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Multi-objective pinch analysis for power system planning

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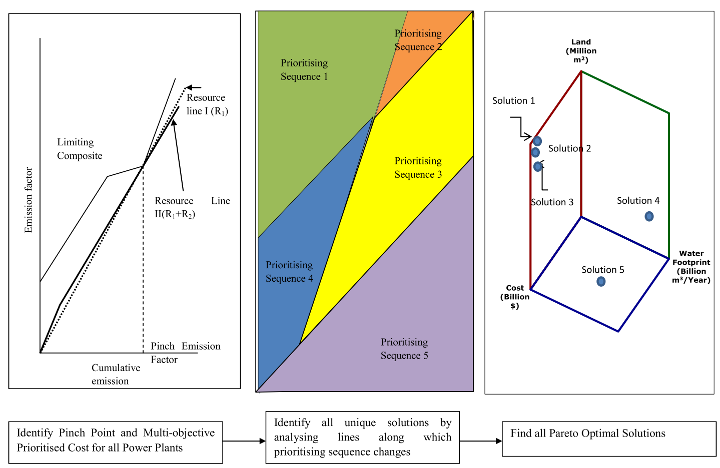
HIGHLIGHTS

- Formulation of Multiple Objectives Pinch Analysis (MOPA) problems proposed.
- Analysis of multiple objectives prioritised cost to identify prioritising sequence.
- Development of a graphical solution space for three objective optimisation problems.
- Minimising cost, land footprint and water footprint for Indian power sector planning.
- Generation of solution space and Pareto optimal front for the Indian power sector.

GRAPHICAL ABSTRACT



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ABSTRACT

Given the rising levels of greenhouse gases and the dependence of power generation on fossil fuels, power system planning with emission constraint is of crucial importance. The objective of emission constrained power sector planning is to identify an optimal energy mix, capable of supplying the required amount of electrical energy while simultaneously keeping emissions within a predefined limit. Cost minimisation is the common objective in power sector planning. Additionally, the choice of one power plant over another involves considering a large number of social, environmental, and economic factors. A multi-objective approach is better suited to address such a complex problem. In this paper, Pinch Analysis, a single objective optimisation method, is modified to address multi-objective problems. It is then applied to simultaneously minimise the land footprint, water footprint, and capital cost associated with energy generation for the Indian power sector. A graphical solution space containing all Pareto optimal solutions for a three-objective problem is also presented. It is seen that for India, the energy mix is dominated by photovoltaic and carbon capture enabled coal power plants. The energy mix for least water footprint contains only photovoltaic power plants while that for least land footprint has a mix of wind, nuclear, small hydel, photovoltaic and biomass. Capital investment is the minimum when biomass and nuclear power plants, along with carbon capture enabled coal plants supply the demand, making biomass the only renewable to feature in the cost optimal mix. Existing coal power plants continue to supply over 35% of the energy requirements for the entire solution space. The overall results highlight the importance of solar PV and carbon capture technology.

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Nomenclature

C	cost coefficient
F_{dk}	total energy demand (MW h)
F_{sj}	total energy supplied by an existing power plant (MW h)
F_{r_max}	maximum potential capacity of a power plant (MW h)
N_d	total number of demands
N_{obj}	total number of objective functions
N_r	total number of existing power plants
N_s	total number of new power plants
f	energy flow (MW h)
q_{dk}	emission factor of demand (t CO_2/MW h)
q_{ri}	emission factor of new power plant (t CO_2/MW h)
q_{sj}	emission factor of existing power plant (t CO_2/MW h)
α	weighting factor of objective function
β	weighting factor of second objective function
ρ	prioritised cost of resource
Φ	objective function

Subscripts

ccs	carbon capture and storage
d	demand
i	index for new power plants
j	index for existing power plants
k	index for demands
l	index for objective functions
max	maximum
p	pinch

1. Introduction

The importance of reduction of emission of greenhouse gases cannot be overstated in light of the present threat posed by global warming. At present, electricity generation is largely fossil fuel based, making power generation sector a major player in the greenhouse crisis. The burning of coal, natural gas, and oil for electricity and heat is the largest single source of global greenhouse gas emissions [1]. Furthermore, energy demand is increasing at a steady rate, making it essential to expand the power generation capacity. There is, therefore, a pressing need to balance electricity generation and emission reduction.

