum mix in either case, a detailed sensitivity analysis is performed to understand system behaviour with change in emission limits.

## Problem statement

There are $N_s$ existing power plants, and a future energy demand. There are $N_r$ new power plants that may be commissioned to meet the future energy demand. It may be noted that power plants running on same fuel and having same emission characteristics are clubbed together as one. Each power plant is characterised by an emission factor EF. Emission factor is the carbon dioxide emitted for each unit of energy generated. So, each new power plant ($i$) will be capable of supplying energy at a known emission factor $EF_i$ and each existing power plant ($j$) will have an emission factor of $EF_j$. The demand will also have a specified maximum emission factor which is the ratio of total emission to total energy demand ($EF_d$).

The energy supplied from a new power plant ($i$) to the demand is denoted as $f_i$ and that from an existing power plant ($j$) is $f_j$. It is possible that some existing power plants are not utilised to their full capacity. The unutilised energy from a power plant ($j$) is denoted by $f_{jw}$ as illustrated in Fig. 1. $F_{sj}$ denotes the total energy from existing power plant j and $F_d$ is the total energy requirement.

For any existing power plant,

$$f_j + f_{jw} = F_{sj} \quad \forall j \in N_s \tag{1}$$

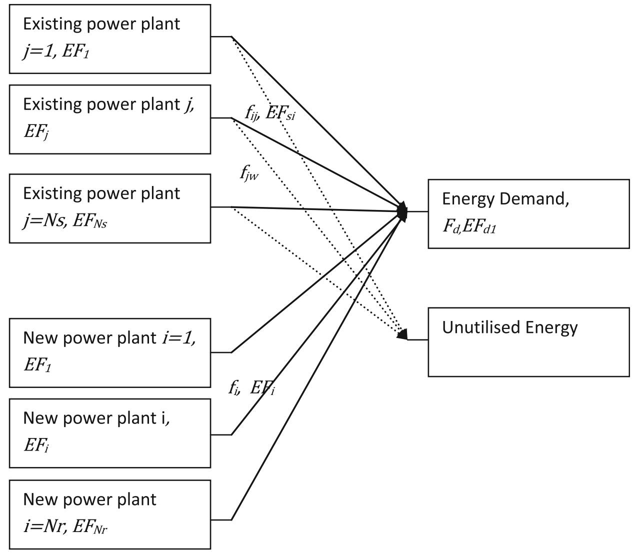



**Fig. 1** Representation of a typical power system planning problem

$$\sum_{i=1}^{N_r} f_i + \sum_{j=1}^{N_s} f_j = F_d. \tag{2}$$

Also, every new power plant,

$$f_i = F_{ri} \leq F_{r\_\mathrm{Maxi}} \quad \forall i \in N_r \tag{3}$$

where, $F_{r\_\mathrm{Max}}$ is the maximum capacity available from the new power plant.

Total unutilised energy ($W$) is expressed as

$$W = \sum_{j=1}^{N_s} f_{jw} \tag{4}$$

Similarly, total new installed capacity requirement ($R$) is expressed as

$$R = \sum_{k=1}^{N_r} F_{ri} \tag{5}$$

By taking an overall summation, it can be seen that

$$R = W - \left[\sum_{k=1}^{N_s} F_{sj} - F_d\right] \tag{6}$$

$$\sum_{i=1}^{N_s} F_{sj} - F_d = \Delta, \tag{7}$$

$\Delta$, the cumulative sum of all existing power plants and future demands, is constant for specified problem data. In addition to all this, the required emission target should also be met.

$$\sum_{i=1}^{N_r} f_i EF_i + \sum_{i=1}^{N_s} f_j EF_j \leq F_d EF_d \tag{8}$$

As setting up a power plant is cost intensive, the first problem addressed here tries to minimise the capital investment while meeting the emission and energy targets. The variables are capacity factors of existing plants and capacity of new plants. The second part of the problem tries to minimise the annualised cost of operation. In either case, the basic problem formulation remains unchanged. Here, the emission target is denoted by $E_T$. The objective can be formulated as:

$$\text{Min} \sum_{i=1}^{N} C_i \tag{9}$$

where $N$ is the total number of new power plants and $C_i$.is the capital cost for the $i$th power plant.

