Market Shaping to Combat Climate Change

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Abstract

Pull mechanisms represent a potentially promising tool by which policymakers can accelerate the pace of socially valuable innovation that can help combat climate change. Pull mechanisms are tools by which government, private, or philanthropic sponsors incentivize innovation by increasing the returns to said innovation generally, i.e.by paying for research outputs. Unlike patents, pull mechanisms do not result in a specific firm ending up with a monopoly over new inventions, which may result in higher prices and lower quantity supplied of the newly invented goods, in turn hampering efforts to rapidly decarbonize the economy. Unlike other tools such as grants, pull mechanisms can be designed to be agnostic across firms and technological pathways, helping sidestep the problem that program sponsors (such as the government) are often highly uncertain which firms or approaches will prove most successful in the long run. For many climate challenges, such as decarbonizing heavy industry like cement or developing cheap means of removing carbon dioxide removal, there is a wide panoply of possible solutions. Many will likely prove technologically infeasible, and others may prove technologically possible but economically unviable. A well-designed firm- and technology-agnostic approach is flexible enough to support different pathways is a useful tool in a toolbox in encouraging innovation under such uncertainty.

Market Failures in Innovation

To achieve meaningful progress against climate change, both in mitigation and adaptation, we need innovations in virtually every aspect of our lives: from the crops we grow to the construction of our buildings, from the surface of roads to the vehicles we drive on them, from our landfills to our heating systems, everything needs to change. And it needs to change rapidly and at scale.

But the commercial incentives to create and scale up climate-friendly innovations are often incommensurate with the social value of those innovations. Across sectors, innovation has been found to generate extraordinarily high social returns, and the existence of those large returns, a clear sign we are underinvesting in innovation. Innovation provides benefits not just to the innovating firm, but also to consumers (through improved product quality and/or lower prices), imitating firms, and to broader society by enabling further technologies and businesses that build on the backs of the new innovation. For instance, inventions like the Internet, human genome mapping, and the transistor enabled entire industries to be built on the backs of that earlier innovation. In a 2020 working paper, Jones and Summers find the average dollar of R&D

spending in the United States of America yielding between $5 and $20 in social benefits domestically, with the benefits of the marginal dollar spent being similarly high (Jones and Summers 2020).[1]

Even under a patent system, firms capture a small percentage of the social value of innovation. Nordhaus 2004 found “only a miniscule fraction of the social returns from technological advances over the 1948-2001 period was captured by producers, indicating that most of the benefits of technological change are passed on to consumers rather than captured by producers” (Nordhaus 2004).[2] There are three main reasons why investment in climate change innovation is below the social optimal: positive externalities, innovation spillovers, and the hold-up problem.

Externalities

Pollution, for the most part, is an unpriced externality. Except where a carbon or pollution tax fully reflects the social cost of carbon/pollution, firms that emit global warming-inducing particles into the atmosphere do not internalize the cost those emissions impose on the rest of the planet. Pollution reduction is a classic public goods problem. One cannot restrict the benefits of a cleaner atmosphere only to paying customers–the climate is a global phenomenon.

Consider an innovation that produces clean cement (i.e. a cement that embodies half the emission of existing products) at the same price as the going market rate plus some small increment. Absent external incentives, private purchasers pursuing their narrow self-interest will opt for the regular, more polluting cement: the benefits of the innovation are diffused across the rest of the globe, while the costs of purchasing the greener product are borne entirely by the purchaser. Aware of this dynamic, firms may be reluctant to invest in decarbonization innovation for fear that such efforts will struggle to be rewarded in the market.

Innovation Spillovers

Innovations by one firm can often result in benefits to other firms. A firm has little incentive to spend vast sums on research and development when most of the benefits of such innovation are enjoyed by other firms that do not compensate the original researcher for their efforts. In brief, what are some of the channels of spillovers?

First, there is direct copying. Not all innovations and techniques are patentable, or are cases where patents are unenforceable. Second, there may be demonstration effects to innovation,

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[1] Jones, Benjamin and Lawrence Summers. 2020. “A Calculation of the Social Returns to Innovation.” NBER Working Papers 27863.