Various techniques like demand side management and energy conservation measures can reduce emissions from power generation to a certain extend. For a conventional coal power plant, 1% efficiency improvement decreases carbon dioxide (CO_2) emission by 2.5–3% [2]. However, new renewable power plants with low or zero carbon emission are a long term solution to this problem. While renewable power sources are the viable and long term solution, a sudden and complete departure from the fossil fuels is not practical as renewable sources such as wind and solar PV are more capital intensive than fossil fuel based sources. It is, therefore, necessary to find an appropriate mix of sources that can supply rising energy demands without overshooting the emission targets, thus giving rise to emission constrained power system planning problem.

In the context of this paper, the objective of power system planning with emission constraint is to meet the energy demand, while satisfying the emission targets set by the corresponding nation. Given the importance of emission constrained planning, researchers have used multiple methods to address this problem. One common approach used is that of mixed integer linear programming MILP). MILP has been used for emission constrained power system planning of Malaysian energy sector [3], Chinese energy sector [4], Canadian energy sector [5], Greek energy sector [6], Taiwanese energy sector [7], etc. Various modes based on MILP, such as Integrated Resource Planning Model (IRPM) [8,9] and Market Allocation model (MARKAL) [10,11] are also used for emission constrained power system planning. Both IRPM and MARKAL are data intensive as well as computationally involved methods. MARKAL is usually used for primary energy analysis across sectors, and not specifically suited for power system planning. IRPM depends of external demand forecasting and is primarily for centralized planning.

Pinch Analysis is another linear optimisation tool used for carbon constrained power sector planning. Linnhoff and Dhole [12] used Pinch Analysis for emission targeting in a chemical process plant. Although emissions targeting by Pinch Analysis was introduced in this study, the early applications were limited to optimisation within industrial facilities, and not to regional or national energy sectors. Pinch Analysis was first extended to the carbon constrained energy sector planning by Tan and Foo [13]. Subsequently, carbon emission Pinch Analysis was applied to the Irish electricity sector [14,15], New Zealand's energy sector [16], Malaysian energy sector [17], etc. Lee et al. [18] extended Pinch Analysis to target the amount of low-carbon resources needed to meet a given energy demand and emission limit, as low-carbon energy resources are often less expensive than zero carbon resources. Foo et al. [19] developed a tabular and algebraic approach, called cascade technique, to overcome the limitation of graphical Pinch Analysis where the accuracy of the solution depends on visual resolution. Tan et al. [20] and Pekala et al. [21] have further expanded carbon emission Pinch Analysis to include the possibility of carbon capture units. Various unique challenges associated with carbon capture such as availability of carbon sinks and constraints associated with injection rates were also addressed [22]. Walmsley et al. [23] used Pinch Analysis to study the effects of California (USA) reaching its renewable electricity targets and Ho et al. [24] used Pinch Analysis to study off-grid energy systems. Bandyopadhyay and Desai [25] discussed cost optimal design of isolated energy systems and its effect on overall emissions. Pinch Analysis is a robust and simple method for carbon constrained power system planning. However, it is inherently a single objective optimisation framework. In reality, power system planning is a complex problem involving a large number of social, environmental and economic factors. A single objective optimisation approach may not be able to account for all the factors involved.

A number of approaches have been proposed for multi-objective optimisation in power system planning. For example, Ren et al. [26] applied multi-objective linear programming to identify an optimal operating strategy for distributed energy systems. The objective functions were cost minimisation and emission minimisation and compromised programming method was adopted to find an optimal solution. Similarly, Dufo-López et al. [27] used strength Pareto evolutionary algorithm to minimise the life cycle emission and levelized cost of energy for a standalone power system. A similar approach involving multi-objective evolutionary algorithms was used by Mahbub et al. [28] to model a future energy system using Denmark as an example. A study on the Croatian energy sector [29] tries to minimise the net present value of the energy system, and the net present value normalised over energy generation while simultaneously maximising the share of