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State-of-the-art generation expansion planning: A review

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HIGHLIGHTS

- A state-of-the-art review of the generation expansion planning problem is presented.
- Integration of transmission and generation expansion planning is of added value.
- Short-term dynamics have significant aspects on long-term power investments.
- Electricity and natural gas interdependence creates increasing synergies.
- Storage, electric vehicles and demand-response are key aspects in system design.

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ABSTRACT

The long-term Generation Expansion Planning (GEP) problem determines the optimal type of energy technologies, size, location, and time construction of new power generation plants, while minimizing total cost over a long planning horizon and being subject to a series of constraints. Due to its complex nature, its effective implementation requires the consideration of a wide range of aspects including economic, environmental, regulatory, technical, operational, social, as well as potential interdependencies with other complementary sectors. As a consequence, the traditional cost-based approaches have been extensively modified and updated, leading to more advanced ones including, at least partially, some of the above described aspects. This work provides a comprehensive review of the most recently developed approaches dealing with the Generation Expansion Planning problem from a variety of perspectives, organizing them into seven key categories including the interaction of generation expansion planning with: the transmission expansion planning, natural gas system, short-term operation of power markets, electric vehicles, demand-side management and storage, risk-based decision-making, as well as with applied energy policy including security of supply. The main goal of this work is to stress the multi-dimensionality of the generation expansion planning execution, creating the need for an in-depth investigation and consideration of synergies with other complementary sectors. Reviewing results have the objective of providing useful insights into the current state and future challenges of the GEP decision-making.

1. Introduction

The Generation Expansion Planning (GEP) stands as one of the most discussed topics within the academia and decision makers in the energy sector. The GEP has initially tackled the needs of centralized power systems, with vertically integrated state-owned electric utilities having monopoly in generation, transmission, distribution and retail sectors. However, the liberalization of electricity markets as well as technological developments has led to a rapid transformation of power systems and electricity markets. New challenges have steadily arisen, which have been gradually incorporated into the GEP problem. In this work, we aim to present the methodologies developed for the GEP, focusing on addressing the new challenges. We have identified seven generic categories of new challenges for the GEP problem. Those are:

- integration of generation and transmission power system, placing special emphasis on the role of electricity trade,
- consideration of risk assessment in generation expansion planning,
- integration of electric vehicles in power systems,
- integration of long-term GEP with short-term power systems operation,
- power and natural gas systems interdependence,

Abbreviations: DSM, demand-side management; GEP, Generation Expansion Planning; MIBLP, Mixed Integer Bi-Level Linear Programming; MILP, Mixed Integer Linear Programming; MINLP, Mixed Integer Non-Linear Programming; TEP, transmission expansion planning

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- energy storage and demand-side impacts on GEP, and
- policy implications on power investments, highlighting the role of supply of security.

The above classification has been identified, following a thorough literature review. Electric vehicles are considered as a separate category for energy storage, due to the fact that electric vehicles stand as a fast-growing, new load that has to be met, while energy storage is organized with demand-side, as they are both options for shifting existing load. There exist several GEP methodologies that tackle more than one of the above categories; however this classification enables organizing GEP methodologies based on their focus, rather than on the methodological framework they adopt. This stands as the main difference of this review paper compared with other review papers of the GEP problem [1–4]. The main objective of this review paper is to extensively analyze and outline the multi-dimensional aspects of the GEP decision making, indicating both the internal (operational, environmental, regulatory, economic and financial issues of the industry) and the external factors (interactions with other sectors, new elements and influencers of the power system including storage, electric vehicles, demand response, and electricity trade) that make GEP implementation a highly complex task. GEP has been evolved into a process that requires the assistance and collaboration of a wide range of professionals including engineers, decision makers, lawyers, economists, social scientists, while public acceptance constitutes a key component and prerequisite for its effective execution in the context of energy transition. The power systems have been evolving fast over the last decades, thus the GEP problem had to consider how the power plants interact with other critical components of the power systems. The integration of generation with transmission power systems is critical, as the transmission constraints affect the location and sizing of new generation units. The renewable energy resources have created new challenges for the GEP problem, due to their stochastic nature. The variability of power generation from renewable energy resources and the uncertainty it creates for the power systems' operation, is expected to be tackled with the integration of electric vehicles and electric storage, which stands as another important challenge of the GEP problem. The evolution of a centralized power system to a smart one with distributed generation and flexible demand is an important challenge of the GEP, thus several methodologies target to integrate the long-term energy planning with both demand-side management and short-term operation of power systems. This integration is usually implemented by incorporating the unit commitment problem into the GEP. Moreover, the fast penetration of natural gas over the last years in the mix of both power capacity and electricity generation has created new challenges for the GEP problem. This is tackled by the integration of power with natural gas system, which provides a holistic approach when examining their synergies and interdependence. The natural gas disputes over the last years have raised the importance of energy security, which strongly affects the GEP problem, requiring also a risk-based assessment of the long-term planning. Last but not least, another challenge of the GEP problem is the consideration of the applied policies, which stands as an important issue in all countries.

