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Systems capacity expansion planning: Novel approach for environmental and energy policy change analysis

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ABSTRACT

Planning for power systems generation expansion follows environmental policies incorporating technologies based on renewables to reduce CO_2 emissions. These policies are susceptible to unpredictable changes, given dynamic economic and political contexts. This paper analyzes the impact of changes in energy policies, motivated by different environmental objectives. The analysis is done through a novel approach coupling Dynamic Programming and Multi-objective programming to generate several energy policy scenarios and their trade-offs, representing plausible policy changes in the different stages of the planning horizon. The results indicate a clear Pareto front and that energy policy scenarios with abrupt changes should be avoided in favor of scenarios with gradual changes. "Greener" energy policies in a given planning stage are not necessarily the best ones considering the full planning horizon, considering the unfolding impacts of current decisions into the future. The approach is useful in improving planners' future vision from myopic into a perspicacious one.

1. Introduction

Advances in technology change the way we produce, use and allocate resources, especially energy and water. For example, desalination plants have long been incorporated into water supply systems, while photovoltaic and wind plants are now part of power systems. Integrating renewable power sources into power grids is a common agenda worldwide given concerns regarding CO_2 emissions and climate change, resulting in the adoption of low-carbon technologies (Iyer et al., 2015). However, economic growth policies still drive national plans, and the occurrence of financial crises, global markets, and economy volatility, among other factors, draw a complex environment for planning. Decision-making must take into account uncertainty and the added complexity that may motivate policy change (Schwenker and Wulf, 2013). While one cannot be sure about the future, it is possible to evaluate how to best adapt current policies as our perception, priorities and knowledge change. The methodology proposed in this paper fulfills this goal.

Capacity expansion methodology is applied in planning for different public services including electrical power, water resources, schools, and roads, given most of those systems already exist. The main objective of capacity expansion is to determine the size and timing of facilities to be added at minimal costs (Luss, 1982). It might also require consideration of other objectives like minimizing emissions of greenhouse gas effects and the incorporation of renewables. All in a highly uncertain environment.

For power generation expansion planning, Dynamic Programming (DP) approaches have been widely applied, among other methods including stochastic optimization, genetic algorithm (GA), fuzzy set theory, artificial neural networks, network flows and simulated annealing (Kagiannas et al., 2004). When other objectives need to be included, the problem can be addressed with multi-objective optimization, (e.g. multi-objective linear programming - MOLP), stochastic optimization, multi-criteria analysis, decision analysis and tradeoff analysis (Tekiner et al., 2010). Uncertainties have been included by focusing on demand (Davis et al., 1987), demand and resources availability (Gorenstin et al., 1993), demand and price parameters (Ahmed et al., 2003). Li et al. (2014) studied policies in generation expansion planning, including renewables as constraints with a minimum percentage. Popular incentive systems as feed-in tariffs, quota obligation, emission trade and carbon tax can also be incorporated as constraints (Careri et al. (2011). Rebennack (2014) included fulfillment of emissions quotas as an objective, while Aghaei et al. (2013); Tekiner et al.

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(2010) had minimization of CO_2 emissions as an additional objective function. Most recent efforts consider the inclusion of modeling high quantities of renewable generation (Vithayasrichareon et al., 2015). The methodology in the later applies generation portfolio analysis concepts to account for risk and uncertainties of gas and carbon prices. The role of coal, gas, and renewables is analyzed for peak demand in future (2030) generation portfolios in the Australian Power System.

The inclusion of policy uncertainty in recent literature about power systems expansion is still limited. Most of the work in environmental policy evaluates causal effects of policies implemented by governments and authorities in terms of achieving outcomes of interest (Percoco, 2014). In planning expansion capacity, Zhou et al. (2011) investigate an optimization approach to design incentive policy for investment in renewable energy in generation expansion planning. Zhou et al. (2013) apply a planning approach associated with a fractal-based robust methodology for environmental policy analysis.

When policy uncertainty is investigated, it often focuses on financial research and the influence of government policy changes over stock prices. As in Pástor and Veronesi (2012), who define two types of uncertainties: political uncertainty that relates to uncertainty about whether the current government policy will change; and impact uncertainty, corresponding to uncertainty about the potential impact of new government policy on the profitability of the private sector.

Some examples of environmental policy effectiveness and the impact related to renewable energy portfolios and others to climate policies such as taxation on fossil fuels are highlighted through the "green paradox" concept, put forth by Sinn (2012). Li (2014) warns about the undesirable effects of climate policies and the need for their improved design. Since climate policies are subject to uncertainty, they become vulnerable to changes.

