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Renewable integration through transmission network expansion planning under uncertainty

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ABSTRACT

In this paper we bring together a stochastic mixed integer programming model for transmission network expansion planning, incorporating portfolios of real options to address the evolution in time of uncertain parameters, with the adjusted generalized log-transformed model, to expand the number of correlated parameters that can be modeled. We apply these methods to evaluate the potential contribution of underwater transmission investments to increase renewables penetration in the Azores archipelago. The approach also includes expansion lead times, due to the large timespans involved in the construction of new transmission lines. Our analysis focuses on a set of the four closest islands in the archipelago, Pico, Faial, S. Jorge and Terceira, and shows that even though investments are delayed and the future network configuration varies according to the evolution of renewable generation scenarios, an investment in underwater transmission, if technically feasible, within the assumptions of our model, could in fact contribute to increase renewables penetration, by enabling islands with an excess in generation from renewable sources to supply other islands in a deficit situation.

1. Introduction

Contemporary societies are highly dynamic, constantly challenging their energy infrastructures and requiring adjustments in generation and transmission networks. Electricity demand often exhibits significant shifts, driven by factors such as population dynamics or consumer habit changes. The evolution of supply, in turn, greatly depends on aspects such as available generation capacity, alternatives for expansion, costs of generation technology, or environmental concerns. In this sense, the transmission system seeks to optimally satisfy consumers by allowing demand to be reliably fulfilled at a minimum generation cost.

The prosecution of this goal periodically leads to the identification of beneficial investments in transmission lines, but these infrastructure developments cannot be viewed simplistically as commitments in static contexts. Decisions on the timing, scale, location and type of capacity expansions need to consider how to best adjust to uncertainty [1], as they usually involve significant irreversible investment costs, feature initial long lead times related to construction, and then typically face uncertain circumstances to unfold throughout their long lifetimes. The ability to perform well under diverse and changing circumstances is thus a key requirement for transmission networks, and one that can best be addressed when sources of flexibility, i.e., real options [2], are explicitly considered in long-term planning.

Engineering practice is typically focused on designing for specifications. From a traditional risk-management perspective, a project is seen as successful if it complies with expectations defined beforehand. This view, however, is myopic as it takes risk merely as the probable occurrence of negative outcomes, thus capping specifications to escape uncertainty and neglecting potential value from overdesign. In large-scale projects, such as electricity transmission networks, the magnitude of these uncertain costs and benefits can be significant, and their public impact considerable. Therefore, engineering systems design should take a more holistic view of risk, which is common in finance, not only considering the chance of downsides, but also weighing in the positive outcomes that may result from exposure to risk.

Considering the previously described limitations, portfolios of real options emerge as a relevant approach to analyse investments in a transmission network [3] defines portfolios of real options as "*combinations of multiple assets and multiple real options written on these assets subject to constraints*". Applying this definition to the transmission investment problem, the transmission lines are the multiple risky assets,

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the flexibility in the investments and in the use of the transmission lines translates to the multiple real options, and the physical characteristics of the network, influencing power flows and losses, establish the constraints.

In this paper, we adopt the perspective of a single Transmission System Operator (TSO) facing generation capacity uncertainty in a regulated context, with the ability to choose a single set of expansion decisions in the present, and contingency expansion decision plans for the future, considering potential alternative unfoldings of events. This is achieved by studying different future possible scenarios based on the evolution of uncertain parameters, and by using a decision process that weighs the consequences of decisions based on the probabilities of occurrence of the scenarios. This decision structure differs from the majority of current multi-stage models, whose outcome is a static investment plan, as in the case of Monte Carlo simulation-based approaches, which often consider multiple scenarios, but a single sequence of decisions.

We extend the work previously reported in [4] with a stochastic mixed integer linear programming (MILP) model for transmission planning, consisting of an expansion of an earlier single-stage model [5] to a multi-period setting, using portfolios of real options [3], and including contributions from capacity expansion [6] and transportation network design [7] research. Driven by practical concerns, we now extend that work to include a higher number of stochastic parameters using the Adjusted Generalized Log-Transformed method [8], which allows us to increase the number of stochastic parameters to more than two. Moreover, we incorporate expansion lead times in the model to address the significant timespans involved in the construction of new transmission lines.

We apply this improved model to the analysis of transmission expansion in the Azores archipelago, in the scope of its efforts to reduce dependency on fossil fuels. The Regional Government of the nine-island archipelago, located off the Portuguese coast towards the middle of the Atlantic, has defined a goal of 75% for electricity generation based on renewable sources, to be achieved by 2018 [9]. However, the renewable potential differs among islands, leading to energy imbalances. While some remain in deficit, others not only will be self-sufficient, but in fact have the capacity to generate a surplus. Thus, this surplus could be used to improve the overall utilization of renewable electricity in the archipelago, if the excess power could be transferred between islands. This paper contributes to the existing literature by presenting:

1. An application of AGLT to TNEP under uncertainty using portfolios of real options to model a higher number of uncertainty correlated parameters,
2. A study of renewables penetration improvement based on transmission network expansions, considering sensitivity analyses of uncertainty parameters.

The paper is organized as follows: Section 2 presents a review of prior literature on electricity transmission network expansion planning; Section 3 describes the methodology used; Section 4 introduces the case of the Azores islands and describes the data; Section 5 presents the results of the numerical study and sensitivity analyses; Section 6 closes the paper with conclusions and future work perspectives.

2. Literature review

It has long been asserted that transmission system expansion is a key enabler of renewable energy integration [10]. Much work in this field has focused on expanding transmission networks to remote areas with substantial renewable resources. The National Renewable Energy Laboratory's (NREL) four-year study on wind integration in the United States Eastern Interconnection found that high penetrations of wind power (20–30% of demand) require significant investment in new transmission capacity [11]. A similar massive modeling effort was commissioned by the European Union around the same time, and carried out by the EU transmission system operators [12]. The European Wind Integration Study identified 150 transmission projects within the EU that would be needed, to support wind integration. Out of that number, 35 projects were identified as essential for the sole purpose of integrating renewable energy into the EU power system (as opposed to congestion management) [13].

Few studies, however, have used optimal transmission network expansion planning (TNEP) models to validate its relation to increased renewable energy production. Recently, several authors have included various uncertainties facing transmission planners into their optimal TNEP problem. For example [14], model a game between the transmission planners and the generating firms, considering uncertainties and the possibility to delay investments. They conclude that optimal transmission plans change dramatically when uncertainty is ignored. For a stylized case study of the Great Britian transmission system, they show that the cost of ignoring uncertainty ranges from 4 million pounds sterling to 111 million. In a similar vein [15], add the cost of uncertainty with wind power production using a reserve market constraint and show the effect wind uncertainty has on the transmission expansions. Both studies, however, assume the addition of new renewable generation capacity. To the best of the authors' knowledge, this study is the first to demonstrate that transmission expansion itself increases renewable production in the power system, with neither specific regulation requiring this, nor new renewable generation investments.

Currently, wind is considered the most cost-effective source of renewable energy and with the least greenhouse gas emissions, but also the one with most variable output [16]. This volatility introduces complexity into modeling optimal integration of renewable energy into the electricity system, particularly when also considering optimal expansion of the transmission system. Uncertainty in renewable power generation is typically included in power system modeling via historical production information [17,10], with generation predictions on an hourly timescale. Less common is an annual capacity factor approach to approximate renewable energy production [18]. In this paper, we adopt a novel approach for inclusion of renewable generation uncertainty as an aggregated stochastic process. To the best of the authors' knowledge, this representation of renewable generation uncertainty has not been used before in transmission expansion planning, though a recent paper on optimal, short-term dispatch adopts a similar uncertainty representation [19].

Transmission Network Expansion Planning (TNEP) is a class of problems concerned with the identification of optimal decisions on the size, time, location and type of transmission line investments (construction or upgrade), considering the physics of power flows as well as relevant economic aspects, in varying degrees of complexity as suitable to the envisaged applications. TNEP literature is reviewed in [20] and [21] but both reviews fall short in the categorization of uncertainty, namely in considering investment decisions with a contingency plan. Within the present section we argue in favor of models with these characteristics.

Traditional approaches to solve TNEP addressed network expansion decisions in static settings, aiming at removing overloads [22] or reducing them to meet an acceptable minimum reliability threshold [23]. To facilitate optimization, reliability has, in some approaches, been substituted by load curtailment costs [24]. Load curtailment can be viewed as the amount of energy demand that the network will not be able to satisfy, and its costs can be viewed as monetized social costs for under-design. On the other hand, a higher accuracy in the calculation of power flows has been achieved with the inclusion of transmission losses [25].

Another line of research has focused on dynamic settings, extending the above-mentioned approaches to address the evolution of TNEP parameters in time and considering the possibility of postponing expansions, in multi-period versions of TNEP. An early contribution by [26] featured continuous investment variables, constrained only by Kirchhoff's current law. More recent contributions in this line of work are [27–29].