The constraints are

$$\sum_{i=1}^{N_r} F_i + \sum_{j=1}^{N_s} F_j = F_d \tag{10}$$

$$\sum_{i=1}^{N_r} E_i + \sum_{i=1}^{N_s} E_j \leq E_T \tag{11}$$

The energy produced by the $i$th power plant $F_i$ is obtained by multiplying installed capacity by capacity factor (CF) and total time. $F_j$ and $E_j$ are the energy and emission produced by the $j$th existing power plant.

$$F_i = P_i \times \text{CF}_i \times 8760 \tag{12}$$

$P_\text{i}$ is the added installed capacity of the $i$th source power plant. The emission from $i$th power plant is obtained by multiplying energy generated by emission factor ($\text{EF}_i$).

$$E_i = F_i \times \text{EF}_i \tag{13}$$

Similarly, capital cost is a function of type of resource and installed capacity, with $C_{mwi}$ being the cost per megawatt capacity of the $i^{th}$ power plant.

$$C_i = P_i \times C_{mwi} \tag{14}$$

Overall cost is a function of capital cost and O&M charges.

$$C_{ovi} = \frac{P_i \times C_{mwi}}{n_i} \times \text{CRF} + F_i \times C_{O\&m_i} \tag{15}$$

where $n_i$ is the life time of the $i$th power plant and CRF is the capital recovery factor. Here, $C_{ovi}$ replaces $C_i$ in the objective function (equation 9). The existing power plants will also contribute to operating cost. While annualising capital cost, it is assumed that the capital is spread equally over the life of the power plant. Then, each of these annual costs is brought to present value using capital recovery factor (CRF). CRF of a power plant is a function of discount rate ($d$) and the life ($n$) of the power plant (Kulkarni et al., 2007).

$$\text{CRF} = \frac{d \times (1+d)^n}{(1+d)^n - 1} \tag{16}$$

The objective of this study is to develop an algebraic methodology to determine an optimum energy mix capable of meeting the energy and emission targets at a minimum cost. The proposed methodology is based on the principles of pinch analysis.

## Prioritising power plants

The method of limiting composite curve has been used for this study. This method was introduced by Wang and Smith (1995) for water targeting. It involves plotting a limiting composite line of all existing sources and demands and then plotting a resource line such that resource utilisation is minimised. A typical limiting composite curve may be obtained by plotting quality against cumulative quality load. An algebraic technique, named composite table algorithm (CTA) (Agrawal and Shenoy 2006; Shenoy 2010), is used to get the limiting composite curve. When applied to the problem of power system planning, CTA gives the net emission load deficit (i.e. tonnes of carbon dioxide) as a function of emission factor.

The first column of CTA is the emission factor (quality), arranged in ascending order. For each interval of emission factor, the net energy deficit is calculated by subtracting the energy demand up to that interval from the energy available from various power plants up to that interval. Then, the emission for each interval is calculated by multiplying the net energy deficit by the emission factor difference for the corresponding interval. The final quantity calculated is the total emission for each interval, which is the sum of emissions calculated in the previous step. A plot of total emission against the emission factor will give the limiting composite curve as shown in Fig. 2. A resource line (i.e. new power plant) is then plotted starting from the resource

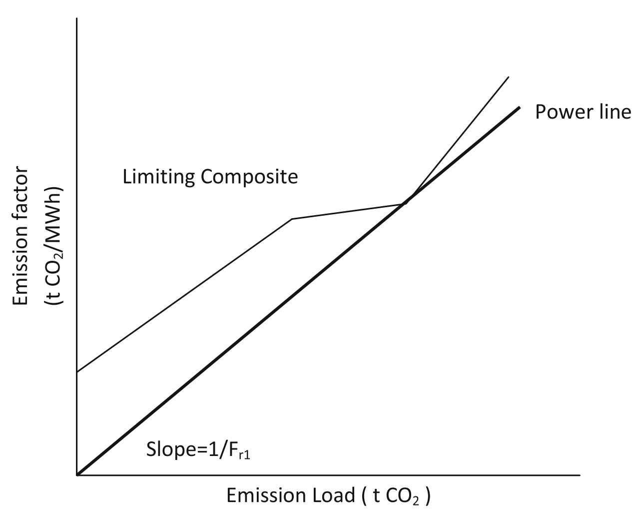



**Fig. 2** Limiting composite curve with one power plant

emission factor such that it just touches the limiting composite curve. The emission factor at which the resource line meets the limiting composite curve is the pinch emission factor of the system. It may be noted that the inverse of slope of resource line gives the energy needed to be generated from a new power plant.

This method can be used to add a new power plant to an existing power system. If multiple power plants are present, there arises a problem of which type of power plant is to be added first. Adding a power plant with the least emission factor may not always be cost effective. On the other hand, due to presence of an emission constraint, addition of the power plant with the least cost may not always be feasible. In short, there is a trade off between the emission and the cost. In addition to the above factors, the present state of the system also plays a critical part in the selection of new power plants. A concept called prioritised cost, introduced by Shenoy and Bandyopadhyay (2007) for prioritizing multiple resources in resource integration problems, can be extended to power system.

In order to obtain a method for prioritising new power plants, consider adding a new power plant to the system, as shown in Fig. 2. Another power plant ($R_2$) has an emission factor less than pinch emission factor, but greater than that of the first power plant. Energy generated ($F_{r1}$)by the first power plant in the initial case (with only one power plant) is

$$F_{r1} = Q_p / \left(\mathrm{EF}_p - \mathrm{EF}_{r1}\right) \quad (17)$$

In the second case, total demand is met by two power plants $R_1$ and $R_2$ with energy generated $F'_{r1}$ and $F_{r2}$ where $F'_{r1}$ and $F_{r2}$ respresent the energy supplied by power plants $R_1$ and $R_2$, respectively (see Fig. 3). A new power line is now obtained, with the energy needs above emission factor $\mathrm{EF}_{r2}$ being met by a combination of both power plants.

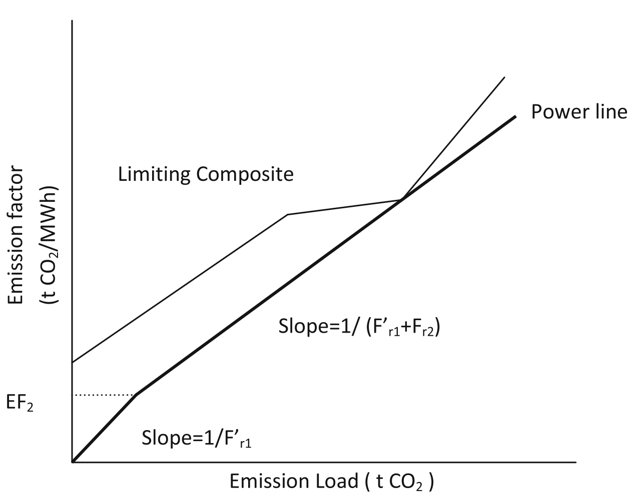



**Fig. 3** Limiting composite curve with more than one power plant

Since total emission load at pinch is same for both these cases,

$$F_{r1} \times \left(\mathrm{EF}_p - \mathrm{EF}_{r1}\right) = F'_{r1} \times \left(\mathrm{EF}_{r2} - \mathrm{EF}_{r1}\right) + \left(F'_{r1} + F_{r2}\right) \times \left(\mathrm{EF}_p - \mathrm{EF}_{r2}\right) \quad (18)$$

Rearranging, it can be seen that

$$F_{r1} - F'_{r1} = F_{r2} \times \left(\mathrm{EF}_p - \mathrm{EF}_{r2}\right) / \left(\mathrm{EF}_p - \mathrm{EF}_{r1}\right) \quad (19)$$

It should be noted that while $F'_{r1}$ and $F_{r2}$ are the optimum energy generated as far as emission reduction is concerned, the objective here is to minimise cost. So, adding a second power plant is optimal only if the overall cost is lowered by the addition. In short, the amount saved due to reduction of energy generated of first-power plant should be greater than the cost incurred to install the second-power plant.

$$\left(F_{r1} - F'_{r1}\right) \times C_{mw1} \geq F_{r2} \times C_{mw2} \quad (20)$$

Substituting from equation 19,

$$F_{r2} \times C_{mw1} \frac{\left(\mathrm{EF}_p - \mathrm{EF}_{r2}\right)}{\left(\mathrm{EF}_p - \mathrm{EF}_{r1}\right)} \geq F_{r2} \times C_{mw2} \quad (21)$$

Therefore, it can be concluded that introduction of the second power plant is optimal only if

$$\frac{C_{mw1}}{\left(\mathrm{EF}_p - \mathrm{EF}_{r1}\right)} \geq \frac{C_{mw2}}{\left(\mathrm{EF}_p - \mathrm{EF}_{r2}\right)} \quad (22)$$

The quantity $\frac{C_{mwi}}{\left(\mathrm{EF}_p - \mathrm{EF}_{ri}\right)}$ is called the prioritised cost of the power plant $(\mathrm{Pr\,.Cost}_i)$. This proves the following result.

**Theorem** *Installation of a power plant is optimal if its prioritised cost is the least.*

From equation 22, it can be seen that the prioritised cost of a power plant is proportional to its actual cost and inversely proportional to the difference between the pinch emission factor and the emission factor of the power plant. Therefore, the prioritised cost of any energy source depends on the present state of the system, i.e. the pinch emission factor of the overall system. This characteristic of prioritised cost is significant as it points out how the optimum energy mix can be different for different systems even if the targets are the same, because the pinch emission factor depends on the types of power plants present in existence.

It may also be noted that no power plant above pinch point can be used. The prioritised cost of such resources will be negative and has to be excluded from the analysis. Therefore, no power plant, however inexpensive it may be, can be considered if its emission factor is higher than the pinch emission factor.