[2] Nordhaus, William. 2004. “Schumpeterian Profits in the American Economy: Theory and Measurement.” NBER Working Papers 10433.

where one firm's successful innovation raises competitors' estimated probability of the profitability or success of that approach, incentivizing them to adopt or further pursue that method (Mansfield 1961).[3] If a cement producer demonstrates a low-carbon cement plant using an alternative cement chemistry at a competitive price, while their specific processes may be patentable, the public existence of the successful innovation is a signal to other firms that they should consider redoubling their efforts into similar approaches. Third, people leave successful and innovative firms and join other firms (or start their own firms), bringing with them implicit knowledge about what does or does not work (Stoyanov and Zubanov 2012).[4] Fourth, firms can share trade secrets with their business partners and suppliers, diffusing knowledge throughout the broader economic ecosystem (Fadeev 2023).[5] Researchers have identified shared suppliers as an important route for knowledge diffusion, including in the specialized machine tools industry and the semiconductor industry (Rosenberg 1963, Lim 2009).[6] [7] Further, supplier innovation can influence buyers' innovation, and that buyers' innovation can influence their supplier's innovations (Isaksson, Simeth and Seifert 2016).[8] Suppose a cement plant asks a supplier to produce a specialized piece of machinery that can handle their novel cement chemistry product. Now when another company orders from the supplier for a similar innovation, the supplier is already competent at producing similar products.

A fifth channel is that new technologies can unlock new economics for other firms that may not have been previously possible. In the context of climate change, improvements in energy efficiency or improvements in energy technologies could lower overall prices, enabling other, more energy-intensive technologies in entirely different domains to become price-competitive in the market. The social surplus enabled by those other technologies was enabled by the initial innovation, but the original innovators are not compensated for those efforts.

These effects can be quite large. Bloom, Schankerman and Van Reenen 2013 find that, due to spillovers, the social rate of return of innovation to be 55%, and that the "this implies under-

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[3] Mansfield, Edwin.1961. "Technical change and the rate of imitation." Econometrica, 29 (4): 744-766.

[4] Stoyanov, Andrey and Nikolay Zubanov. 2012. Productivity Spillovers Across Firms through Worker Mobility, American Economic Journal: Applied Economics 4 (2): 168-198.

[5] Fadeev, Evgenii. 2023. "Creative Construction: Knowledge Sharing and Cooperation Between Firms."

[6] Rosenberg, Nathan. 1963. Technological Change in the Machine Tool Industry, 1840–1940. The Journal of Economic History 23 (4):414–443.

[7] Lim, Kwanghui. 2006. "The Many Faces of Absorptive Capacity: Spillovers of Copper Interconnect Technology for Semiconductor Chips. Industrial and Corporate Change." http://dx.doi.org/10.2139/ssrn.562862.

[8] Isaksson, O., M, Simeth, M. and Seifert, R. (2016). Knowledge spillovers in the supply chain: Evidence from the high tech sectors. *Research Policy 45*(3). 699-706. https://doi.org/10.1016/j.respol.2015.12.007

investment in R&D, with the socially optimal level being over twice as high as the level of observed R&D" (Bloom, Schankerman and Van Reenen 2013).[9]

Hold-up Problem

The hold-up problem occurs when firms need to undertake unrecoverable investments, and buyers can exploit those sunk costs to extract costs close to marginal costs. Would-be innovators, fearing this dynamic will result in a final price that is insufficient to recoup their sunk costs, shy away from investing large amounts in research and development.

Consider the following example from climate adaptation: heat-tolerant sorghum. Suppose a heat wave induced large-scale crop failure in sub-Saharan Africa. An inventor of heat-tolerant sorghum may face social or explicit government pressure to sell their product at cost (or to give it away), lowering the incentive to invest in inventing such a product.

Inefficiencies Associated with Patents

Patents do not fully prevent innovations from being copied by others, as discussed above: pharmaceutical companies have for example perfected the science of finding very similar molecules that deliver a similar impact to new drugs (so called "me too" drugs). However, even in cases where innovations are protectable by enforceable patents and spillovers are sufficiently modest that there exists a large commercial incentive to invest in innovation, patents do not produce a socially efficient innovation environment and it may still be desirable for the government to intervene. Because patents create temporary monopolies for the patent-holder. that monopoly will generally result in higher prices and lower quantities supplied than under a purely competitive market post-patent.

That poses two distinct complications for climate change innovation. First, time is at a premium. Carbon dioxide emitted today, unless removed through some net-negative process, will remain in the atmosphere and will contribute to warming for centuries. A patent system that delays meaningful deployment until the expiration of the patent may thus incur large social costs. Second, the higher prices may exclude low- and middle-income countries from adopting the new technology. Many of the most cost-effective forms of carbon abatement may exist in low- and middle-income countries building new infrastructure and structures for the first time, instead of retrofits that occur in richer countries (Glennerster and Jayachandran 2023).[10] If the delay or

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[9] Bloom, Nicholas, Mark Schankerman, John and Van Reenen, J. 2013. "Identifying Technology Spillovers and Product Market Rivalry." *Econometrica* 81 (4): 1347-1393

[10] Glennerster, Rachel and Seema Jayachandran. 2023. "Think Globally, Act Globally: Opportunities to Mitigate Greenhouse Gas Emissions in Low- and Middle-Income Countries." NBER Working Papers No. 31421.

higher prices result in pursuing fossil fuel-intensive infrastructure instead, that may create lock-in effects that are difficult to reverse later.

