CHEMICAL ENGINEERING TRANSACTIONS

VOL. 45, 2015

A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet

Guest Editors: Petar Sabev Varbanov, Jiří Jaromír Klemeš, Sharifah Rafidah Wan Alwi, Jun Yow Yong, Xia Liu

ISBN 978-88-95608-36-5; **ISSN** 2283-9216 DOI: 10.3303/CET1545138

Multi-Objective Pinch Analysis with Multiple Resources

Govindankutty S. Krishna Priya[a], Santanu Bandyopadhyay*[a], Raymond R. Tan[b]
[a]Department of Energy Science and Engineering, Indian Institute of Technology Bombay, Powai, Mumbai 400076, India
[b]Chemical Engineering Department, De La Salle University, Manila 2401 Taft Avenue, 0922 Manila, Philippines
santanub@iitb.ac.in

Pinch Analysis is an optimization technique that has been applied to a wide array of problems ranging from water networks to power systems. In general, Pinch Analysis is applied to single objective optimization problems. A characterizing parameter, called prioritized cost, has been developed to identify a cost optimal solution with multiple resources. In this work, Pinch Analysis is extended to address multi-objective Pinch Analysis problems with multiple resources. This is achieved by assigning a weighting factor to each objective and calculating the prioritized cost based on this variable. As the weighted prioritized cost is a linear function, it is possible to identify key values of the weighting factor where the order of priorities shifts. This greatly reduces the complexity of the problem and makes it possible to identify all the viable resource combinations. The plots of prioritized cost as a function of weighting factor can be obtained for any number of available resources. Using the prioritizing order given by these plots, Pinch Analysis can be extended to solving multi-objective optimization problems. The proposed methodology is demonstrated using the Indian power sector as an example with objectives to simultaneously minimize the capital investment and emission of oxides of nitrogen while keeping the carbon dioxide emission within prescribed limits.

1. Introduction

In light of rising electricity demands and a pressing need to curb greenhouse emissions, power system planning with emission targeting is of great relevance. The common objective considered during power system planning is cost minimisation. However, quite often, cost is not the only criterion involved in the selection of an optimal resource. Multi-objective optimisation problems are hence common in power system planning. Pinch Analysis is a method commonly used in power system planning with emission targeting. It was applied to carbon constrained power system planning (Tan and Foo (2007), pumped hydel storage to minimize supply demand mismatch (Rozali et al., 2013), a renewable based smart grids (Giaouris et al., 2014), and multi-period optimisation of power systems (Ooi et al., 2014).These problems have largely been single objective formulations aimed at minimizing the cost while meeting an emission limit.While such formulations are of great relevance, the selection of one type of power plant over another is a complex decision which requires satisfying multiple requirements ranging from cost to social acceptability. Hence, there is a need for multi-objective optimisation techniques in the power sector. In this paper, the concept of solving linear multi-objective problems using Pinch Analysis is discussed. Initial framework of this formulation was developed by Tan and Bandyopadhyay (2013). The methodology is extended and then applied to the Indian electricity sector. The multiple objectives considered are cost minimisation and minimisation of oxides of nitrogen (NO_x) for a specified energy and emission target. The results obtained are discussed along with the sensitivity of objective function to emission limit.

2. Problem Statement

The general problem may be stated as follows. 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 new power plant *i* supplies energy at a given emission factor (EF_i) and each existing power plant j has an emission factor EF_j. Emission factor is the carbon dioxide emitted for each unit of energy generated. The future energy demand is to be met

Please cite this article as: Krishna Priya G.S., Bandyopadhyay S., Tan R.R., 2015, Multi-objective pinch analysis with multiple resources, Chemical Engineering Transactions, 45, 823-828 DOI:10.3303/CET1545138

with a specified emission factor (EF_d). Energy supplied from a new power plant ii to the demand is denoted as f_i and that from an existing power plant *j* is denoted as f_j. It is possible that some existing power plants are not utilised to their full capacity, leading to unutilised energy (f_{jw})as illustrated in Figure 1.