The present paper aims at providing an overview, from a technical (engineering) perspective, of the key aspects that influence, and/or going to exert even more significant impacts in the future, on the whole decision-making framework of GEP problem. Although the literature review undertaken is extensive, the paper does not state that the presented literature is complete, as a different focus of the review paper might have tackled GEP from a different discipline perspective, while each of the seven selected aspects/categories can be itself the subject of a more detailed distinct review paper. There are also many works in the literature addressing the GEP problem, considering only one or some of the categories identified as key determinants in the present manuscript. Other aspects such as electric vehicles and demand-side programs are mainly studied in the context of short-term operational scheduling of power systems (unit commitment problem), and their impacts on the long-term planning have yet to be adequately investigated. Our paper has adopted a methodological framework for conducting the review, taking into account that a contemporary, systematic and robust long-term generation expansion planning should satisfy the following conditions:

1. Consideration of all the available options from the supply side (electricity generation technologies, energy storage when acting as a supplier in cases of discharging, electric vehicles in vehicle-to-grid operating mode, as well as electricity trading, in terms of imports through available interconnections).
2. Consideration of all the available options from the demand side (energy efficiency, demand-side programs, energy storage during time periods of charging, electric vehicles in grid-to-vehicle operating mode, as well as electricity trading, in terms of exports through available interconnections).
3. Historically, conventional power units have been designed as base-load power units (typically run throughout the year with the exception of their scheduled maintenance periods) to cope with electricity demand profiles characterized by relatively low fluctuations and variability, as well as by typical and predictable daily, weekly and seasonal patterns. Power systems with high penetration of variable renewables are characterized by increased requirements for flexibility, which should be provided by swiftly dispatching conventional power units (supply side), including both thermal and renewables, being able to ramp up and down more frequently and more quickly, operate often at partial loads and to start up and shut down with greater frequency. In that context, the demand-side can also play a crucial role in terms of flexibility provision, through demand-side programs, storage, and electric vehicles. All these elements should be carefully designed in the framework of an affordable, low-carbon GEP, which guarantees high degrees of flexibility potential.
4. An increasing share of renewables decreases the market profitability of conventional thermal units due to the so-called merit-order effect (economic dispatch), raising concerns regarding the long-term economic viability of these units. Negative marginal prices have started to be frequent phenomenon in the electricity markets' operation. In addition, it implies indirect impacts on conventional power units, on the grounds that it raises the requirements for balancing services and congestion management in the power system. However, frequent occurrences of negative wholesale prices provide also incentives and price-signals for potential investors and market participants to invest in highly flexible power sources (e.g., storage) and/or to adapt their production or/and consumption more flexibly to the variable renewable feed-in. As a consequence, the introduction of competitive forces in the power markets creates the need for a market-based investigation of the GEP problem, thus the consideration of short-term operational aspects into the decision-making is of great significance for the economic viability and technical feasibility of the implemented long-term GEP.
5. The significant penetration of renewables into the power systems may lead to their concentration in new remote areas without adequate existing transmission options. It goes without saying that public acceptance comprises a prerequisite for their installations. Therefore, an effective GEP implementation should go in line with the transmission expansion planning, which extends simultaneously the absorption potential of electricity generation from intermittent and variable renewable energy sources, especially during extreme windy and/or sunny days, eliminating undesired events of transmission congestion in transmission lines. In that context, from an economic viewpoint, the evaluation of the lost load value constitutes a determining factor, highlighting the importance of the proper design of long-term GEP.
6. The increasing interdependence of the power sector with other ones