Market failures would persist even with carbon pricing

A price on carbon, whereby firms would be charged a fee or tax proportional to the amount of CO_2-equivalent emissions they produce that fully reflected the social cost of carbon, would help correct some of the aforementioned market failures. For instance, producing a metric ton of ammonia in the United States produces roughly 2.6 metric tons of greenhouse gas emissions (Liu, Elgowainy and Wang 2020).[11] Depending on the carbon price, a producer could charge a higher pre-tax amount for a greener ammonia, since they would pay less in carbon fees and taxes. If the carbon price level is set equal to the social cost of carbon, then there would be no market failure stemming from unpriced externalities.

However, innovation for climate change would still be under-incentivized under such a regime because it would not address the other market failures discussed above: specifically, it would not address large knowledge spillovers the hold-up problem associated with innovation for any green market with a small number of buyers. Third, the aforementioned analysis assumes that the carbon price is equal to the *global* social cost of carbon. Domestic social costs of carbon (the effect of a marginal unit of emissions on the polluting country itself) are often small fractions of the total global cost, even for large countries like the United States. As a result, if the carbon price is only set to the domestic social cost, then there will still be a large, unpriced global externality that results in inadequate global innovation.

General Push v. Pull

Having established that commercial incentives for climate change innovation development and widespread dissemination are generally incommensurate with their social value, even under the existence of a patent scheme and carbon pricing, what tools do policymakers have to address this problem?

The standard toolkit governments and philanthropic organizations use is “push funding”. “Push funding” refers to mechanisms where a sponsor pays for inputs (Kremer and Glennerster 2004).[12]

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[11] Liu, Xinyu, Amgad Elgowainy, and Michael Wang. 2020. “Life cycle energy use and greenhouse gas emissions of ammonia production from renewable resources and industrial byproducts.” Royal Society of Chemistry Green Chemistry. https://www.osti.gov/servlets/purl/1657142

[12] Kremer, Michael and Rachel Glennerster. 2004. Strong Medicine: Creating Incentives for Pharmaceutical Research on Neglected Diseases. New Jersey: Princeton University Press.

Examples of push funding include grants, equity investments in private firms, research and development tax credits, and public funding for national laboratories and basic science.

One drawback of this approach arises when there is considerable uncertainty from the planner about who to reward with this push funding, or when potential push recipients possess substantial amounts of asymmetric information (Kremer, Levin and Snyder 2020).[13] Suppose the government wished to spend $500 million for a series of small demonstration plants for near-zero carbon cement plants. As the technology largely does not yet exist, part of that funding would be for research to get the technology to a readiness level such that a small pilot facility could be built. While firms themselves know the state of their own private research and how close they are to being pilot-ready, the government may struggle to identify which plants are more or less promising. In a grant application, firms have every incentive to play up how certain their technological prospects are, making it difficult for the government to distinguish the lemons from the peaches. As a result, the government risks funding projects that are highly likely to fail, or leaving potentially highly likely projects out in the cold, all for want of an efficient means of differentiating the two.

An alternative approach is to use "pull funding". As mentioned previously, pull funding mechanisms increase the incentive to innovate by increasing the returns from innovation. A canonical example of pull funding is to use a prize, but it also encompasses volume guarantees, and other "pay for results methods". If well-designed, these mechanisms can sidestep the asymmetric information problem as firms will self-select out from participating if they believe their probability of success is too low. After all, they only receive the money if they are successful in their innovations.

However, different pull mechanisms have different advantages and drawbacks and are suited to combating different climate change challenges. There are also a lot of design details to get right if a pull mechanism is to be effective.

Perhaps the simplest form of pull mechanism is a prize: the sponsors set out the criteria for an innovation and the first one to come up with an innovation that meets the criteria is given a one off prespecified monetary reward. Prizes are frequently used, though they are often very small compared to the problem they are seeking to fix. We use the example of a prize for a novel cement chemistry to illustrate some of the economic challenges associated with prizes. Prizes need to be scaled to the size of the challenge and in practice are often far too small. If the US cement market is $15 billion and a single cement plant costs $1 billion, a $100 million prize for inventing a novel cement chemistry is unlikely to induce many to participate and, most

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[13] Kremer, Michael, Jonathan Levin, and Chris Snyder. 2020. "Advance Market Commitments: Evidence from Theory and Experience." AEA Papers and Proceedings 110: 269-73.

importantly, unlikely to lead to the large investment needed for mass adoption. Moreover, prizes often lack a crucial *market test*. Participants in prizes will optimize for winning the prize reward, which may differ subtly (or even substantially) from the preferences of consumers in hard-to-articulate ways. As a result, one may have to pay out a prize to an innovation that will do little to combat climate change, because the winning product met the terms of the prize but could not gain traction in the market.

