NBER Industrial Decarbonization Proposal: Low-Carbon Investment Incentives and Climate Policy

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1 Investment in Low-Carbon Industrial Production

A defining characteristic of decarbonization in hard-to-abate industrial sectors such as cement and steel production is that this transition will require substantial sunk cost investment in new plants using low-carbon technologies and upgrades of existing plants to accommodate low-carbon technologies. In cement, for example, it is difficult to envision a largely decarbonized sector that continues to produce Portland cement and that does not make use of some form of carbon capture and storage.[1] Once captured, this CO_2 might be stored as part of broader "carbon management" ecosystems, such as using underground aquifers, or added to wet concrete itself. In either case, cement production facilities will need to be constructed or retrofitted to include carbon capture devices, both of which entail substantial sunk costs.

Designing and implementing climate policies to incentivize efficient sunk cost investment have proved challenging. The first-best policy for correcting the unpriced greenhouse gas externality is well understood to be a carbon tax equal to the social cost of carbon (or an equivalent emissions trading system). However, additional complexities arise in settings where firms are able to exercise market power, which includes most industrial sectors.[2] Even without market power, the production non-convexities introduced by binary, lumpy investment decisions (i.e., to retrofit or not to retrofit) mean that the Pareto efficient outcome may not be implementable as a competitive equilibrium.[3] Understanding the relationship between market structure, carbon pricing policies, and incentives to install costly low-carbon technologies remains underexplored in the literature.

Moreover, many recent policy discussions related to industrial decarbonization are focused not on direct carbon pricing but on various second-best industrial policies. These alternative policy instruments include various forms of procurement policies, such as advance market commitments,

[1] Alternative decarbonization pathways would entail developing cement chemistries other than Portland cement, which today accounts for 95% of all cement production in the U.S. About 60% of the CO_2 associated with Portland cement production is a chemical byproduct from the calincation of limestone, which cannot be avoided through fuel switching, electrification, or process efficiencies. See Fennell et al., 2022.

[2] Building on the theoretical work of Buchanan (1969), Fowlie, Reguant, and Ryan (2016) memorably demonstrated the importance of market power in outcomes from carbon pricing policies, using a model of the cement industry.

[3] Here it is useful to remember that the second welfare theorem, which states that any Pareto efficient outcome can be implemented as a competitive equilibrium given appropriate transfers, depends on an assumption of convex production sets. Hart (2021) and Stern, Stiglitz, and Taylor (2021) have acknowledged the potential importance of non-convexities in the climate transition.

"green" purchase programs, and pooled purchases;[4] loan guarantees and other programs that reduce investment costs;[5] and integrated environmental and trade policies such as border adjustment benchmarks.[6] While these alternative policy instruments vary in their specific structure, virtually all are aimed at incentivizing sunk cost investment in low-carbon production methods. Yet very little empirical research in economics has examined the potential impact of these second-best policies on incentives for low-carbon investment.

In this project, we will develop and estimate a dynamic model of new technology adoption, production, and exit in the U.S. Portland cement market. We will then use the model to evaluate how price- and non-price-based policies might affect incentives for sunk cost investment in low-carbon technologies. Cement production is an ideal setting for studying these issues for two reasons. First, as researchers have documented in previous papers, many characteristics of the cement industry allow researchers to gain traction in empirical modeling, such as the fact that it is a homogenous product or that long-term storage is generally not possible. Second, the industry experienced a significant technological transition from the 1970s to the 2010s, as plants upgraded to precalciner kilns. This technology was far more fuel efficient – 25-35% more efficient than the older kilns that they replaced – but costly to install (Macher, Miller, and Osborne, 2021). Therefore, we can use our model to understand which market structures most closely approximated optimal investment in the new technology and how different policy instruments might have resulted in more or less efficient investment.

The intended contributions of this project are threefold. First, this paper extends earlier efforts to model environmental policy and technology adoption decisions using the Portland cement industry. Second, this paper examines the role of production non-convexities in the climate transition, an issue that is closely related to but conceptually distinct from the impact of market power. Finally, this paper extends counterfactual policy analysis to newer types of policy instruments currently under discussion for industrial decarbonization, such as procurement policies or border adjustment standards with or without domestic carbon pricing.

