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A Pinch Analysis based Approach to Power System Planning with Carbon Capture

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The rising energy demands and pressing need for reduction of greenhouse emission necessitates carbon capture technologies an important part of future power systems. While graphical and analytical methods for including carbon capture in power system planning has been explored, this paper suggests an algebraic method for including carbon capture using Pinch Analysis for power system planning. This method first identifies the viability of carbon capture technology in a given system using the concept of prioritised cost. It then allows for calculating the quantity of existing power plants to be retro-fitted. It also takes into account unique aspects of carbon capture technologies: parasitic loss associated with carbon capture units and variation in existing sources that come about with the introduction of a Carbon Capture and Storage (CCS) unit. For example, if existing coal power plants are being retro-fitted, it means that the availability of energy from coal decreases. This interdependency between two energy sources (the CCS unit, and existing power plant) had to be taken into account. The proposed methodology is applied to Indian power sector.

1. Introduction

The world's energy needs are on a constant rise. At the same time, the high concentration of green house gases is also a major problem. However, a sudden and complete departure from the fossil fuels is not practical. Also, most renewable are more capital intensive than fossil fuel based sources. Carbon capture technologies are an attractive option as they allow the continued use of fossil fuels while simultaneously reducing the greenhouse emission. Pinch analysis has been applied to various aspects of power system planning including introduction of carbon capture(Tan and Foo, 2007), using pumped hydel storage to minimize supply demand mismatch (Rozali et al., 2013) a renewable based smart grids (Giaouris et al., 2014), and multiperiod optimisation of power systems (Ooi et al., 2014). This work presents a novel pinch analysis based approach for targeting power generating systems which incorporates carbon capture units by retro-fitting existing power plants. While developing the Pinch Analysis based approach, a few unique characteristics of the system had to be considered. First is the parasitic loss associated with the retro-fitting unit. The second is the variation in existing sources that come about with the introduction of a carbon capture unit. For example, if existing coal power plants are being retro-fitted, it means that the availability of energy from coal decreases. This interdependency between two energy sources (the carbon capture unit, and existing power plant) had to be taken into account. The objective of this paper is to identify the cost optimal energy mix given the energy demand and emission target. All existing power plants have an installed capacity and an emission factor. All new energy sources have a specified emission factor. The cost coefficients of all new energy sources are known. The carbon capture unit also has a cost coefficient and an emission coefficient. The energy demand is specified along with the emission limit associated with it. The proposed methodology is divided into two key parts. The first is to identify whether introduction of carbon capture units is economical. The next part of the work concentrates on identifying how much energy from an existing power plant is to be passed through the retro-fitting unit. Using the source composite curve, it is possible to identify the amount of energy that is to be supplied to the carbon capture unit. The method developed is then applied to the Indian power sector and results obtained are discussed. It should be noted that cost and emission factor of power plants are the only characteristics that have been

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considered in this study. All the same, the method developed can be used to identify an initial solution for overall planning and has application in various other systems.

2. 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. It should be noted that here, similar power plants (say coal power plants) 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 particular emission factor (EF_i) and each existing power plant (j) will have an emission factor EF_j. The demand will also have a specified emission factor which is the ratio of total demand to total emission (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}.Let it be possible that existing sources can divert a part of their energy (f_{ccs}) through carbon capture unit. The unit considered here is of fixed outlet concentration (C_{out}). A CCS unit with fixed removal ratio is also possible; however, it is at present beyond the scope of this work. The objective considered is the minimisation of capital cost such that energy and emission limits are met.
For any power plant,

$$f_j + f_{jw} + f_{jccs} = F_{sj} \forall j \tag{1}$$

$$\sum_{i=1}^{N_r} f_i + \sum_{j=1}^{N_s} f_j + (1-k) \sum_{j=1}^{N_s} f_{jccs} = F_d \tag{2}$$

Also, every new power plant,

$$f_i \leq F_{rk\_maxi} \forall i \tag{3}$$

where, F_{rk_max} is the maximum capacity available for the new resource. Total unutilised energy (waste) and total installed capacity requirement can be expressed as

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

$$R = \sum_{i=1}^{N_r} f_i \tag{5}$$

By taking an overall summation, it can be seen that

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

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

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

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

As setting up a power plant is cost intensive, the 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. Here, the emission target is denoted by E_T. The problem can be formulated as:

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

whereN_r is the total number of new power plants.
The energy produced by the i^{th} power plant f_i is obtained by multiplying installed capacity by capacity factor (CF) and total time.

$$F_i = P_i * CF_i * 8760 \tag{10}$$

P_i is the added installed capacity of the i^{th}source.The emission from i^{th}source is obtained by multiplying energy generated by emission factor

$$E_i = F_i * EF_i \tag{11}$$

Similarly, capital cost is a function of type of resource and installed capacity

$$C_i = P_i * C_{mwi} \tag{12}$$

3. Proposed methodology

In order to solve this problem, two quantities need to be identified. The first is the prioritised cost of the CCS unit itself. This quantity should give the conditions under which it is economical to use a CCS unit instead of a new energy source. The second is the amount of energy to be passed through the CCS unit for optimising the cost. This section will deal with deriving these conditions. The overall layout of the problem is explained in Figure 1.

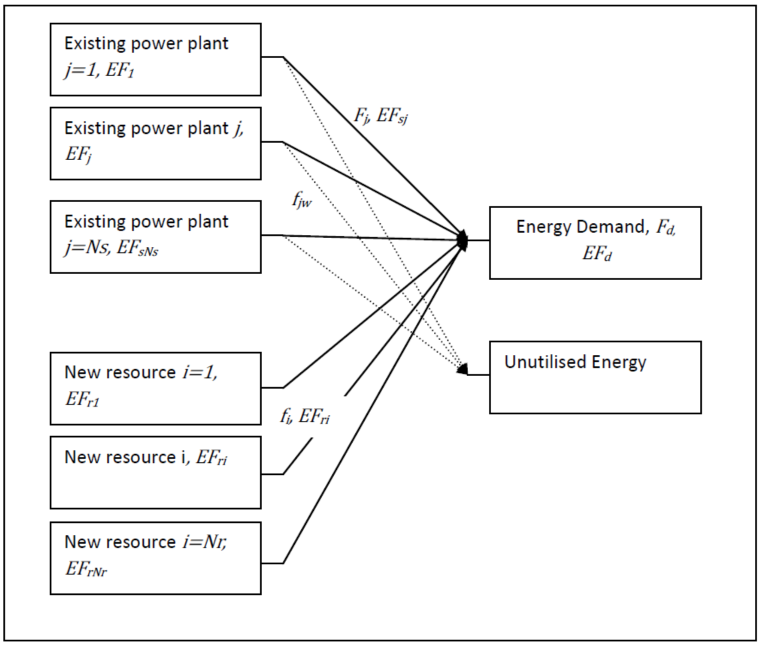

Figure 1: Typical power system planning problem with CCS retro-fitting

3.1 Prioritised cost

In order to decide whether CCS retro-fitting is more profitable than a new energy source, consider the equation for waste generation as per Pillai and Bandyopadhyay (2007). The net waste generated in a system can be divided as given in Eq(13).

$$W = \sum_{i,(EF_{si} \geq EF_p)}^{N_s} F_{sj} + \sum_{k,(EF_{dk} \geq EF_p)}^{N_d} F_{dk} + \sum_{i,(EF_{si} < EF_p)}^{N_s} F_{sj} * \frac{(EF_{sj} - EF_r)}{(EF_p - EF_r)} + \sum_{k,(EF_{dk} < EF_p)}^{N_d} F_{dk} * \frac{(EF_{dk} - EF_r)}{(EF_p - EF_r)} \tag{13}$$

The resource requirement can then be obtained using Eq(6). Here a general case with multiple demands is considered, though in a power system planning problem, there will only be one demand. N_d is the total number of demands and each demand F_{dk} has an emission factor EF_{dk}.The first two terms give the waste above pinch and the last two give the waste generated below pinch. Consider a CCS retro-fitting plant with a parasitic loss factor ∝ and emission factor EF_{out}. While considering the use of CCS retro-fitting, the following two options are possible. The first case is that the energy to be supplied to the CCS unit comes from a resource with an emission factor higher than pinch emission factor. Let ∂ be the amount of energy transferred to the retro-fitting unit. In this case, the equation for waste will be modified into,

$$W' = \sum_{i,(EF_{si} \geq EF_p)}^{N_s} F_{sj} + \sum_{k,(EF_{dk} \geq EF_p)}^{N_d} F_{dk} - \partial + \sum_{i,(EF_{si} < EF_p)}^{N_s} F_{sj} * \frac{(EF_{sj} - EF_r)}{(EF_p - EF_r)} + \sum_{k,(EF_{dk} < EF_p)}^{N_d} F_{dk} * \frac{(EF_{dk} - EF_r)}{(EF_p - EF_r)} + (1-\propto) * \partial * \frac{(EF_{out} - EF_r)}{(EF_p - EF_r)} \quad (14)$$