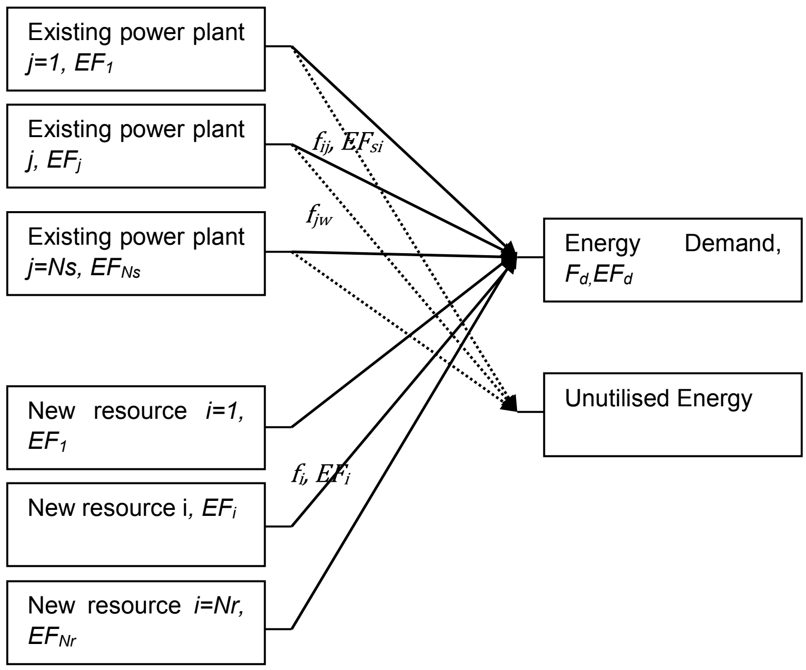

Figure 1: Representation of a typical allocation problem

Energy balances for any power plant as well as for the overall system may be expressed as follows:

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

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

$$f_i \leq F_{i\_max} \quad \forall i \tag{3}$$

Where, F_{i_max} is the maximum energy available from new power plants (maximum potential). Total unutilised energy (waste) may be expressed as:

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

Total new installed capacity requirement:

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

By taking an overall summation, it can be seen that

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

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

Δ, 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.

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

As setting up a power plant is cost intensive, it is important to minimise the capital investment while meeting the emission and energy targets. In addition to carbon dioxide, power plants emit a large number of other gases which are harmful to the environment. It is important to minimise these as well. As an example, NO_x is considered here. The objective is to simultaneously minimise the cost and NO_x emission. 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:

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

Where N is the total number of new power plants and C_i is the cost function containing a component of capital cost and one of NO_x emission. The constraints are as follows:

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

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

The energy produced by the i^{th} power plant F_i is obtained by multiplying installed capacity by capacity factor (CF) and total time.

$$F_i = P_i * CF_i * 8{,}760 \tag{12}$$

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:

$$E_i = F_i * EF_i \tag{13}$$

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

$$\Phi_i = P_i * C_{mwi} \tag{14}$$

$$\Psi_i = F_i * C_{noxi} \tag{15}$$

Where Φ_i is the objective function pertaining to capital minimisation and Ψ_i corresponds to NO_x emission. As all the constraints as well as the objective functions are linear, this is a multi-objective linear programming problem. The bi-objective problem practically converges to determination of optimal points that satisfies both these objectives simultaneously. To determine these points, the concept of weighted objective can be adopted; for linear systems, this summation always results in a Pareto optimal solution. Assuming a weight *w* for total cost energy supply and a weight of (1 – *w*) for the total energy invested, a single objective (*C*) can be formulated.

$$C_i = w\Phi_i + (1 - w)\Psi_i \tag{16}$$

To get the entire Pareto optimal front, weight w can be varied between 0 and 1. On the other hand, a Pareto optimal point can also be generated keeping one the objective fixed and solving the formulation to optimize the other objective. The procedure is repeated multiple times in order to get all optimal points. Given the objective function, it is possible to identify the prioritising order of resources available. The method for identifying prioritised cost is discussed in Krishna Priya and Bandyopadhyay (2013). Using the same technique, the prioritised cost of plant *i* in this case can be identified as:

$$Pr.Cost_i \frac{w\frac{C_{mwi}}{CF} + (1-w)C_{noxi}}{EF_p - EF_i} \tag{17}$$

The prioritised cost allows for identifying a prioritising order. In short, it says that a resource (power plant) needs to be considered only if its prioritised cost is lower than that of all resources with a lower emission factor. This method is illustrated next using the Indian power sector as an example.

3. Case study: Indian power sector

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 (CEA, 2007) predicts India's annual electricity consumption to be 1,900 TWh by 2020. While increasing power production capacity is of prime importance, it is equally important to reduce the overall emission from power sector. It is safe to assume that total emission will have to be reduced by around 20 % of present value by 2020. For the purpose of this project, the target has been set to 703 Mt of CO_2 which is a 25 % reduction from that of 2007. It is important to note that CO_2 is not the only dangerous emission caused by the power industry. In order to illustrate the suggested method, minimising NO_x emission is considered as an additional objective here. The data of resources available is listed in table 1. In order to clearly illustrate the variation of prioritised cost, convenient units have been chosen.

Table 1: Future power sources

Resource	Limit (GW)	Operating Capacity factor	Tonnes of CO_2/ MWh[e]	NO_x (100 g/MWh)[f]	Cost (10^6 Rs/MW)
Coal	NA	0.72[d]	1.08	43.4	40[g]
Nuclear	10.00[b]	0.82[b]	0.02	0	52[g]
Hydro	148.70[a]	0.50[a]	0	0	70[a]
Wind	47[c]	0.14[c]	0	0	50[h]
Biomass	19.50[c]	0.70[c]	0.15	22	30[h]
Small Hydro	15[c]	0.50[c]	0	0	125[i]
Solar	NA[c]	0.20[c]	0	0	200[h]
Coal with CCS	NA	0.9	0.1	43.4	52 [g]

Compiled from data available on a- NHPC (2012); b- NPCIL (2012), c- MNRE (2008); d- NTPC (2012); e-Tan et al. (2009); f-Mittal et al. (2012); g-CEA (2004); h-Banerjee et al. (2006); i-Nouni et al. (2008)

Based on the data available, the prioritized cost of various power sources is plotted against the weighting factor (Figure 2). The points of intersection of these lines specify the weighting factor at which the priorities of power sources may change. This change will also depend on the emission factor of the power sources involved. A new power source is viable only if its prioritized cost is lower than that of all other sources with lower emission factor. The prioritized cost of coal power plants is significantly higher than that of others and is not shown in the plot. It can be seen that at lower values of weighting factor, the resources with low NO_x emission like solar energy and hydroelectric power play a part in the final energy mix. However, as the weightage for cost minimization increases, this comes down, and new coal power plants with carbon capture units take over. From Figure 2, it can be seen that up to a weighting factor 'P' renewable such as hydroelectric and wind power plants have lower prioritised cost along with nuclear energy. As expected, the energy mix obtained at low values of weightage reflects this observation. It should be noted that, as the unrestricted resource, solar energy supplies a large portion of the load. However, at a weighting factor 'O', coal power plants with carbon capture becomes more viable than solar energy, and as it is not a limited resource, plays an important part in the mix. Beyond point 'P' the mix is stable. It should be noted that not all intersection points alter the mix. For example, at weightage ‘Q’, biomass becomes more viable than nuclear energy. However, as both these resources are limited, they are both used exhaustively.

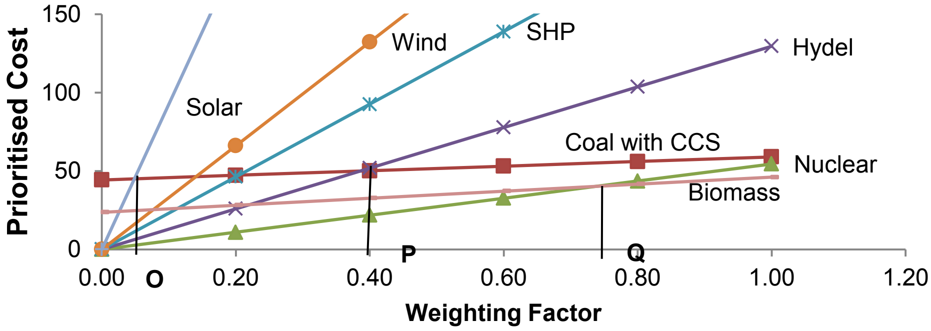

Figure 2: Prioritised costs of various energy sources

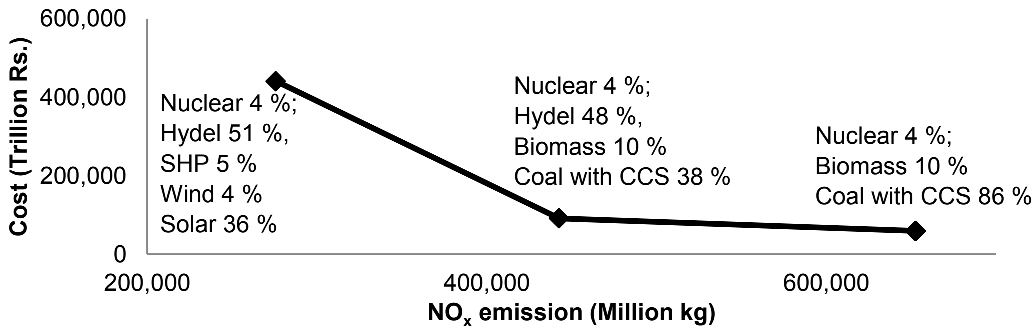

Figure 3: Pareto optimal front and variation in energy mix at key points

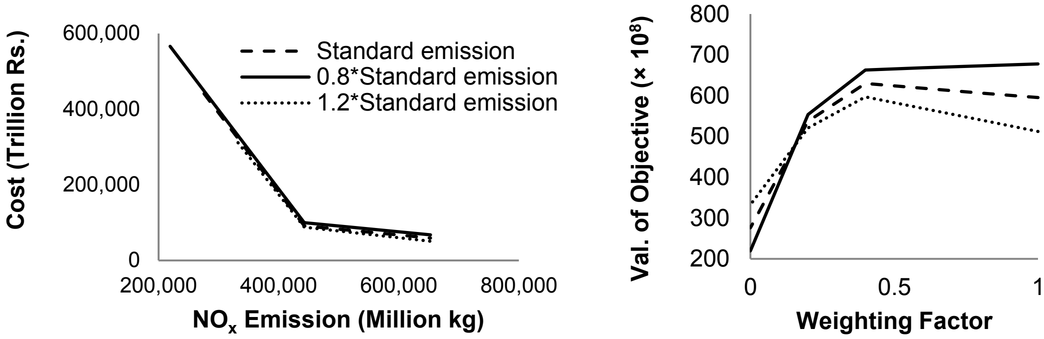

Figure 4: Sensitivity of Pareto optimal front and overall cost to emission limit

The Pareto optimal front here is a plot of capital cost vs. NO_x emission. It is found to be a piecewise linear plot with three key points corresponding to solution at weighting factors corresponding to regions between 0 and ‘O’, ‘O’ and ‘P’ and the region beyond ‘P’. The variation in the mix of new power plants is shown in Figure 3. It shows the three possible energy mixes along with the Pareto optimal front of the system. It can clearly be seen that as the weightage for cost minimization increases, the resources migrate from renewables to fossil fuels (coal power plants with carbon capture units). It is also seen that some fraction of existing coal power plants are being shut down to meet the constraints. The fraction of coal power plants shutdown varies from 23 % when weighting factor is zero to 35 % when the weighting factor is one.
The emission limit of the system is varied and the variation of overall cost function across the range of weighting factors was studied. Figure 4 gives the variation of cost function as weighting factor and emission limits are varies. For most values of weighting factor, the overall cost increases as the emission

limit is made more stringent. However, it is seen that these curves intersect at lower values of weighting factor. This leads to some interesting conclusions. At lower values of weighting factor, trying to achieve a lower carbon dioxide emission limit is more economical than relaxing the emission limit. This is largely because the resources with low carbon emission (i.e., renewables) also have a low NO_x emission.