It is difficult, or even impossible in some circumstances, to spell out all possible considerations that may be relevant to a consumer in a prize payout criterion without becoming so overly prescriptive as to exclude other promising efforts. For example, suppose one set a prize for decarbonizing cement that specified (a) a maximum threshold for embodied carbon, (b) a maximum price to produce, and (c) minimum performance standards (including performance under stress, heat, acidity, wind, and any other possible factor that may be relevant to the performance of cement). However, it turns out that the winning innovation–that meets all the specified criteria–ends up having such a long cure/set time that it is incompatible with existing construction industry practices and thus struggles to gain adoption. The prize money was wasted. Conversely, if one did set maximum cure/set times, the prize competition may end up excluding a hypothetical variant that was vastly superior on global warming impact but whose cure time was slightly above the maximum allowed. The point is not that cure/set times in particular need to be accounted for in a prize, but that there are a panoply of possible factors that are relevant for market adoption but impossible for planners to specify in advance without being overly restrictive. What if the winning innovation requires such specialized expertise to build that it’s infeasible at scale? What if the economics are contingent on a rare form of mineral that is uneconomical to mine at scale? Ideally, the easiest way to solve this problem is to use a market test: to link payouts to performance in the market.

One pull mechanism that incorporates a market test is the advance market commitment (“AMC”). An advance market commitment is a legally binding commitment for the sponsor to pay a subsidy per unit of a good sold into the market for a prespecified quantity, conditional on that good being invented and meeting some minimum performance requirements. One can also condition the AMC subsidy on the innovative firm agreeing to sell the product at a price close to the marginal cost of production even after the prespecified subsidized quantity is exhausted, thus solving the higher price problem from the patent monopoly. As a result, firms (a) self-select into investing in R&D based on their own private information about their probability of success, since they only get paid if they succeed, and also (b) the planner does not need to specify every possible relevant criteria in advance.

An example of such an “AMC” is the pneumococcal AMC, where donors committed $1.5 billion for a pneumococcal conjugate vaccine (PCV) to target a strain of pneumococcus that afflicted children in low- and middle-income countries (Kremer, Levin and Snyder 2020).[14] The AMC paid out a subsidy per dose, conditional on the vaccine meeting certain performance thresholds and the firm capping the price of the vaccine at $3.50/dose (Kremer, Levin and Snyder 2020).[15] While knowing the counterfactual is impossible–one cannot observe a world in which the pneumococcal AMC did not exist–Kremer, Levin and Snyder show that rollout of PCV in eligible countries occurred faster than for a comparable rotavirus vaccine. Had PCV rollout occurred at the same pace as rotavirus vaccine rollout, “67 million fewer children under age 1 would have been immunized, amounting to a loss of over 12 million DALYs [disability adjusted life years]” (Kremer, Levin and Snyder 2020).[16]

There are also conditions where an AMC is not ideal. Consider the case of accelerating COVID-19 vaccine innovation as was done by Operation Warp Speed in the United States. Athey et al. concluded that an advance market commitment would not be the appropriate tool in this situation (Athey 2022).[17] One advantage of an AMC is that it results in firms self-selecting out of participation if they believe their probability of success is low. In the case of COVID-19, where the economic costs per day were so great, policy planners want even highly marginal participants to be investing their resources and efforts into developing vaccines. If one wanted to encourage marginal candidates to participate using an AMC, planners would have to set a very high subsidy rate in order to compensate marginal participants for their high risk of failure. However, it would be inefficient to also pay candidates with higher probabilities of success such a high subsidy rate. Moreover, without contracting explicitly on capacity, “the firm's commercial incentives are to save costs by investing in smaller capacity, fulfilling the order over a longer period but generating the same revenue from the contract” (Castillo et al. 2021).[18] As a result, the recommendation was for the government to pay for capacity, essentially reimbursing firms for the costs of building out manufacturing capacity for vaccine candidates even prior to FDA approval. This mechanism also helped accelerate the pace of vaccine rollout, as firms had large numbers of doses ready to deploy soon after they received regulatory signoff.

Climate-specific considerations for pull mechanisms

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[14] Kremer, Michael, Jonathan Levin, and Chris Snyder. 2020. “Advance Market Commitments: Evidence from Theory and Experience.” *AEA Papers and Proceedings* 110: 269-73.

[15] Ibid

[16] Ibid

[17] Athey, Susan, Juan Camilo Castillo, