[*PRICES VS. QUANTITIES WITH CAPITAL INERTIA: ELECTRICITY AND CARBON PRICING IN THE SHORT AND LONG RUN*]

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Overview

Decarbonization requires massive, rapid investment in low carbon technologies, notably in the electricity sector. Yet related markets for risk sharing are notoriously acknowledged to be missing or at least incomplete, which impairs investment incentives and warrants the use of long-term contracts (Joskow, 2022; Keppler et al., 2022). This is notably recognized in the recent electricity market design reform in the EU (Fabra, 2023), which promotes contracts for difference and power purchase agreements. In turn, these contracts will increasingly interact with the carbon price in the EU carbon market, which is the main decarbonization policy in the EU. These interactions and associated impacts on investment incentives, installed capacities, and contract properties deserve further analysis.

In fact, impacts on installed capacities can be different in nature given that a carbon price is technology-neutral, whereas long-term contracts tend to be technology-specific. In principle, "perfect" carbon pricing could partly compensate for the absence of long-term risk markets for electricity (Dimanchev et al., 2024). However, in practice, the carbon market is also subject to various frictions, notably limited foresight (Quemin & Trotignon, 2021), while simulation models that formally represent the electricity and carbon markets with endogenous investment are few and typically assume "ideal" markets (e.g., Bruninx et al., 2020; Pahle et al., 2025). Moreover, the relatively higher capital intensity of low-emission technologies constrains their development, and existing modeling efforts indicate that investment becomes riskier—in turn, reduced and or delayed—as electricity price volatility tends to be higher with greater penetration of renewables (e.g., Jimenez et al., 2024; Lebeau et al., 2024).

The objective of this paper is to examine these emerging trends with new contractual arrangements for electricity and "imperfect" carbon pricing. The main contribution is the development of a modeling framework for studying investment dynamics and the role of long-term contracts in carbon and electricity markets subject to frictions.

Methods

The model is composed of two main blocks that build on and extend Lebeau et al. (2024). The first block is a multi-year optimization problem that determines the optimal generating fleet, i.e., a Generation Expansion Planning (GEP) problem with a multi-year carbon constraint. The second block simulates investment and closure decisions of a representative market actor. This operates as a loop where, for each year, entry and exit decisions are made based on expected individual asset profitability using a gradient descent method. This approach captures the iterative decision-making process of a typical investor and enables the incorporation of risk aversion (here, through certainty equivalents). The advantage of this two-block model is that the information transfer from the first block (representing a "perfect" market) and the second block (simulating an "imperfect" but more realistic market) can be varied. In particular, if—and only when—the simulation model is supplied with information in line with GEP outcomes, it can iteratively reconstruct the optimal fleet (Lebeau et al., 2024).

The modeling framework extends that of Lebeau et al. (2024) by endogenizing the carbon price (i.e., allowing it to respond to changes in installed capacity dynamics and associated emissions) with various degrees of responsiveness. In each part of the model different methods are used to ensure that the price of carbon and the price of electricity are co-determined. This modeling property is a key contribution of the paper. Specifically in the first block, the carbon price is derived from the dual variables of the multi-year optimization problem, and two calculation methods are deployed depending on whether intertemporal flexibility in the carbon market (i.e., banking) is allowed or not. In the second block, the carbon price is determined by iterative search so that the emissions of the generating fleet meet the emission constraints. We consider that imperfections in the carbon market are reflected in the simulation model: by a parameter capturing market actors' myopia. Convergence of the carbon price in the second block is helped by an heuristic based on the price behavior observed in the first block. This heuristic leverages differences in emission rates and generation costs between technologies and cumulative emissions as inputs.

Results

The main results are threefold. First, intertemporal flexibility in emissions through banking in the carbon market leads to more stable carbon prices and sustained investment dynamics—with banking, short-run and long-run carbon prices coincide. Figure 1 depicts the carbon price paths we reconstruct from the dual variables of the optimization model when banking is allowed or not. In the absence of banking, the price surge at the end is due to a lack of investments in the previous years, and it triggers needed investments at a "too" late stage. Those investments can be delivered in a more smoothened and cost effective way with banking. Further, we characterize how different paths for emission caps (enforcing the same overall emission target) affect carbon prices and induced investment dynamics with and without banking. For instance, we compare a "linear" cap as in the EU carbon market with a one-step staircase cap as in the sulfur trading system in the US, among other types of cap paths.

Second, we study how price and quantity-based regulations differ in a generation fleet of long-lived assets, that is, in the presence of adjustment costs and capital inertia (Williams, 2010). The investment dynamics and overall emissions under an "equivalent" carbon market and tax differ, and we compare the nature and relevance of the information or signal conveyed by the dual variables (prices) compared to their primal constraints (quantities). Notably, emissions tend to be lower overall under a tax, even when there are no frictions in the carbon market.

Third, we analyze how frictions in the carbon market (i.e., limited foresight and price responsiveness) affect the rate of decarbonization and investment dynamics in the electricity market. For instance, a perfectly responsive carbon price is conducive to the optimal decarbonization path without the need for long-term contracts, even in the presence of risk aversion in the electricity market (the risk premium in borne by the carbon price). When actors exhibit myopia in the carbon market, their propensity to invest is diminished, leading to lower and delayed in investment in low-carbon assets. This effect is increasing with the degrees of myopia and inertia in price responsiveness. Long-term contracts have the potential to compensate for this investment deficit and delay. The next step in our work is to study how contract properties (e.g., duration, shape) hinge on the degree and nature of imperfections in the electricity and carbon markets.

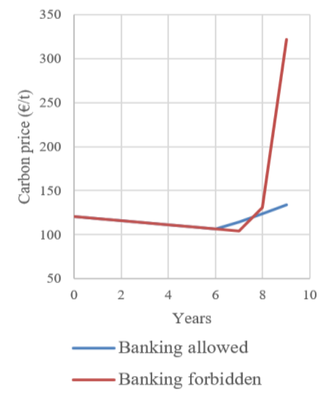

Figure 1 – Evolution of carbon price in the optimization model

Conclusions

Intertemporal flexibility in the carbon market allows the long-run constaint on emissions to be reflected in short-run carbon prices, which leads to stable carbon prices over time and sustained investment dynamics in the electricity sector. In an industry with capital inertia on the supply side as in the electricity sector, we also show that price and quantity based regulations are not equivalent in terms of investment dynamics and, in turn, decarbonization. In the absence of market frictions, the rate (cost) of decarbonization is lower (higher) under a carbon market than a carbon tax. In the presence of market frictions, the introduction of long-term contracts for electricity can restore optimal investment incentives, which depends on their characteristics and adoption by market actors. Further work will also study the coexistence of different types of long-term contracts with different types of market actors.

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