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Model based approach for planning dynamic integration of renewable energy in a transitioning electricity system

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ABSTRACT

Reality of climate change threats have spurred mitigation interventions across the world. For electricity sector, the interventions are predominantly in terms of mainstreaming renewable energy sources. Consequently, there is a consistent increase in the share of renewable energy-based electricity systems which has caused emergence of several new challenges. The challenges have emerged both with respect to planning and management of the transitioning electricity systems. These new challenges are because of shift away from supply-chain influenced conventional energy resource supply to nature influenced dynamic renewable energy resource supply; shift from conventional firm power to renewable intermittent power; operational complexities due to frequent and steeper ramps; and need for matching dynamic demand for power. We propose, develop and validate a novel approach for better representation of these resource-supply-demand dynamics in evolving suite of generation expansion models with operational details. First, we discuss development of an electricity generation expansion planning model with operational details. Second, to model the dynamic nature of renewable energy resources and demand for power, we develop an approach for generating annual wind and solar resource profiles, and representative load curves respectively, and harmonizing them before they are fed into the generation expansion model. We validate this approach using India's electricity system data and use the model to evaluate implications of varying levels of renewable energy integration. We find that this increased penetration of renewable energy while bringing significant climate change benefits creates substantial capacity redundancy leading to lower capacity utilization of the overall system.

1. Introduction

Electricity is current of electrons maintained through a motive force extracted from energy gradients, i.e., wind, solar, hydro, combustion. And the electricity system operates by real time matching of demand and supply. On account of increasing demand and the retirement of existing capacity, decisions are made about deployment of new power generation capacities. These decisions involve selection of energy technologies from an entire gamut of different options. With advancements in science and technology, there are several technological options for supplying electricity to meet demand with either more efficient use of conventional fossil fuels or without using them at all [1–3]. Each power generation technology is characterized by a set of attributes and attribute values determine how generation technology contributes to or impacts technical, economic, social and environmental goals of electricity system, i.e., load (or demand), reserve margin and system externalities, e.g., emissions, water use. Every energy technology has significant benefits as well as costs [4]. Fossil fuel (coal and natural gas) based technologies are cheaper and reliable but emit more CO_2 and pollutants, which has implications for climate change and local pollution. In contrast, renewable energy sources such as solar and wind do not have operational emissions, but they are not always available due to fluctuations in their resource availability, i.e., solar insolation and wind respectively which gives rise to a situation where both demand and supply have prominent variations at short time scales [5]. The major transformation in electricity systems is a shift from resource planning and fuel procurement management influenced fossil fuel supply to renewable resource supply that is influenced by nature. Thus, a loss of human control over resources, i.e., renewable energy adds further challenges as well as complexity to planning this transformation. Consequent upon all these considerations of technical feasibility, reliability, availability of natural resources and emissions, generation technology evolution in the electricity space is a matter of intense scientific enquiry as well as public discourse [3,6–11].

There is an entire array of possible interventions for electricity system in transition which Lund, et al., (2015) in their review classify

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as: interventions on demand-side, network (i.e., transmission and distribution), supply-side (i.e., fossil and renewable), and, the electricity market [12]. They can also be categorized into – (i) time shifting of load and/or generation which helps in better matching of demand and supply: demand side management (responsive loads), coupling with other energy sectors, i.e., transportation, storage, smart grids (prosumers, i.e., electricity consumers who produce their own electricity at different points in time), and (ii) spatial aggregation through transmission network [13]. Out of all these aspects, in this paper we focus on electricity generation portfolio – which is expected to undergo an imminent and massive augmentation – with emphasis on dynamic integration of renewable energy into the expanding electricity generation capacity. Transmission and storage although important are beyond the consideration of this work. This emphasis is in view of the imminent climate change mitigation interventions which intend to move the system away from conventional fossil fuel-based power generation and seek a mainstream role for solar and wind energy dominated renewable energy systems. These in turn are expected to cause emergence of several new challenges as brought out in the subsequent sections.

In the following section we review the state of art identify the relevant open questions and issues, and, focus on contributions of this work relative to them. Underscoring the complexity and imminence of planning in an electricity system with significant renewable energy, which is a shift away from traditional supply-chain management decision making for securing supply of fossil fuels to depending on nature influenced uncertain renewable energy resource supply, this paper contributes to bridging the methodological gap by proposing an approach for better representation of renewable resource dynamics with in the evolving suite of generation expansion models with operational details for planning dynamic integration of renewable energy in transitioning electricity systems. The approach utilizes clustering algorithm on the time series data on electricity demand and resource availability for wind, hydro and solar to generate numeric inputs for the mathematical model.

2. Literature review

The solution to the problem of electricity system generation expansion lies in establishing the relationships amongst the generation options, availability of corresponding energy resources, electricity system feasibility, i.e., real time matching of demand and supply with additional requirement of reserves, financial resource requirements for exercising a particular choice of technological pathway and systemic implications of such a choice. As a first step these relationships must be established after which the problem essentially is to arrive at an optimal combination of technologies, which meet the electricity system feasibility requirements, has relatively higher input efficiency, and produces desirable outcomes in terms of sustainability. While developing roadmaps for 139 countries [14] have called for electrification of all energy sectors which provides context for researching generation expansion. About the first aspect, literature has recent instances of different electricity system network representation/configurations/specifications to account for and model the dynamics introduced by a changing technology landscape, i.e., variable renewable generation in particular [1,13,15–18]. As far as the second aspect is concerned, i.e., arriving at an optimal combination of technologies which meet the system feasibility requirement, generation expansion problem has been formulated with multiple objectives: cost minimization, revenue stream maximization, minimization of cost of non-access, minimization of emissions of CO_2 and N_2O and SO_2 [8,15,19,20].

Generation expansion planning models in literature typically deal with economic and environmental considerations. From a time horizon perspective, power system studies vary from hours to weeks, e.g., unit commitment, to multiple years as is the case with generation expansion models [21,22]. Beyond these conventional categories, Balachandra & Chandru [19] have emphasized on the need for another category of intermediate range tactical planning models by integration of the dynamics of demand variations to introduce the realism of operational planning with the perspective of strategic decision making to minimize cost of electricity supply demand matching. This was one of the earliest suggestions to move away from traditional load duration curve, towards inclusion of operational planning details with in the strategic decision making. More recently Palmintier & Webster [16] have demonstrated the need to include operational details which were conventionally dealt with in unit commitment models in the capacity expansion models to capture the intra hour dynamics introduced by integration of variable renewable electricity, i.e., frequent and bigger ramps, which has been corroborated by several researchers [23,24].

Balachandra [25] has analyzed the implications of private sector participation in capacity additions on public utility and consumers to show negative impacts of high guarantees offered to the private sector in terms of reduced utilization of both the existing and new public capacity and high consumer prices. In present context, similar issues about capacity utilization and consumer price, i.e., renewable integration causing conflict of capacity utilization between renewable capacity and conventional capacity and driving the cost up, are associated with integration of renewable energy [16,26]. It entails high flexibility requirements from conventional generators which has implications for their design to ensure safe operation [27]. These concerns around capturing the operational dynamics of renewable energy are relevant for several nation states where variable renewable electricity generation has been promoted through government initiatives in terms of setting ambitious targets [28] and several policy directives [8] like renewable purchase obligation, renewable energy certificates, and feed in tariffs.

To account for variable renewable electricity generation, which is expected to constitute the evolving generation technology pathway [12,28–30], there is a demonstrated need to include operational level details [19] and inter hour dynamics to capture the generator cycling behavior i.e., startups, minimum output levels in the conventional generation expansion planning models [6,16]. While generation expansion models with operational details have been evolving [16,31–34] degrees of freedom remain as to how electricity system components, i.e., temporal resolution, resource variability, technological operation etc. are represented within these models. There is a tradeoff between the planning time horizons (length) versus the operational details and within year temporal resolution that can be accounted for in a generation expansion model. This pose a significant modelling challenge and is a fertile ground for active research [9,24,35]. Researchers have made efforts to reduce the computational load and overcome intractability by implementing column generation approaches to [36,31] cover the specificity of contemporary efforts to deal with these issues and what they lack. For sake of brevity we don't repeat those findings here. They go on to present a multi-region, multi-period generation expansion model with realistic operational details and use one 24-h load curve for each month for each of 12 months across years with in their model [31,37]. In general, literature points to the lack of a nuanced study of operational regimes, spatial and temporal resolution with in generation expansion modelling in general [2,3,35] and specifically to lack of proper treatment of how temporal resolutions are determined and derivation of corresponding resource availability and demand profiles.

We deal with this issue and present an approach to systematically tackle the questions around how supply and demand are represented in generation expansion models and derivation of representative profiles used to study renewable integration in power systems. This study contributes to the new body of knowledge by underscoring the need for systematic representation of supply and demand variations, and, capacity utilization in generation expansion models which is followed by proposition and implementation of methods for the same which includes obtaining load profiles from aggregate projections and harmonizing the extracted representative loads and resource profiles to ensure