Germany, one of the European countries that have adopted policies for deploying low-carbon technologies, has more than doubled its renewable energy sources between 2000 and 2009, where the wind power is the most important (Reuter et al. (2012). However, implementation of such policies has a cost. In 2013, it was estimated that an amount of US$120 billion was spent in global subsidies for renewable energy technologies (IEA, 2014). Recently the UK has announced an earlier end to subsidies for new on-shore wind farms (BBC News, 2015). Australia's prime minister banned the federal clean energy from investing in wind power (Schlanger, 2015). While reasons behind these policy changes are beyond the scope of this paper, they indicate how policies are subject to change.

If policies change during the planning process, adjustments are necessary to prevent the plan from becoming obsolete. This fact may tempt politicians to opt for broader indicative strategies that may not give clarity or certainty about other interests, as highlighted by Parker and Doak (2012). It will be useful for planners, managers and decision makers to understand in advance the possible impacts of the policy they intend to change on the main plan's effectiveness.

This paper presents an approach for analyzing such impacts, using a combination of multi-objective optimization (MOLP) and dynamic programming (DP), applied to the power capacity expansion problem. Our approach considers specific policy changes at different stages of the time horizon plan and their outcome in terms of cost, CO_2 emissions and decisions to invest in different power sources. The approach generates a Pareto diagram with multiple possible policy change scenarios. To illustrate the methodology, a simplified planning generation capacity expansion is presented, where policy change scenarios have been analyzed and classified.

This paper contributes to the existing body of knowledge by introducing a novel approach to evaluate how a given change on "*energy policy*" may affect the final outcome in terms of cost and CO_2 emissions. While change may be unavoidable giving uncertain exogenous factors, how it is conducted may yield different trade-offs. The methodology proposed in this paper is designed to identify dominated, undesirable trade-offs, so the decision maker can focus on the best ones (at the Pareto frontier) when faced with necessary changes. The proposed methodology couples DP and MOLP to solve a multi-objective optimization problem in expansion capacity, classifying policy changes according to its impact on the optimal power expansion strategy. This illustrates that not all logical policy changes will deliver the expected results.

The remainder of this paper is organized as follows: Section 2 presents the proposed approach. Section 3 describes an application through a hypothetical planning generation capacity expansion. Section 4 shows the results of the application for different scenarios. Finally, in section 5 the conclusions are presented.

2. Proposed approach

The methodology proposed here analyzes energy policy changes and its effect through the planning time horizon over the generation capacity expansion in terms of costs, CO_2 emissions and mix of selected energy generation sources, considering:

a) Technologies that use different natural resources.
b) Intermediate decisions about the selection of technologies that will affect the final planning objectives.
c) Policies that could change from one stage to another during the planning process, which are the basis for technology decisions.
d) The leading objective of capacity expansion is fixed at the beginning of the process.

This approach is based on Bellman's Principle of Optimality, summarized by Lew and Mauch (2007) as "optimal policies have optimal sub-policies." The capacity expansion problem will be optimized with a policy of minimum costs ("*leading policy*"), with sub-problems divided into stages and solved using Dynamic programming (DP) for capacity expansion methodology.

In the capacity expansion problem, a possible total incremental capacity is represented by the decision variable x. For each possible x in a given DP stage, there are multiple combinations of individual power sources r that add up to x. A multi-objective linear programming algorithm − MOLP is run at each DP stage to optimize the values of r considering two objectives: minimize cost and minimize CO_2 emissions. The MOLP is constrained so that the sum of all r is equal to x. Given the two objectives, MOLP produces a Pareto front indicating the trade-offs (Meza et al., 2007) for each possible x, at each DP stage. Each point in the Pareto front is a combination of r values resulting in a given cost and a given CO_2 emission. The points also receive a label indicating the level of preference among the two objectives (e.g. a point with high cost and low CO_2 emission indicates a stronger preference towards environmental protection).

The question now is which point (i.e. combination of r values) should be selected so the DP can move to the next stage. To answer this, we first define "*energy policy*" as the level of preference between the two objectives behind a given point in the Pareto front. For example, a strongly environmental energy policy means a point at the far right of a given Pareto front (low CO_2 emission, high cost). We also define a "*change in the energy policy*" when the level of preference between the two objectives changes from one DP stage to the next. However, when and how the preferences (and the