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Robustness methodology to aid multiobjective decision making in the electricity generation capacity expansion problem to minimize cost and water withdrawal

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HIGHLIGHTS

- Power generation expansion and technology selection to minimize cost and water use.
- Capacities of power plants are subjected to uncertainty at the time of construction.
- Methodology finds robust solutions in view of objective value losses and feasibility.
- Robustness as secondary criteria facilitates multiobjective decision making.
- Case study illustrates how the methodology may provide insights for decision making.

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ABSTRACT

This paper deals with the electricity generation capacity expansion problem to minimize cost and water withdrawal. Each solution prescribes locations and technologies for new power plants, and their designed capacities. A two-stage methodology is proposed to aid decision making by identifying the few alternatives from the many efficient solutions that are robust to uncertainties. The first stage finds solutions that are efficient in view of cost and water withdrawal objectives. The second stage finds the subset of first-stage solutions that are robust when the designed capacities of power plants are subjected to uncertainties at the time of their construction. The methodology is applied in a case study for the electrical grid in Texas, USA. The trade-off among technologies and locations, and the effect of uncertainty are considered to answer strategic questions for expansion planning. Experimental results suggest that the methodology prescribes locations, capacities and type of technologies for new power plants in Texas that tend to maintain their prescribed values of cost and water withdrawal when facing unforeseen implementation conditions, while satisfying the required generation capacity.

1. Introduction

Several studies have shown the degree of dependency of electricity generation on water availability [1–4]. Water is intensively used for cooling processes in thermal power plants, such as in natural gas and coal-fired facilities. Approximately 40% of total freshwater withdrawals in the U.S. are used in thermoelectric power plants and water scarcity is a cause of concern for power grid operators. During the 2011 drought in Texas, a heat wave caused demand for electricity to reach historic levels, while less than half of the water supply was available due to the drought. In some cases, water had to be diverted from farm areas. Some facilities had to reduce operations during night so that the necessary water would be available for operation during the day, when demand would reach its peak [5,6]. Despite the connections between water and electricity generation, to the best of our knowledge, this is the first study to consider the minimization of both cost and water usage in the capacity expansion problem. While conventional technologies, such as coal and natural gas, may contribute towards minimizing the electricity generation cost, renewable technologies, such as wind and solar, play an important role in minimizing water usage, in particular within locations where droughts are more severe. Hence, the trade-off between cost and water usage should

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be analyzed in view of the many available technologies and locations for capacity expansion.

The consideration of uncertainty is fundamental to this paper; for instance, at the time of building the power plants, uncertain events or situations not considered in the optimization model may occur (e.g. changes in regulation and environmental policies, access to limited financing resources, unexpected land availability or environmental changes, etc.) forcing those power plants to be built with capacities different to the ones prescribed by the optimization model, which in turn force design revisions to make the altered system operable under the new capacities. This example illustrates how systems may be implemented somewhat different to how they were originally prescribed by an optimization model. This study considers the uncertainty affecting the designed capacities of the power plants at the time of implementation; this is here referred to as "implementation uncertainty". In the previous example, one would consider a solution to be robust if the final power plant capacities yield a total cost and water withdrawal close to the values previously prescribed by the optimization model; furthermore, assuming that small constraint violations associated with a solution not meeting the total demand require minor system design modifications, the solution could also be considered robust if it is almost feasible under the final off-target capacities. Arguably, this issue may be avoided by increasing the fidelity of the model; however, in most real-life problems model fidelity will be limited by the complexity of the mathematical formulation, time constraints, availability and accuracy of modeling information, among other factors.

Motivated by the need to protect against implementation uncertainty and the challenges associated with having to trade off from a large number of available solutions, this paper presents a two-stage robustness methodology. The first stage considers the biobjective optimization problem to minimize cost and water withdrawal and finds the corresponding set of efficient solutions. Each solution prescribes a set of locations and technologies for new power plants, and their designed capacities. The second stage considers the problem of finding the few efficient solutions that tend to maintain feasibility and their prescribed cost and water withdrawal objective values in the face of unforeseen deviations of their specified capacities at the time of implementation. A novelty of the methodology is that the modeling of uncertainty presented here is not conflictive with models considering problem data uncertainty. In fact, data uncertainty may be taken into account when solving the first stage problem; this is illustrated in a numerical experiment in Section 6. In the two-stage methodology, hedging against implementation uncertainty would be considered hierarchically secondary with respect to solving the first stage problem, hence providing the decision maker with additional criteria to break ties among many combinations of technologies and locations for the new power plants.