## Indian electricity sector: a case study

### An overview of Indian energy sector

India is the world's fourth largest economy with a fast growing energy market. Power generation is increasingly based on fossil fuels, which in 2009 accounted for around 85 % of the country's electricity generation, compared with 75 % in 1990. Coal is the main fuel for electricity production (70 % in 2009). Among $CO_2$ free energy sources, wind energy has started to develop significantly but it accounted for less than 2 % of the total (ABB 2011). The present power scenario of India is tabulated in Table 1. At present, the renewable include wind (14,476 MW), solar (18 MW), small hydro (3,006.8 MW) and biomass (2,632 MW) (Ministry Of New And Renewable Energy, Government of India 2011).

Overall, India's need for power is growing at a prodigious rate, annual electricity generation and consumption in India has increased by about 64 % between 1997 and 2007, and its projected rate of increase (estimated at as much as 8–10 % annually, through the year 2020) for electricity consumption is one of the highest in the world (ICLEI South Asia, 2007). The 17th electric power survey published by the Central Electricity Authority (2007) predicts India's annual electricity consumption to be 1914508 GWh by 2020. India's current power capacity is 30 % short of demand (Central Electricity Authority 2007).

While increasing power production capacity is of prime importance, it is equally important to reduce the overall emission from power sector. For the purpose of this article, the emission target has been set to 702.1206 Mt of $CO_2$ which is 25 % less than that of 2007. It maybe noted that this target is fixed without any basis and purely hypothetical. Actual reduction of $CO_2$ emission, if any, will be decided Indian Government based on the economic and societal development. In order to achieve the energy and emission targets, an appropriate mix of resources must be identified for power generation. Possible options available are listed in Table 2. The estimated potential of each and corresponding capacity factors are also tabulated. Of these, it may be possible to improve the capacity factors of coal and natural gas power plants. It has been assumed that with the present fuel crisis, no more diesel and natural gas is likely to be used for future power generation.

**Table 2** Future power sources

| Resource | Limit (GW) | Capacity factor | Tonnes of $CO_2$/MWh |
|---|---|---|---|
| Coal | NA | 0.72[b] | 1.08[f] |
| Natural gas | NA | 0.65[b] | 0.45[f] |
| Nuclear | 9.55[c] | 0.82[c] | 0.02[a] |
| Hydro | 148.70[d] | 0.50[d] | 0.12[a] |
| Wind | 47[e] | 0.14[e] | 0.07[a] |
| Biomass | 19.50[e] | 0.70[e] | 0.11[a] |
| Small Hydro | 15[e] | 0.50[e] | 0.12[a] |
| Solar | NA | 0.20[e] | 0.20[a] |

Compiled from data available on
[a] Tan et al. (2009)
[b] NTPC (2012)
[c] NPCIL (2012)
[d] NHPC (2012)
[e] MNRE (2008)
[f] CEA (2011)

To demonstrate the effectiveness of the methodology developed, an optimum energy mix for India in 2020 is identified here. Two separate examples are considered here, one for minimising capital investment and one for minimising the overall annual cost. In developing and underdeveloped countries where there is a dearth of capital, the case involving minimising capital investment may be more relevant. However, an approach to minimise overall cost, including the operating cost may be more complete. The emission target used in this exercise is completely hypothetical. In addition, the actual energy mix for India will be influenced by a variety of social, environmental and political factors, which has not been accounted for in this

**Table 1** Present Indian Energy Scenario

| Region | Coal (GW) | Gas (GW) | Diesel (GW) | Nuclear (GW) | Hydro (GW) | Renewables[a] (GW) | Total (GW) |
|---|---|---|---|---|---|---|---|
| Northern | 24.23 | 4.13 | 0.013 | 1.62 | 14.42 | 3.50 | 47.93 |
| Western | 33.10 | 7.90 | 0.017 | 1.84 | 7.44 | 5.93 | 56.25 |
| Southern | 20.98 | 4.69 | 0.939 | 1.32 | 11.33 | 10.13 | 49.39 |
| Eastern | 21.12 | 0.190 | 0.017 | 0 | 3.88 | 0.356 | 25.56 |
| North Eastern | 0.060 | 0.787 | 0.143 | 0 | 1.11 | 0.224 | 2.32 |
| Islands | 0 | 0 | 0.070 | 0 | 0 | 0.006 | 0.076 |
| All India | 99.50 | 17.71 | 1.19 | 4.78 | 38.20 | 20.13 | 181.55 |

CEA (2008)
[a] MNRE (2008)

**Table 3** Values for calculating prioritised cost

| Technology | Lifetime[a] | Capacity Factor[b] | O&M charges ($/MWh)[a] | Capital Investment ($10^6$ $/MW) |
|---|---|---|---|---|
| Coal | 40 | 0.9 | 14 | 0.8[c] |
| Coal with CCS | 40 | 0.9 | 17.5 | 1.04[c] |
| Nuclear | 40 | 0.9 | 2 | 1.04[c] |
| Hydroelectric | 50 | 0.5 | 900 | 1.3[d] |
| SHP | 35 | 0.5 | 0 | 2.48[e] |
| Biomass | 30 | 0.7 | 480 | 0.6[f] |
| Wind | 35 | 0.14 | 0 | 1[f] |
| Solar | 30 | 0.2 | 480 | 4[f] |

