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Renewable-based generation expansion under a green certificate market

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ABSTRACT

Quota obligations represent a policy instrument to reduce carbon emissions and incentivize renewable-based electricity generation. This support scheme places an obligation on generating companies to comply with a quota of renewable-based production. Eligible renewable units receive one certificate for each MWh, while fossil-based generating companies must buy certificates to comply with the requirement. This paper proposes a family of generation expansion models that include both an electricity and a certificate market to investigate to which degree a given quota obligation and non-compliance penalty incentivize the capacity expansion of renewable-based generation. Two market players are considered, namely, a renewable-based generating company with null operating cost and a weather-dependent capacity factor; and a fossil-based generating company with a fixed capacity and known fuel cost function. First, a complementarity model that determines the optimal capacity of the renewable-based producer considering a perfectly competitive market is proposed. Next, market players are assumed to compete in quantities à la Cournot to maximize their profits, being the generation expansion model formulated as a mathematical problem with equilibrium constraints. The relevance of properly setting the non-compliance penalty for each level of competition to comply with a given quota obligation is quantified and discussed using an stylized example.

1. Introduction and motivation

Renewable energy sources, such as wind and solar, have a huge potential to satisfy future electricity demand while reducing greenhouse gas emissions. Yet their stochastic weather-dependent production and high capital costs keep renewable energy sources from being fully competitive in the current marketplace [1,2]. In order to overcome these barriers, most countries with ambitious sustainable targets have recognized the need for environmental policies that promote the development of renewable-based electricity generation [2,3]. In fact, the European Commission acknowledges in Ref. [4] that "Energy markets alone cannot deliver the desired level of renewables in the EU, meaning that national support schemes may be needed to overcome this market failure and spur increased investment in renewable energy".

Support schemes for renewable energy sources are classified into price-based and quantity-based measures depending on whether the government set the price or the volume of a given policy, respectively [5–8]. Feed-in tariff (FIT) is a price-based policy under which electric utilities are obliged to purchase the electricity produced by renewable energy sources at a tariff decided by the government and guaranteed for a specific period of time, usually of several years. Renewable portfolio standard (RPS), also known as quota obligations, combined with tradable green certificates (TGC) is a quantity-based support scheme through which a fixed quota of the electricity sold by suppliers has to be produced from renewable energy. Tradable green certificates are used to track and verify the compliance as follows. Qualified renewable electricity producers obtain one green certificate for each unit of generated power. The excess of certificates of renewable electricity producers can then be purchased in the certificate market by non-renewable producers to comply with the established quota and avoid a non-compliance fine.

Both feed-in tariff and quota obligations are support schemes widely used in European member states [8–10]. As of 2012, feed-in tariff was used in Austria, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Lithuania, Luxembourg, Latvia, Malta, Netherlands, Portugal, Spain, Slovenia, Slovakia and UK to support some kind of

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renewable energy source technology. Likewise, Belgium, Italy, Norway, Poland, Romania, Sweden and UK employed quota obligations and green certificates to comply with their national environmental targets. Similarly, reference [11] provides insight into the policy factors driving wind power development in the United States. Finally, the interested reader can check [12] for a worldwide overview of support schemes for renewables.

Although several works in the technical literature investigate, either from a theoretical or empirical perspective, the effectiveness of different support schemes in promoting the integration of renewable-based electricity production into current power systems [13–18], there is not a unanimous answer to this question. In this paper, we particularly focus on the effects of a quota obligation and a green certificate market on the capacity expansion decisions of renewable energy power producers.

Several works investigate the consequences of implementing a certificate market as a mechanism to further integrate renewable electricity production into current power systems, which we classify into two groups. In the first group we include the models in which generation capacity constraints are disregarded and thus focus on the impact of green certificates on operation decisions of market players [15,18–21]. Conversely, the second group encompasses those studies that also analyze the influence of green certificates on capacity expansion decisions [2,14,16,22–25].

Within the first group, reference [20] studies the interactions between the power and certificate market and its effects on price and consumption through a deterministic model that assumes a perfectly competitive market. Also under the assumption of perfect competition, the model proposed in Ref. [21] is used to analyze how the design of green certificate markets impact the distribution of costs across several countries. Authors of [18] consider a monopoly framework in which a unique firm in the market produces two kinds of energy (renewable and depletable) and compare the effects of FIT and RPS on produced quantities, market prices and social welfare. The work presented in Ref. [15] compares the performances of FIT and RPS in an imperfect electricity market in which players behave strategically to maximize profit. Reference [19] develops dominant firm-competitive fringe models to investigate how market power impact certificates and electricity prices. It is also worth mentioning that the results and conclusions in Refs. [15,19] rely on the assumption that marginal costs of renewable generation are much higher than those of conventional fossil-based generation. Finally, even though most countries with quota obligations apply a non-compliance penalty that effectively sets a ceiling on certificate prices [8], this feature is not accounted for in any of the above mentioned works.

Among the works that investigate the impact of certificates on capacity investment decisions, references [16,22,26] assume exogenous power and certificates prices and thus disregard the impact of capacity decisions on market outcomes. Authors of [22] present a multi-year generation expansion planning model that accounts for constraints on energy balance, renewable energy quotas and CO_2 emissions and assumes known energy market prices, fuel costs and regulatory policies. A similar model is proposed in Ref. [16] to analyze the impact of some of the most popular support schemes for renewables (namely feed-in tariffs, quota obligation, emission trade, and carbon tax) on generation planning decisions. Reference [26] adopts a real options approach to compute investment timing and capacity decisions for renewable power generation under different support schemes, namely, feed-in tariffs and renewable energy certificate trading.

Conversely, authors of [23] do account for the impact of capacity expansion decisions on market outcomes through a static equilibrium model that assumes a perfectly competitive market and incorporates both green certificates and CO_2 emission permits. Also under a perfect competition hypothesis, reference [24] develops a mathematical model to describe the simultaneous equilibrium of the electricity and green certificate markets and its effects on capacity expansion. Authors of [14] propose a generation expansion model that considers possible oligopolistic behavior of firms and also includes support schemes, such as carbon emissions trading and tradable green certificates. In the short term, firms compete in quantity as in the conjectural variations approach, while firms compete in capacity à la Cournot in the long term. Besides, the green certificate market is modeled as a perfectly competitive one and thus certificate prices are not accounted for. The proposed model represents an open-loop capacity equilibria since it assumes that capacity and production decisions are made simultaneously by generating companies. However, as proved in Refs. [27,28], the open-loop capacity equilibrium does not always coincide with the more accurate closed-loop equilibrium, in which generation capacities are determined first followed by production decisions in the spot market.

Finally, the impact of long-term certificate contracts on the performance of renewable support schemes is discussed in Ref. [25]. Ref. [2] proposes a bilevel model to determine the most effective incentive policies under renewable portfolio standards in the context of generation expansion planning. It is also worth mentioning references [21,29,30] in which the appropriate harmonization of green certificates markets across European member states is discussed.

In this paper we propose a family of capacity expansion models for renewable-based generation that include the trading of both electricity and certificates in a liberalized market with a given quota obligation. Under the assumption of a perfectly competitive market, the generation expansion model is first formulated for price-taker generating companies as a complementarity problem. Conversely, the generation expansion model is formulated as a mathematical problem with equilibrium constraints (MPEC) to model a closed-loop decision process in which capacity decisions are determined first anticipating the outcomes of an imperfect market under which generating companies compete in quantity à la Cournot. Unlike most existing works on this topic, a non-compliance penalty is accounted for in all proposed models.

The main contributions are thus threefold. Firstly, we use the proposed models to investigate the impact of the quota obligation level and the non-compliance penalty on capacity expansion decisions and the resulting share of renewable-based generation. Secondly, we determine the values of such parameters that lead to the desired penetration of renewable-based generation while maximizing the social welfare. Finally, we analyze how the level of competition in a liberalized market influences the design of an optimal support scheme to incentive investment in renewable-based generating capacity.

The rest of the paper is organized as follows. Section 2 presents the different mathematical models proposed in this paper to investigate the effects of a certificate market on the capacity expansion of renewable-based generation. Section 3 illustrates the features of the proposed models using an stylized example and analyzes how the quota obligation, the non-compliance penalty and the competition level among power producers impacts both the installed renewable-based capacity and the achieved social welfare. Finally, Section 4 concludes the paper.

2. Generation expansion models

In this Section the proposed capacity expansion models for renewable-based generation are presented and discussed. From the perspective of a central-planner approach, we formulate in Section 2.1 a single-level quadratic optimization problem that determines