The theoretical contributions of this paper indicate the relevance of the methodology for practical purposes; specifically, sufficient conditions are developed to show when the set of robust locations and technologies will be unaffected by the level of uncertainty. Furthermore, the practitioner may apply the methodology even in situations when he/she has no knowledge about the range of uncertainty, circumventing limitations of traditional optimization techniques that hedge against uncertainty, such as stochastic programming [7] and robust optimization [8,9].

The applicability of the two-stage methodology is illustrated in the context of the electrical grid in Texas, USA, to demonstrate how it could be used to answer strategic questions related to the tradeoff among the different technologies and locations, and the effect of uncertainty for long-term capacity expansion. In addition to the strategic importance of water, the consideration of Texas is convenient since its electrical grid is confined to the State and it is managed by a since agency (i.e. ERCOT). Results show that a plan purely based on minimizing cost, as well as other common sense approaches for selecting an alternative, may lead to solutions that are highly affected by uncertainties. In contrast, the methodology breaks ties among the many alternatives and focus decision making on technologies and locations for new power plants in Texas that tend to maintain their prescribed values of cost and water withdrawal, and satisfy the required generation capacity in face of unforeseen conditions.

The remainder of this paper is organized as follows. Section 2 discusses the related literature on the electricity generation capacity expansion problem. Section 3 provides the relevant background on multiobjective optimization and robustness. Section 4 introduces the model and problem formulation. Section 5 describes the robustness assessment methodology. Section 6 shows the experimental analysis applied in the case of Texas, while Section 7 provides concluding remarks.

2. The electricity generation capacity expansion problem

The electricity generation capacity expansion problem considers a regional power generation system where electricity can be generated using conventional and/or renewable technologies. Because of growing demand for electricity, power grid operators must consider the planning of new power plants for capacity expansion [10]. Given a set of potential locations for new power plants and available technologies to choose from, the electricity generation capacity expansion problem is defined as the optimization problem to find new facilities needed, their location, the type of technology to use in each location, and the corresponding design capacity to satisfy the given forecasted loads (i.e. capacity expansion). Although not considered in this paper, the problem could also deal with cases where existing power plants are planned to be retired due to environmental regulations and the availability of newer, more efficient, and cleaner substitute technologies. In this case, the existing capacity from the power plant scheduled to be retired would be included in the total required capacity expansion.

The literature on the problem is vast. Earlier studies mainly focused on single objective optimization models to minimize total cost for the required expansion [11–15]. More recently, studies have also considered the minimization of greenhouse gas emissions incurred from the capacity expansion [10,16–19]. Few studies have considered water requirements when addressing the capacity expansion problem [20], albeit without considering cost objectives. Novel to this paper is the consideration of a two-stage optimization approach, using cost and water withdrawal as the main criteria in the first stage, and measures of robustness as criteria in the second stage. Details of the problem formulation are made precise later in this paper.

The related studies have tackled uncertainty in different ways. In [13,21], demand for electricity was assumed to be uncertain, given by a discrete set of scenarios. The authors solved the problem using stochastic and robust optimization techniques, respectively. Solving such large-scale problems is typically challenging due to the exponential number of possible scenarios of uncertainty. Techniques for generating only a representative set of scenarios are explored in [22]. In [23], future fuel prices were also assumed to be uncertain, and the problem was modeled as a two-stage stochastic mixed-integer program to minimize the expected cost and the conditional value-at-risk. In [24], a time-dependent objective function maximizes the net present value of the capacity expansion and fuel prices are assumed to follow a random walk process. In [18], a simulation model was used to obtain operation patterns of the new power plants prescribed by an optimization