Renewable and Sustainable Energy Reviews 98 (2018) 346–360

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A comprehensive review on expansion planning: Models and tools for energy policy analysis

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ARTICLE INFO

Keywords:
Energy policy
Expansion planning
Generation
Renewable energy
Transmission

ABSTRACT

Energy systems are quickly evolving through the development of new technologies and the emergence of new operational and market design paradigms. In particular, the global push for sustainability is driving the transition towards a pronounced redesign. In fact, renewable energy integration is occurring at a massive scale, and several other exciting developments are finding their place in modern energy systems, such as distributed energy resources, demand response, energy storage technologies, and local energy markets. In this dynamic context, the process of energy policy design and implementation has found new challenges, and in supporting this key process, expansion planning models and tools can play an essential role. For example, these models can be employed to estimate the impact of a multitude of policy instruments. Thus, there is a wide interest in these tools and a variety of such models, as evidenced by a rich literature and a fast-paced evolution of this research area. Motivated by this, this work presents a comprehensive and up-to-date review on expansion planning models and tools with emphasis on their application to energy policy analysis. In particular, this paper reviews the most significant policy instruments, with an emphasis in renewable energy integration, the optimization models that have been developed for expansion planning, and existing decision-support tools for energy policy analysis. Finally, this paper also discusses the trends in the literature and the most pressing current challenges in the development and use of expansion planning models for energy policy analysis.

1. Introduction

The world's energy landscape is undergoing pronounced transformations as a result of the global need for sustainability. One of the most pressing and urgent challenges is keeping the global average temperature within certain limits, which has led governments to take different concrete measures to make energy systems less dependent on fossil fuels [4]. Fortunately, the development of new innovative technologies presents a promising context to try to achieve sustainability goals. However, when integrating these technologies into energy systems, several objectives need to be balanced, taking into account economic, environmental and social outcomes. For this purpose, a thorough process of energy policy analysis needs to be carried out by regulators in order to find the best possible strategy for each country or state, and in this process, several models and tools for capacity expansion planning can play a key role. Motivated by this, the purpose of this paper is to provide a comprehensive review on the state-of-the-art of expansion planning models for energy policy analysis.

Among the innovative technologies driving the current energy transition, the most significant impact has yet been produced by renewable energy sources (RES), specially volatile RES, namely wind and solar power. However, much is expected from several other technologies and concepts that are already playing an important role, and which could account for substantial impacts in the future, such as multiple forms of energy storage devices, demand response mechanisms, local energy markets, cryptocurrencies, and multiple smart grid developments. In parallel, new policies are required to fight against climate change and address the impact on the reliability and security of the energy sector. Some examples include energy efficiency incentives, renewable portfolio standards, carbon capture and storage

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https://doi.org/10.1016/j.rser.2018.08.043
Received 19 October 2017; Received in revised form 18 July 2018; Accepted 23 August 2018

developments, and emission trading systems. In order to integrate all of these technologies and concepts into the energy system, several policy instruments can be employed to achieve desired goals and strike the right balance among multiple conflicting objectives. Further, understanding the potential impact of these technological and policy changes on the operation of the system and its long term development is of key interest to regulators, industry participants, researchers, and society as a whole.

In this context, long-term planning models for capacity expansion are very important tools for energy policy analysis. These models are employed to project the evolution of energy systems, handling large amounts of input and output data, possibly taking into consideration large geographic regions over long time horizons (e.g. 20 years or more) [84]. In fact, these models usually take into account investments in generation units, transmission investments, and some operational aspects. There are many factors that can affect energy systems in such long-term horizons, but overall, the purpose of these models is to understand the consequences and impacts of present investment and policy decisions in the evolution and performance of the system in the future. With this, when analyzing different energy strategies, policy makers can run expansion planning models under different conditions to assess the potential consequences of several possible decisions, to get insights about the effects of different policy instruments or potential technology developments on the system as a whole. Under these different scenarios, capacity expansion models can provide the optimal changes to the power system, and the expected path it will follow if electricity markets are efficient.