A brief note on existing literature before describing the model and data: Fowlie, Reguant, and Ryan (2016) made important contributions to our understanding of the dynamic impact of market-based environmental policies in the concentrated, trade-exposed cement sector. Yet they do not explicitly model the decision to adopt precalciner technology by incumbent firms, and they assume that new entrants always adopt the frontier technology. For this reason, their model cannot be used to evaluate the impact of alternative policy instruments on low-carbon technology adoption, which is necessary for deep decarbonization of many industrial sectors. From a theoretical perspective, their paper is also focused specifically on the impact of market power in shaping the outcomes of environmental policy, and their policy evaluations are limited to policies that directly price carbon emissions. Macher, Miller, and Osborne (2021) focus directly on the precalciner technology adoption decision, but they stop short of building a full dynamic model that can be used for counterfactual policy evaluation. Interestingly, they find in their initial study of precalciner adoption that firms in more competitive regional markets were *less* likely to adopt the new technology than were

[4]See, for example: James Leggate. "New York Governor Signs Low-Embodied-Carbon Concrete Bill." *Engineering News Record*. January 4, 2022. `https://www.enr.com/articles/53355-new-york-governor-signs-low-embodied-carbon-concrete-bill`. Accessed November 22, 2022.

[5]Personal communication with Michael Kearney, The Engine, Massachusetts Institute of Technology. November 18, 2022.

[6]Kopp, Pizer and Rennert, 2022.

their less competitive counterparts. This finding raises additional questions about the impact of market sturcture on low-carbon technology adoption, beyond the market power channel identified in Fowlie, Reguant, and Ryan. Moreover, while a full welfare analysis of technology adoption patterns is outside the scope of Macher, Miller, and Osborne, it will inform the current analysis.

2 Dynamic Model, Data, and Estimation

Below we outline a brief sketch of our model of dynamic technology adoption, production, and exit in the cement industry. The empirical model builds on models of dynamic games in the tradition of Ericson and Pakes (1995), and more specifically on earlier models of the cement industry in Ryan (2012), Miller and Osborne (2014), and Miller, Osborne, Sheu, and Sileo (2022). Our dynamic game is played by N firms, which we index by $i \in \mathcal{I} = \{1, 2, ..., N\}$. Time is discrete and indexed by t. Firms maximize their expected discounted flow of profits, $\mathrm{E}_t[\sum_{\tau=0}^{\infty} \beta^\tau \pi_{i,t+\tau}]$, where β is the (common) discount factor and $\pi_{i,t}$ are firm profits in period t.

Every period, firms make three sets of dynamic decisions for each of their plants. First, at the start of each period, incumbents decide whether to close each of their plants ("exit"). For each plant that closes, they receive a scrap value, ϕ_{it}^{exit}, drawn from the distribution $F^{\text{exit}}(\cdot)$. Second, remaining firms decide whether to upgrade their kilns at any of their plants not already equipped with precalciner technology, incurring a sunk cost of $\phi_{it}^{\text{retrofit}}$, drawn from $F^{\text{retrofit}}(\cdot)$, for each plant that they retrofit. Finally, firms decide which of their plants will produce in the period, paying a fixed cost $\phi_{it}^{\text{produce}}$ drawn from $F^{produce}(\cdot)$ for each plant that does so.

After these three sets of dynamic decisions, firms play the stage game to determine current period profits. In each period, profits depend on firm actions and the current state vector $\mathbf{s_t}$, where $\mathbf{s_{it}}$ represents the capacity, location, and production technology of firm i's plants in period t. This component of the model will draw on the static auction model developed in Miller, Osborne, Sheu, and Sileo (2022), in which firms submit bids to compete in a second-score auction. This modeling framework captures a number of the most salient features of the industry, including the spatial differentiation that arises due to transportation costs, the spatial price discrimination that emerges as a result, and plant-level capacity constraints. Despite this richness, equilibrium is simple to compute because it can be fully characterized by plant-level quantities (in this way it is similar to Cournot), so it is promising in the context of the dynamic game.