The new resource requirement will be modified to

$$R' = W' - (\Delta - \propto * \, \partial) \quad (15)$$

The last term of Eq(15) accounts for the parasitic loss. The savings in new resource due to addition of retro-fitting unit

$$R - R' = -\propto * \, \partial + \partial - (1-\propto) * \partial * \frac{(EF_{out} - EF_r)}{(EF_p - EF_r)} \quad (16)$$

In order for this modification to be economical,

$$(R - R') * Cost_{res} \geq (1-\propto) * \partial * Cost_{ccs} \quad (17)$$

Substituting Eq(16) in Eq(17), the following condition can be obtained

$$\frac{Cost_{res}}{(EF_p - EF_r)} \geq \frac{Cost_{ccs}}{(EF_p - EF_{out})} \quad (18)$$

Eq(18) gives the condition under which CCS retro-fitting is economical if the emission factor of power plants to be retro-fitted is higher than pinch emission factor. The second case handles situations where the power plants to be retro-fitted has an emission factor less than the pinch emission factor, the equation for waste generation will be modified as

$$W' = \sum_{i,(EF_{si} \geq EF_p)}^{N_s} F_{sj} + \sum_{k,(EF_{dk} \geq EF_p)}^{N_d} F_{dk} - \partial * \frac{(EF_{in} - EF_r)}{(EF_p - EF_r)} + \sum_{i,(EF_{si} < EF_p)}^{N_s} F_{sj} * \frac{(EF_{sj} - EF_r)}{(EF_p - EF_r)} + \sum_{k,(EF_{dk} < EF_p)}^{N_d} F_{dk} * \frac{(EF_{dk} - EF_r)}{(EF_p - EF_r)} + (1-\propto) * \partial * \frac{(EF_{out} - EF_r)}{(EF_p - EF_r)} \quad (19)$$

where EF_{in} is the emission factor of energy entering the CCS unit.The equation for modified resource requirement will be given by Eq(15).
The savings in new resource due to addition of retro-fitting unit

$$R - R' = -\propto * \, \partial + \partial * \frac{(EF_{in} - EF_r)}{(EF_p - EF_r)} - (1-\propto) * \partial * \frac{(EF_{out} - EF_r)}{(EF_p - EF_r)} \quad (20)$$

In order for this modification to be economical,

$$(R - R') * Cost_{res} \geq (1-\propto) * \partial * Cost_{ccs} \quad (21)$$

Substituting Eq(20) in Eq(21), the following condition can be obtained

$$\frac{Cost_{res}}{(EF_p - EF_r)} \geq \frac{(1-\propto) Cost_{ccs}}{(EF_{in} - EF_{out}) - \propto (EF_p - EF_{out})} \quad (22)$$

In a case where parasitic loss is zero, Eq(18) and Eq(22) can be modified as

$$\frac{Cost_{res}}{\left(EF_p - EF_r\right)} \geq \frac{Cost_{ccs}}{\left(\max\left(EF_p, EF_{in}\right) - EF_{out}\right)} \tag{23}$$

It can be seen from Eq(23) that maximum gain can be obtained by filtering resources at or above pinch emission factor. Therefore, for maximum savings, only sources at or above pinch emission factor will be considered for retro-fitting.

3.2 Calculating amount to be retrofitted

The second part of the solution is to find out how much energy is to be retrofitted. In the initial problem (without retrofitting), there can be two possibilities. The internal sum of sources and demands (Δ) can either be positive or negative. If the internal sum shows a deficit of energy supply, it must be possible to completely eliminate waste generated. Therefore, the amount of energy to be retro-fitted can be obtained by equating modified waste to zero

$$W' = W - \partial + (1-\propto) * \partial * \frac{(EF_{out} - EF_r)}{(EF_p - EF_r)} = 0 \tag{24}$$

Rearranging, it can be seen that

$$\partial = W * \frac{(EF_p - EF_r)}{\left(EF_p - EF_{out}\right) + \propto (EF_{out} - EF_r)} \tag{25}$$

Similarly, if there is a surplus in the original problem, the minimum waste possible is this surplus minus any parasitic loss

$$W' = W - \partial + (1-\propto) * \partial * \frac{(EF_{out} - EF_r)}{(EF_p - EF_r)} = \Delta - \propto * \partial \tag{26}$$

$$\partial = R * \frac{(EF_p - EF_r)}{\left(EF_p - EF_o\right)(1-\propto)} \tag{27}$$

Using the method developed here, the problem of emission constrained power system planning with CCS retro-fitting can be solved.