The high complexity of modern energy systems makes it very difficult to create highly representative models in long-term horizons. Thus, many expansion planning models with various attributes and focuses have been developed, with varying levels of detail on different specific aspects. The challenge is to address the aspects relevant for a given study with a proper level of depth, while maintaining a holistic view of the system as a whole, and keeping computational tractability [143]. In particular, tuning the time and space scales in an expansion planning model is critical. For example, if the volatility of RES is modeled with high temporal resolution, the computational burden is increased and the resulting optimization problems may not be solvable in a reasonable running time. Similarly, representing the transmission network with high detail may also result in large optimization problems, whereas a poor spatial representation may misrepresent transmission issues, such as transmission congestion. A similar trade-off is faced with uncertainty sources. Using stochastic models can provide robust solutions with respect to various uncertainties, but adding too much complexity in uncertainty representation might obscure the analysis for other aspects of the problem and tractability issues may emerge. Recent models also try to address the human dimension, which takes into account human behavior, indirect costs and socio-political barriers. However, these last factors are generally poorly understood. Given all of these complexities, there is a wide variety of expansion planning models that can be a tremendous support for the analysis of different energy policies, and understanding their subtleties is key to find the right model for each study or set of energy policy questions.

Several papers have carried out literature reviews on expansion planning models. For example, [76] and [107] provide extensive reviews on transmission expansion planning problems, while [75] provides a detailed review of generation and transmission expansion planning. Also, [39] and [59] cover different expansion planning tools with focus on RES integration, and [1] provides a review on expansion planning with focus on distributed energy resources. Also, several papers have carried out reviews on energy policy analysis. For example, [166] and [180] provide a thorough overview on the state-of-the-art in wind and solar energy policy, respectively, while [30] reviews a multitude of energy policy instruments and discusses their role in the overall innovation level of the energy sector. A detailed report on expansion models, its scopes and applications is presented in [57], covering European organizations which uses power system modelling tools. In [94], a framework to guide the selection of a planning model is presented, based on its suitability to perform policy oriented analysis for a given purpose.

In complement to previous works, the present paper provides a thorough and updated review on expansion planning models and tools, with focus on the key role that this field of knowledge plays in modern energy policy analysis. In contrast to previous works, this review emphasizes the role expansion planning models can play in the study of different energy policy instruments, whereas most of the previous reviews consider these areas rather separately. Further, another important contribution of this review paper is to provide an in-depth analysis of the trends in the literature and the energy transformations foreseen ahead, providing key discussions on several important challenges that will require new expansion planning models and energy policy insights, including topics such as distributed energy resources, demand response, local energy markets, agent-based simulations, and the resilience of energy systems, among others.

The remainder of this paper is organized as follows. Section 2 presents a review of policy instruments for renewable energy integration. Section 3 presents a review of expansion planning models and discussion on their potential for energy policy analysis. Section 4 compares several existing decision-support tools for energy policy analysis based on expansion planning models. Section 5 synthesizes and discusses the trends and challenges in the use and design of expansion planning models for energy policy analysis, and conclusions are drawn in Section 6.

2. Policy instruments for renewable energy integration

Renewable energy is a central pillar of sustainability. It is essential for the reduction of greenhouse gas emissions, and further, it enhances the technology diversification of the energy mix, which helps to hedge fuel price risks, it supports strengthening economic growth by creating jobs, and it is also key to facilitate access to electricity [52]. Given these attributes, several countries have employed a variety of different policy instruments to promote the development of renewable energy in its multiple forms.

Moreover, sustainability has become one of the most important objectives for policy makers. International agreements have been signed, such as the Paris Agreement in 2015 and the Kyoto Protocol in 1997, within the framework of the United Nations. These agreements have tried to limit worldwide greenhouse gas emissions, and among their consequences are big efforts to include RES into the grids of the world. At the same time, technological breakthroughs in manufacturing, material science and power electronics, have led solar and wind power technologies to expand significantly. A few years ago, their costs were much higher than the cost of conventional technologies, so external incentives were a must for these clean technologies to be incorporated into the power grid [187]. Thus, the design of *effective* (capability of achieving a goal that would not be achievable without it) and *efficient* (measured by the amount of intervention such as taxes and subsidies) incentive policies for the promotion of renewable energy became a major study subject [213].

In what follows, we provide a summary of the most prevalent policy instruments for renewable energy integration:

- **R&D funding.** These instruments consist of financial support to improve current electricity generation technologies, and to develop novel ways of using other resources in a sustainable way. Though funding policy has mostly shown a positive correlation with the penetration of RES [175], it has been argued that it does not show a positive correlation with energy efficiency improvements [208], and that it has not had a deep government support [123].
- **Tax credits and grants.** Investment and production tax credits, and cash grants, are measures that have been implemented by the US