[a] Mallah and Bansal (2010)

[b] Tan et al. (2009)

[c] Central Electricity Authority (2004)

[d] NHPC (2012)

[e] Nouni et al. (2008)

[f] Banerjee 2006

study. Though the problem solved here is to minimise carbon dioxide, other emissions may also be targeted in a similar fashion. However, this is beyond the scope of this study.

To calculate the CRF, a discount rate of 14 % has been assumed in this study. The values used in calculating prioritised cost are given in Table 3. It is assumed that the capacity of fossil fuel based power plants cannot be more than 0.9. So, the capacity factor of existing coal, diesel and gas power plants are allowed to vary between zero and 0.9.

## Minimising capital cost

The method of limiting composite curve has been applied here to solve the problem of minimising capital investment. The limiting composite curve of the existing system can be plotted with the data available. The existing power sources and the energy demand to be met are arranged in ascending order of emission factor (column 1 of Table 4). Emission factor for energy demand can be calculated by dividing the emission target by energy demand. It should be noted that in this method, sources are considered as negative and demands as positive. The net energy deficit for each interval of emission factor is calculated (column 3 of Table 4). The emission corresponding to each interval is calculated by multiplying the energy deficit of that interval and the difference in emission factors binding that interval (column 4 of Table 4). Cumulative emission can then be obtained by adding up individual emissions. The plot of cumulative emission and emission factor is shown in Fig. 4. The negative part of the limiting composite curve can be ignored as the demand in that region is already accounted for internally. If a zero emission power plant was to be added to the system, the point in the limiting composite curve with maximum slope would correspond to an emission factor of 1.08 making it the pinch emission factor of the system. Using the pinch emission factor, the prioritised costs of various types of power plants can be calculated using equation 22. It should be noted that the demand is in terms of energy and not power. So, capacity factor of the system also needs to be taken into account. For example, to find the prioritised capital cost for biomass, the capital cost per megawatt (0.60 million $) is divided by its capacity factor (0.7) to get cost per MWh (0.85 million $). This quantity is then divided by the difference between pinch

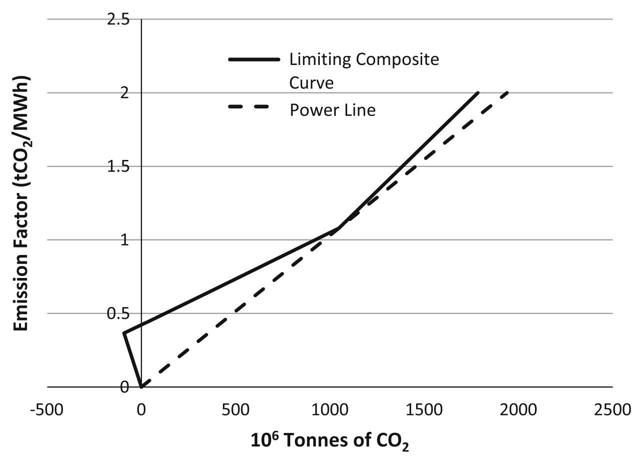



**Fig. 4** Limiting composite curve of existing system

**Table 4** Limiting composite curve

| Type | Emission factor ($tCO_2$/MWh) | Energy (TWh) | Net energy deficit (TWh) | Emission ($10^6$ $tCO_2$) | Cumulative Emission ($10^6$ $tCO_2$) |
|---|---|---|---|---|---|
| Nuclear and renewable | 0 | 0 | 0 | 0 | 0 |
| Energy Demand | 0.366 | −252.30 | −252.30 | −92.52 | −92.52 |
| Natural Gas | 0.450 | 1914.50 | 1662.20 | 138.46 | 45.94 |
| Diesel | 0.640 | −66.65 | 1595.54 | 303.15 | 349.09 |
| Coal | 1.08 | −9.45 | 1586.08 | 697.87 | 1046.97 |
| Arbitrary high value | 2 | −784.48 | $\Delta$ = 801.60 | 737.47 | 1784.44 |

**Table 5** Prioritised order of power plants

| Technology | For minimum capital investment | | For minimum annualised cost | |
|---|---|---|---|---|
| | Type | Prioritised cost ($10^6$ \$/t $CO_2$) | Type | Prioritised cost ($10^6$ \$/t $CO_2$) |
| 1 | Biomass | 0.88 | Wind | 0.004 |
| 2 | Nuclear | 1.09 | SHP | 0.010 |
| 3 | Coal with CCS | 1.17 | Nuclear | 0.018 |
| 4 | Hydro | 2.71 | Coal with CCS | 0.144 |
| 5 | SHP | 5.16 | Solar | 0.886 |
| 6 | Wind | 7.07 | Biomass | 3.03 |
| 7 | Solar | 20.6 | Hydro | 4.11 |
| 8 | Coal | NA | Coal | NA |

emission factor (1.08) and its own emission factor (0.11) to get its prioritised cost (0.88 million $). The order of priority for minimum capital investment and minimum overall cost has been listed in Table 5. Based on prioritised cost, the first power plant to be added is based on biomass.

