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Generation expansion planning optimisation with renewable energy integration: A review

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ABSTRACT

Generation expansion planning consists of finding the optimal long-term plan for the construction of new generation capacity subject to various economic and technical constraints. It usually involves solving a large-scale, non-linear discrete and dynamic optimisation problem in a highly constrained and uncertain environment. Traditional approaches to capacity planning have focused on achieving a least-cost plan. During the last two decades however, new paradigms for expansion planning have emerged that are driven by environmental and political factors. This has resulted in the formulation of multi-criteria approaches that enable power system planners to simultaneously consider multiple and conflicting objectives in the decision-making process. More recently, the increasing integration of intermittent renewable energy sources in the grid to sustain power system decarbonisation and energy security has introduced new challenges. Such a transition spawns new dynamics pertaining to the variability and uncertainty of these generation resources in determining the best mix. In addition to ensuring adequacy of generation capacity, it is essential to consider the operational characteristics of the generation sources in the planning process. In this paper, we first review the evolution of generation expansion planning techniques in the face of more stringent environmental policies and growing uncertainty. More importantly, we highlight the emerging challenges presented by the intermittent nature of some renewable energy sources. In particular, we discuss the power supply adequacy and operational flexibility issues introduced by variable renewable sources as well as the attempts made to address them. Finally, we identify important future research directions.

1. Introduction

Relentless increase in electricity demand calls for new investments in generation capacity on a regular basis. Efficient planning of new generation units is an optimisation problem that entails answering the following four basic questions so as to ensure that the installed generation capacity adequately meets the forecasted demand growth over a medium to long-term planning horizon:

i. WHAT - the types of generation technologies that will be added to the grid
ii. HOW MUCH - the size of each new generation plant
iii. WHERE - the location of these plants
iv. WHEN - the stage of the planning horizon when the new units must be implemented.

Generation Expansion Planning (GEP) has been the focus of active research since the 1950s when linear programming (LP) models were successfully used to approximate the objective function and the constraints to linear functions, starting with the work of Masse and Gibrat [1]. However, the complexity associated with GEP has risen dramatically due to the variety of generation technology options available to the planners, the numerous stakeholders involved and the diversity of constraints derived from limitations imposed by physical processes, generation capacity, reliability of electrical supply, resource availability and economic considerations, among others. Initially, the aim of GEP was to search for the most economical scheme that could provide an adequate supply of electricity to meet the projected demand growth subject to a set of constraints over a planned period of time. The cost function typically included investment, fuel, and generation costs over the entire planning period. LP models cannot deal satisfactorily with the large number of constraints inherent to a realistic GEP problem. Furthermore, the need for greater accuracy in the modelling uncovered non-linear relationships among the decision

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variables and the objective function. To overcome this problem, a variety of mathematical optimisation methods was developed and applied to the GEP problem including non-linear programming (NLP) [2], mixed integer programming [3], dynamic programming [4] and decomposition techniques [5-7]. Moreover various approximations and assumptions were made on the model to keep the optimisation problem computationally tractable. For example, aspects of the real-time operations of the power system were often neglected and parameters like spinning reserves and variable heat rates were rarely considered.

As the portfolio of available generation technologies grew and reliability concerns became more stringent for power system planners, the issue of generation capacity addition developed into a highly constrained, non-linear discrete dynamic optimisation problem. Finding satisfactory solutions to such problems requires complete enumeration of combinations of candidate generation expansion options [8]. Since the number of potential solutions grows explosively with the problem size, an exhaustive search is infeasible. Moreover, planning over the long term inevitably gives rise to uncertainties in each step of the modelling process and in the model parameters. In light of these new dimensions, the traditional least-cost objective function alone could no longer drive the generation expansion decision-making process. Additional objectives were taken into consideration to guide decisions beyond the economic perspective. The GEP literature has been thoroughly surveyed in the past. The reviews have mostly focused on the methodological aspect by analysing the models developed to integrate the latest changes in GEP formulation. For example, heuristic and metaheuristic algorithms are known to provide reasonably good solutions within realistic time to problems that are intractable to conventional optimisation methods. Thus, Zhu and Chow [9] thoroughly reviewed heuristic techniques that could potentially be used to solve single-objective GEP problems. Since these methods were emerging at that time, the authors focused on the various heuristic algorithms as well as their merits and drawbacks. Subsequently, Nara [10] reviewed the actual application of the heuristic methods to power system planning. On the other hand, Hobbs [11] performed a literature survey of optimisation models that incorporated new concepts in GEP: demand side management (DSM) programmes as an alternative to additional generation capacity, the presence of uncertainties in several parameters, inclusion of objectives other than the least-cost and the transformation of the electricity production industry from a centralised monopoly to a more competitive market. The latter was further addressed in a review by Kagiannas et al. [12] where the reformulation of GEP optimisation models to accommodate the changes brought by the evolution from a monopolistic electricity market to a deregulated and competitive one were highlighted. Besides, works related to energy planning models with multiple conflicting objectives were reviewed by Voropai and Ivanova [13], Pohekar and Ramachandran [14], Løken [15] and Wang et al. [16].