The data used to estimate the structural parameters of the stage game are well described in Miller and Osborne (2014) and Miller, Osborne, Sheu, and Sileo (2022). To summarize briefly here, the U.S. Geological Survey (USGS) publishes an annual *Minerals Yearbook* which provides region-level data on the average free-on-board price, total cement production, and total cement consumption. National-level data from the *Minerals Yearbook* includes total production by wet kilns, by older dry kilns, and by modern precalciner kilns, and the fraction of shipments utilizing barge transportation. Finally, the *Minerals Yearbook* also provides the location of customs districts and the quantity and customs value of imported cement. The USGS *California Letter* provides more specific information about trade flows between Northern and Southern California and Northern California, Southern California, Arizona, and New Mexico. The Portland Cement Association's regular *Plant Information Summary* provides the location, owner, and primary fuel of each cement plant, as well as the age, capacity, and technology class of each kiln. Lastly, supplemental data includes fuel prices from the U.S. EIA, plant-level CO_2 emissions from the EPA, county-level con-

struction employment from the Census Bureau, and the location of major navigable rivers from the Army Corps of Engineers.

To estimate the dynamic parameters, we will exploit the information from the *Plant Information Summary* on the timing of plant closures (for the scrap value) and when precalciner technology is installed (for the sunk cost). The reduced-form regression analyses of Macher, Miller, and Osborne (2021) indicate that useful empirical variation exists—for example, consistent with intuition, higher fossil fuel prices lead to more both more closures and more technology adoption. For the fixed cost, we plan to exploit information on which plants are mothballed, which also is reported in the *Plant Information Summary*. We observe from the raw data that plants nearly always produce if demand is reasonably strong, but that some plants stop producing during recessions. Putting this together, we have a clear path to estimating the policy functions that characterize how firms determine plant closures, technology adoption, and production decisions. There are multiple methodologies in the literature that then can be used to recover the dynamic parameters, each with its own strengths and weaknesses. One option is the two-step routine from Bajari, Benkard, and Levin (2007), which was used in Ryan (2012) and Fowlie, Reguant, and Ryan (2016). Alternatives include Aguirregabiria and Mira (2007) and a linear instrumental variables approach developed in Kalouptsidi et al. (2021) and adapted for dynamic games in Caoui, Hollenbeck, and Osborne (2022).

3 Policy Counterfactuals

Counterfactuals will evaluate the impact of different policy instruments on technology adoption decisions, the pace of the precalciner technology transition, and overall welfare.[7] The paper will first evaluate the impact of direct carbon pricing, both to serve as a benchmark and to understand the interaction of carbon pricing, market sturcture, and lumpy investment decisions. Then, attention will also be given to combinations of second-best policies aimed at incentivizing sunk cost investment. For example, to simulate the potential impact of "green" procurement policies, we will define a "green" cement commodity whose production emissions fall below some emissions intensity threshold, and then mandate that a certain fraction of local cement demand be met with green cement wherever available. (All other demand parameters will remain the same, except the size of the "green" and "non-green" markets.) Likewise, in another policy simulation, we might evaluate investment subsidies to "early" adopters of precalciner technology, which would take the form of reduced sunk costs of technology upgrading. In both cases, it would be worthwhile to understand the impact of first targeting sunk cost investment and subsequently adopting direct carbon pricing, relative to the impact of immediately adopting direct carbon pricing. Given that the difficulty of simulating counterfactual equilibria in dynamic games increases substantially with the number of firms, one approach will be to limit these simulations to more geographically isolated markets.

Historical counterfactuals will allow us to examine the impact of policies on precalciner adoption, a lumpy investment decision that reduced CO_2 emissions associated with energy consumption in cement production. Beyond the historical analysis, our dynamic model will also enable forward-looking simulations of potential future market outcomes given the set of technologies that are likely to play a role in decarbonizing cement production, including those reducing process emissions.

[7] As the story of precalciner kilns reminds us, many heavy industries such as cement and steel production have been decarbonizing for decades, as manufacturing increasingly uses more efficient production methods and energy sources with lower carbon content, yet the pace of change is generally too slow to avert the worst consequences of climate change. These policy simulations therefore allow us to investigate how different policy instruments might affect the *pace* of investment in new technologies.

While cement production does not have one clear technological pathway to deep decarbonization, some form of carbon capture is part of virtually all decarbonization pathways that we have seen for Portland cement, given that the process CO_2 emissions from calcination of limestone are all but unavoidable unless alternative cement chemistries are used. As such, we are able to examine the potential impact of our modeled policy instruments on the adoption of carbon capture, using estimates from engineering studies on the sunk cost of carbon capture devices in plant retrofits or new builds, as well as the marginal cost of operating these devices.[8] While certainly more speculative than the historical policy simulations, this set of counterfactuals will provide complementary value-add and clear policy relevance.

4 References

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[8] For example, see Hills et al., 2016.

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