Using optimization models for long-term planning: an overview of the limitations in representing market designs, policy interventions and agent behavior

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Overview

Before the liberalization and deregulation of the electricity markets, state-owned or regulated utilities faced the problem of determining a long-term investment plan which minimized total cost of energy provision (or maximized social welfare). To this end, optimization models were developed and extensively used. Since the liberalization and deregulation of the electricity markets, investments in generation capacity are made by private generation companies. In this regard, the role of power-system planning has changed from determining the optimal investment decisions to steering of the market outcome in the desired direction [1].

Despite this changing context, optimization models have remained to be the most popular tools for long-term planning [2]. Optimization models can now be used for two distinct purposes. A first is to determine the decisions which would be optimal from a societal perspective (i.e., a normative/prescriptive perspective is taken). A second is to analyze the expected outcome of the markets (i.e., a descriptive perspective is taken). The latter perspective is taken in most of the well-known planning models such as NREL's ReEDS model, and is the focus in this work.

To compute the equilibrium, optimization models rely on maximizing total surplus. This approach is based on certain inherent assumptions including the assumption of price-taking agents. This prevents the use of optimization models to compute the equilibrium when agents might exercise market power. To this end, other types of models, such as mixed complementarity problems (MCPs), and multi-level models are better suited [3]. While the inherent assumption of perfectly competitive (i.e., price-taking) agents in optimization models is well known, there are other, less commonly known, limitations which restrict the use of optimization models for computing the market equilibrium. More specifically, certain market designs, policy interventions or behavioral assumptions of agents cannot be represented in optimization models. To the best of our knowledge, there is no general overview of these limitations and the corresponding implications for simulating deregulated markets.

This contribution aims to (i) provide an overview of the limitations of using optimization models to compute the equilibria in competitive electricity markets and (ii) illustrate these theoretical limitations by presenting topical and representative equilibrium problems which cannot be solved directly using optimization models.

Methods

The background on the relation between surplus maximization and determining the equilibrium is addressed based on a literature study. In terms of modeling, two distinct models which can be used to solve an equilibrium problem, namely optimization models and MCPs are compared. From a theoretical analysis based on these models (deploying operations research), conditions can be derived for which an equilibrium problem cannot be formulated and solved directly using an optimization model. A number of representative equilibrium problems which require MCPs or other solution techniques is used to illustrate these limitations.

Results

We show that there are two main sources of limitations of optimization models: a first related to the duality theory and a second related to the integrability of demand (and/or supply) functions.

To determine the total surplus, optimization models need to determine the consumer value by integrating the inverse demand functions. However, asymmetric inverse demand functions are not integrable, and hence, optimization models cannot be used to compute the equilibrium whenever there are asymmetric inverse demand functions. This asymmetry originates from the cross-price elasticities between the different inverse demand functions. This restriction prevents from using many of the econometrically determined inverse demand functions, as these functions are rarely symmetric.

Due to the duality theory, optimization models cannot distinguish between physical or political constraints (e.g., the balance between generation and consumption of electricity, a target for the share of electricity generated from renewable energy sources) and the remuneration in the markets which are implicitly formed around these constraints. As such, all variables, and only those variables contributing to meeting these constraints (either positively or negatively) are valued using the corresponding unique price.

In the full contribution, we provide a number of topical and representative examples where duality prevents from modelling certain market designs (e.g., net metering for residential consumers), policy interventions (e.g., green certificate scheme with minimum price, free allocation of emission allowances to new plants) and assumptions regarding the behavior of agents (e.g., heterogeneous costs of capital).

Here, we elaborate on a single example focusing on the introduction of a scheme for green certificates where a minimum price is imposed. In this scheme, generators receive certificates for each unit of electricity generated using renewable energy sources and suppliers are obliged to present a number of these certificates for each unit of electricity supplied to consumers. This creates a market for green certificates. The generators have the option to sell their certificates directly to the suppliers at the market price, or sell their certificates to the distribution system operator (DSO) which is obliged to buy the certificates at a certain minimum price (the DSO will subsequently sell the certificates to the suppliers at the market price). In this problem, one variable represents the sales of certificates from the generator to the supplier and one variable represents the sales of certificates from the generator to the DSO. Furthermore, a constraint needs to be introduced which enforces that the total amount of certificates sold by the generators is sufficient to cover the obligations of the suppliers. This constraint comprises both variables described above and hence, implicitly assumes that both the sales of certificates to the supplier and the sales of certificates to the DSO are remunerated at the market price. Hence, an optimization model cannot represent the minimum price for certificates while at the same time ensuring that sufficient certificates will be generated.

Conclusions

Power-system planning models typically rely on optimization. Aside from restricting the analysis to competitive markets, this does not allow to model certain market distortions. These distortions can relate to the market design, policy interventions or the behavior of agents. We provide an overview of the limitations of optimization models and provided certain topical examples of equilibrium problems where other solution techniques, such as MCPs, are required.

References

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