Over the last two decades, concerns about the likelihood of fossil fuel prices soaring in the long-term, geopolitical changes, energy security and the environmental impact of the fossil fuels have resulted in concerted efforts to reduce greenhouse gas (GHG) emissions worldwide. Consequently, interest in harnessing renewable energy (RE) resources has intensified. In particular, the consistent growth of intermittent RE resources, mainly sun and wind, has been key to the energy transition. In addition to mitigation of pollutant emissions, the integration of variable renewables in the electricity grid caused the emergence of other crucial aspects in the energy planning scenario such as the reliability, flexibility and efficiency of the power system. This paper evaluates different models that have been applied to account for the push towards a carbon-constrained power system. It reports a wide range of research papers relevant to this topic chronologically, starting from the early minor improvements made to existing models, to state-of-the-art models that deal with contemporary challenges. This review also attempts to propose a classification of approaches adopted in this field. In this context, the paper has been divided into four distinct sections to demarcate different approaches that have been employed to address the needs of decision-makers in response to additional requirements of GEP following the integration of RE in the electricity grid. They are as follows:

- traditional methods of integrating environmental considerations as constraints or external costs in GEP
- formulation of GEP as a multiple-objective optimisation problem whereby the ecological footprint is considered as one of the objectives
- techniques used for the inclusion of additional uncertainties in the planning process brought by variable RE sources
- new dynamics introduced by increased integration of intermittent RE resources in the power system and associated challenges experienced by power system planners

The intricacies of the models as well as their strengths and limitations are highlighted. In addition to methodological contributions, we elaborate on future research with new questions that are being asked by planners working in GEP and the corresponding paradigms that must be captured within the planning models to answer these questions.

2. Early environmental considerations

Initially, environmental impacts were handled as constraints imposed on the operation of the power grid by setting tolerance thresholds for the maximum acceptable emission rates. Another common approach integrated the external costs associated to environmental impacts of energy production by the various power plants in the system.

2.1. Environmental constraints

Sirikum and Techanitisawad [17] added air pollutant emission and concentration limits to the usual capacity, power balance, reliability, location and resource availability constraints of their mixed integer non-linear programming (MINLP) model. The authors appended environmental and investment costs in demand side management (DSM) programmes and outage costs into the objective function. The complex MINLP task was decomposed into two parts. Firstly, a combinatorial problem is solved by GA search to determine a feasible generation mix considering only reserve margin, reliability and location constraints. Then, an optimum level of power generation is found by a continuous LP method under demand, capacity and emission constraints. The proposed technique was validated on seven different case studies of a scaled-down model of the Thailand power system with different planning periods and problem sizes. Chen et al. [18] reported a GEP model that integrates a series of low-carbon factors in the objective function, decision variables and constraints. Additional decision variables are used to indicate the level of retrofit of conventional coal plants with carbon capture and storage (CCS) technologies, the implementation of new low-carbon technology plants and the overall CO_2 traded allowance. In addition to the usual cost components, the economic objective function consisted of income from CO_2 trading mechanisms, CO_2 emission penalty and CCS retrofit expenses. Limits are imposed on the total CO_2 emission levels and on the overall tradable CO_2 allowance. The model was tested on the power system of China to reveal the prospects of CO_2 mitigation measures until 2030. Both [17] and [18] considered only thermal power plants and limited scenarios in their analysis.

Cormio et al. [19] applied a linear programming optimisation procedure based on the energy flow optimisation model (EFOM) to support regional energy planning in Apulia located in southern Italy. The total cost of the entire energy system was minimised by a LP