4. Conclusion

In this paper, a linear, multi-objective optimization problem is solved using the concept of Pinch Analysis. It is shown that available energy sources can be prioritized using their emission factors and prioritized costs. The method is applied to the Indian power sector and the results obtained are discussed. In addition, a sensitivity analysis is carried out to study the system behaviour with variation in emission limit. It is observed that in general, as emission limit becomes more stringent, the optimal value of overall cost function increases. However, it may be more economical to achieve lower emission targets if the weighting on NO_x emission is also high. As this is among the first studies of its kind on Indian Power sector, it is not possible to compare the results to that of other works. However, the method suggested can be used to address the myriad of often conflicting interests that go into the selection of one power generation technology over another.

References

Banerjee R., 2006, Comparison of options for distributed generation in India. Energy Policy, 34, 101–111.

Central Electricity Authority, 2007, Report on 17th Electricity survey of India, <www.cea.nic.in/more_upload/epsr_17_highlights.pdf >, accessed on 23.06.2015.

Central Electricity Authority, 2004. Report of the expert committee on fuels for power generation, <www.cea.nic.in/thermal/Special reports/Report of the expert committee on fuels for power generation.pdf>, accessed on 23.01.2015.

Giaouris D., Papadopoulos A.I., Seferlis P., Papadopoulou S., Voutetakis F., Elmasides C., 2013, Optimum energy management in smart grids based on power pinch analysis, Chemical Engineering Transactions, 39, 55-60.

ICLEI South Asia, 2007, Renewable energy and energy efficiency status in India. <local-renewables.iclei.org/fileadmin/template/projects/localrenewables/files/Local_Renewables/Publications/RE_EE_report_India_final_sm.pdf>, accessed on 23.07.2015.

Krishna Priya G.S., Bandyopadhyay S., 2013, Emission constrained power system planning: a pinch analysis based study of Indian electricity sector, Clean Tech. Env. Policy, 15(5), 771-782.

MNRE, 2008, Annual report 2007-2008, <mnre.gov.in/file-manager/annual-report/2007-2008/EN/index.htm>, accessed on 23.01.2015.

Mittal M.L., Sharma C., Singh R., 2012, Estimates of emissions from coal fired thermal power plants in India. 2012, International Emission Inventory Conference, Tampa, Florida, USA, Session 5, Presentation 6, <www.epa.gov/ttn/chief/conference/ei20/session5/mmittal.pdf>, accessed on 23.06.2015.

Nouni M. R., Mullick S. C., Kandpal T. C., 2008, Providing electricity access to remote areas in India: An approach towards identifying potential areas for decentralized electricity supply, Renewable and Sustainable Energy Reviews, 12, 1187–1220.

NHPC, 2012, <www.nhpcindia.com>, accessed on 23.01.2015.

NPCIL, 2012, Corporate Profile, <www.npcil.nic.in/pdf/Corporate_Profile_2012.pdf>, accessed on 23.01.2015.

NTPC, 2012, NTPC Overview, <www.ntpc.co.in/en/about-us/ntpc-overview/>, accessed on 23.01.2015.

Rozali N.E.M., Alwi S.R.W., Manan Z.A., Klemes J.J., Hassan M.Y., 2013, Optimisation of pumped-hydro storage system for hybrid power system using power pinch analysis, Chemical Engineering Transactions, 35, 85-90.

Ooi R.E.H., Foo D.C.Y., Tan R.R., 2014, Targeting for carbon sequestration retrofit planning in the power generation sector for multi-period problems, Applied Energy, 113, 477-487.

Tan R.R., Foo D.C.Y., 2007, Pinch analysis approach to carbon-constrained energy sector planning. Energy, 32(8), 1422–1429.

Tan R. R., Ng D.K.S., Foo D.C.Y., 2009, Pinch analysis approach to carbon constrained planning for sustainable power generation, J. Cleaner Prod., 17, 940–944.

Tan R.R., Bandyopadhyay S., 2013, Pinch analysis for multi-dimensional sustainable energy systems planning, 4th International Conference on Advances in Energy Research, Indian Institute of Technology Bombay, Mumbai, 520-523.