It is seen that 1,079.35 TWh (1,76.019 GW) of energy is to be supplied by biomass. However, as per Table 2, the maximum possible capacity of biomass is 19.50 GW, of which 2.662 GW is already in use. So, the maximum energy possible is supplied via biomass (103.25 TWh or 16.83 GW) and the next power plant that is added is based on nuclear. The inverse of slope of the new power line will give the energy required from nuclear power plant. It is found to be 893.22 TWh which is about 113 GW installed capacity. However, the maximum installed capacity possible is 9.55 GW of which 4.78 GW is already in use. So maximum possible capacity for nuclear is 4.77 GW, which is equivalent to 37.60 TWh of energy. So, Nuclear energy is maximised to 37.60 TWh and the next type of power plant is added.

Since there are no limits on the coal available (considering national reserves and possibility to import) in near future, the additional energy required can be supplied from coal power plant with CCS. The energy to be supplied from

**Table 6** New power plant and unutilised energy targets for minimum capital investment

| Type | Energy (TWh) |
|---|---|
| Biomass | 103.25 |
| Nuclear | 37.60 |
| Coal with CCS | 925.46 |
| Δ | 801.60 |
| Unutilised energy | 264.72 |

**Table 7** New power plant and unutilised energy targets for minimum overall cost

| Type | Energy (TWh) |
|---|---|
| Wind | 39.88 |
| Nuclear | 37.60 |
| SHP | 52.53 |
| Coal with CCS | 935.09 |
| Δ | 801.60 |
| Unutilised energy | 263.51 |

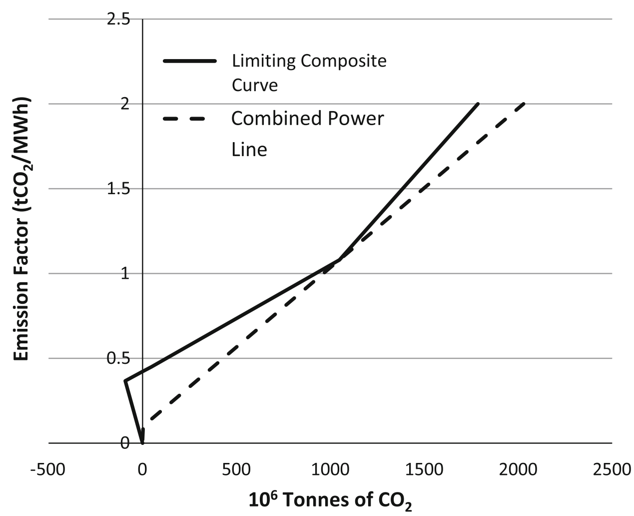



**Fig. 5** Limiting composite curve and combined power line for minimum capital investment

coal with CCS is 925.46 TWh, which is equivalent to 117.4 GW of installed capacity. The limiting composite curve and combined power line for minimum capital investment is shown in Fig. 5.

Using equation 6, the total unutilised capacity of the existing power system can be computed. The energy needed from existing coal power plants has to be reduced by 264.69 TWh (Table 6). These results were verified by linear programming.

## Minimising overall cost

The exercise was repeated to find a mix with the minimum total annualised cost. Annualised cost includes a component of capital cost and a component of operating cost. The prioritised power plants are shown in Table 5.

The method of CTA is applied by adding wind first followed by small hydel power plant (SHP) and nuclear power plants. However, these energy sources are not extensive enough to satisfy the total energy demand. The energy generated from wind, nuclear and SHP are found to be 37.60, 39.88 and 52.53 TWh, respectively, which

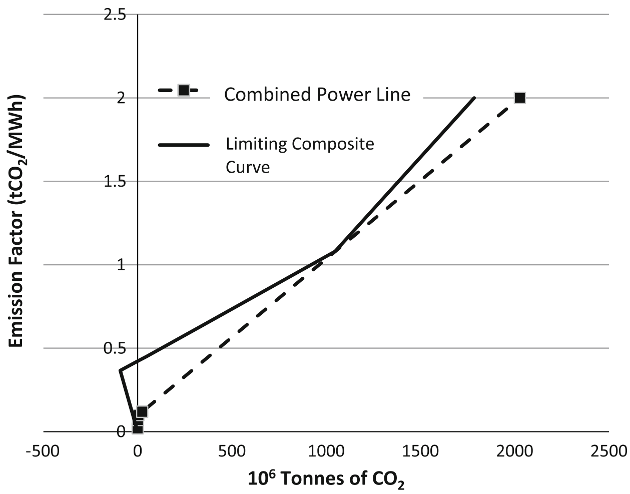



**Fig. 6** Limiting composite curve and combined power line for minimum overall cost

correspond to 4.77, 32.524 and 11.99 GW of installed capacity.

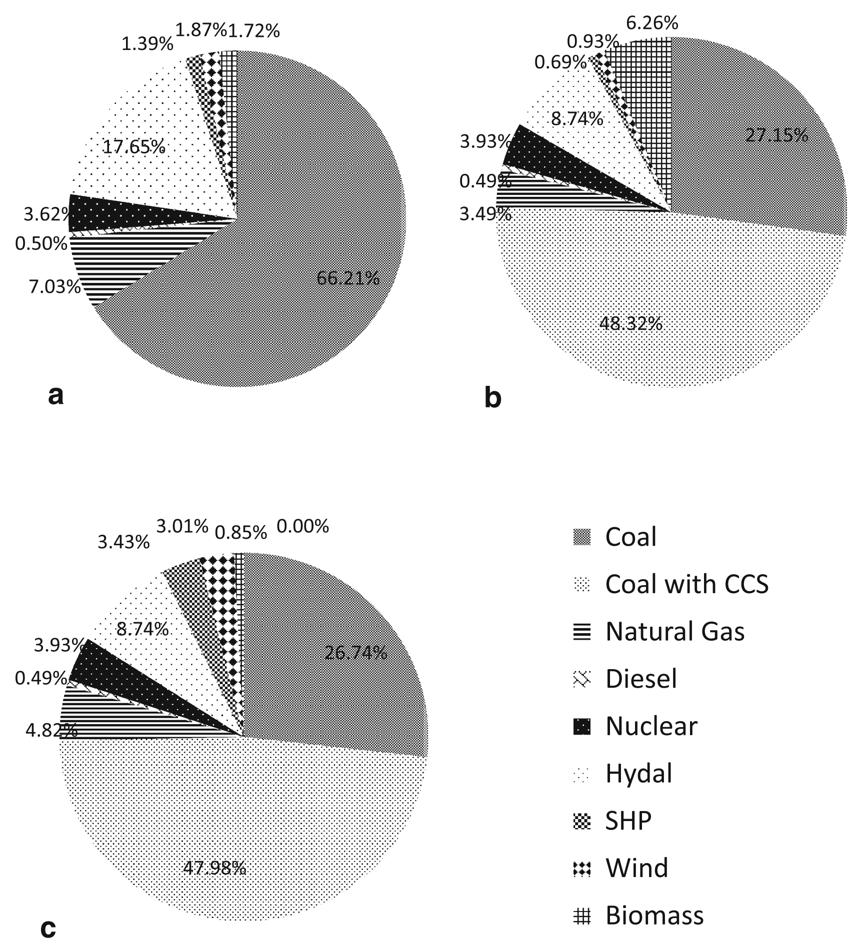
The additional requirement of 935.09 TWh is met by coal with CCS, which is equivalent to about 118.6 GW installed capacity (Table 7). The final limiting composite curve and combined power line are shown in Fig. 6. Expanding and analysing the lower portion of the curve will give a better understanding of the results. It should be noted that the limiting composite curve used here is the same as that represented by Table 4.

It can be seen that the solution obtained for minimising capital cost and minimising overall annual cost have some significant differences. Here, small hydro power projects and wind projects major participants along with nuclear and CCS coal power plants. A few conventional coal power plants are still shut down to meet the emission targets. The pie charts shown in Fig. 7 illustrate the situation.

## Sensitivity analysis

To understand how the mix varies with emission targets, sensitivity analysis has done considering minimisation of operating cost and capital investment. Sensitivity analysis has done for emission limits of 85, 75, 65 and 40 % of 2007 emission. The results for minimising capital cost are presented in Fig. 8. It can be seen that the share of renewables and nuclear energy remain largely unchanged. The trade off is almost exclusively between conventional

**Fig. 7** **a** Present Energy distribution. **b** Distribution for minimum capital investment. **c** Distribution for minimum overall expense



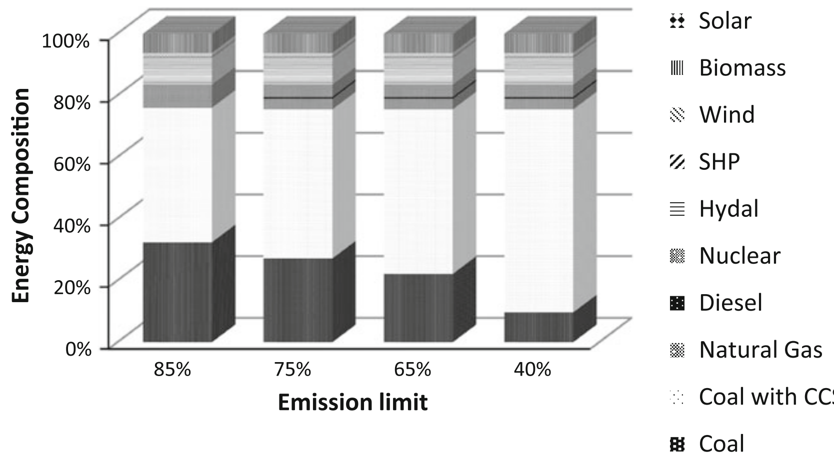



**Fig. 8** Sensitivity analysis for minimum capital investment

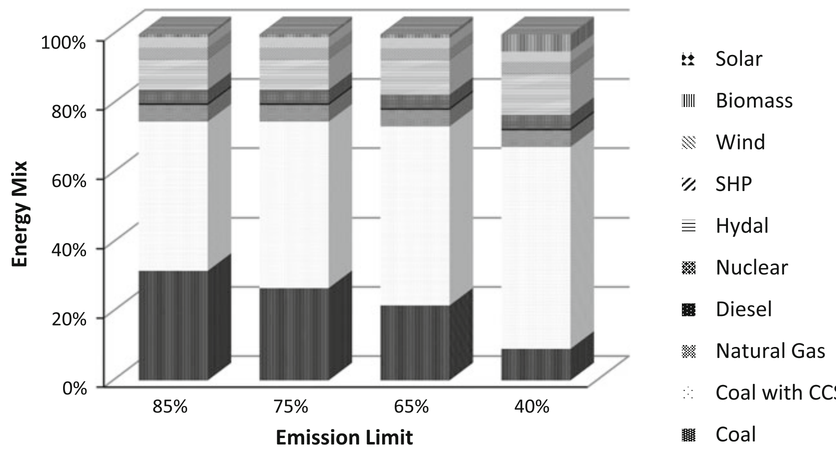



**Fig. 9** Sensitivity analysis for minimum overall cost

coal power plants and coal power plants with CCS. As we move from 85 % target to 40 %, the share of conventional coal power plants reduce from 32.4 to 9.68 %, while that of coal power plants with CCS increase from 43.5 to 65.8 %.

For a minimum overall cost, the share of renewable is found to increase as the emission limits are tightened. The results obtained in this case are shown in Fig. 9 and consists of wind, SHP and nuclear power plants in addition to coal with CCS. The overall share of coal (including CCS) is around 67 % as opposed to 75 % of total in case of maximum capital investment. Biomass, which was the preferred renewable in case of minimum capital investment, was found to be unsuitable. In short, the ideal mix depends to a large extend on the objective function. In any case, the nation will be heavily dependent on fossil fuels for the coming decade.

## Conclusions

In this study, a methodology for power system planning with emission targeting is developed and applied to Indian power sector. The methodology is developed to identify an optimum energy mix that will meet the energy targets and emission constraints at a minimum cost. It combines prioritised cost and limiting composite curve and can be used to identify optimum power plant mix for any given set of sources and demands. This prioritised cost is a trade off between cost incurred, capital as well as operating, and carbon dioxide emission. The significant observation is that in addition to cost and emission factor, the prioritised cost of a power plant also depended on the system pinch emission factor. As for Indian power sector, fossil fuels seem to be the most significant contributors at least for the coming decade, though renewables are slowly on the rise. CCS technology seems to be of great significance as well. It can be concluded from the study that for India, the future depends heavily on biomass and nuclear-based energy generation in addition to the CCS enabled coal power plants if capital investment is to be minimised. Without subsidies or other financial aids, wind and solar energy are not particularly cost effective. The high prioritised cost displayed by these energy sources is largely due to the low-capacity factor of these power plants. While minimising overall cost, incorporating both capital and operating costs, it is seen that the preferred renewables are small hydal and wind, with low-operating cost, instead of biomass. The sensitivity analysis shows that as the emission limits are tightened, the trade off in case of capital minimisation is exclusively between conventional coal power plants and those with CCS. However, the share of renewable increase from 16 to 23 %, when the analysis was done for minimising overall cost by varying emission limits between 85 and 40 % of 2007 emissions. In this study, it has been assumed that none of the existing power plants can be retrofitted to include CCS. However, such a modification may be economically viable. Present research study is directed towards addressing such issues.

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