4. Case Study

India is the world's fourth largest economy and has 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, accounting for 70 % in 2009. The 17th electric power survey published by the central electricity authority (CEA, 2007) predicts India's annual electricity consumption to be 1,900TWh by 2020. For the purpose of this work, the target has been set to 702,000 kt of CO_2 which is a 25 % reduction from that of 2007. The possible options available to us are listed in Table 1. The estimated potential and capacity factor of each are also listed. India's present energy sources can be broken down and the pinch point or point with maximum waste generation is identified as an emission factor of 1.08 t CO_2/MWh. Knowing the pinch quality, the prioritised cost of each of the sources considered can be computed by the formula:

$$Pr.Cost_i = \frac{Costpermegawatt_i}{CF_i * \left(EF_i - EFq_p\right)} \tag{28}$$

Using this formula, it can be seen that nuclear energy has the lowest prioritised cost, followed by new coal power plants with CCS, followed by hydro-power plants, and solar power plants. In this case, only nuclear power plants qualify as all the rest have higher emission and higher prioritised cost. However, as nuclear is a limited resource, if it were to run out, then the next source to be considered will be new coal power plants with CCS as the renewable will eventually be replaced by new coal power plants with CCS. Consider a CCS unit of fixed output emission (0.1 t CO_2/MWh) and capital investment of 12 M Rs/MWh output. Let the parasitic loss be 20 % ($\propto = 0.2$). Compared to nuclear energy, its prioritised cost was computed using Eq(18). The prioritised cost was found to be less than that of nuclear power plant. In this case, it should be noted that waste generation is at pinch emission factor (as retro-fitting those below pinch is uneconomical as per Eq(23)). Also, this problem has a net internal deficit. Therefore, in order to compute the amount of energy to be retro-fitted, Eq(25) will be used. The waste (unused energy) is computed to be 201 TWh. This waste is modified using Eq(25). It is found to be 214 TWh. Note that this waste is subtracted from existing coal based generation. Also, only 80 % of the value obtained (171 TWh) will be available for use due to the parasitic loss. The energy to be supplied from nuclear energy is found to be 813 TWh. However, the maximum energy that can be supplied from nuclear is 37 TWh. It is used to the maximum, and considered as an internal source. The next set of resource to be considered will be new coal power plants with CCS as they have the next lowest emission factor and prioritised cost. The waste generated is calculated and modified using Eq(25) and the data is modified accordingly. The energy to be supplied from new coal based power plants is found to be 759 TWh.

Table 1: Future power sources

Resource	Limit (GW)	Capital Investment (10^6Rs./MW)	t CO_2/ MWh[d]	Capacity Factor[d]
Coal with CCS	NA	52[e]	0.11	0.9
Nuclear	9.55[a]	52[a]	0.02	0.9
Solar	20[b]	200[f]	0.20	0.2
Hydro	148.70[e]	65[e]	0.12	0.5

Data source: a- NPCIL (2012), b- MNRE (2008); c- NTPC (2012); d-Tan et al. (2009) e-CEA(2004); f- Banerjee (2006)

5. Conclusion

In this paper, a Pinch Analysis based approach for carbon constrained power system planning with carbon capture and storage has been developed. The method is algebraic and accounts for unique system characteristics such as parasitic loss and the interdependency between energy supplied by existing power plants and carbon capture units. Using this method, it is possible to identify whether carbon capture technology is viable in a given scenario. If it is found to be feasible, the amount of existing power plants to be retro-fitted can then be calculated. The method has been proven mathematically and applied to the Indian energy sector. The results obtained are verified independently. It should however, be noted that this method has an exception. The method is based on the assumption that either the resource needed or the waste generated can be equated to the internal surplus or deficit. But, if the output concentration of the retro-fit unit is greater than the load emission factor, it is possible for this condition to be violated. Such a case has not been considered here and needs to be addressed in the future.

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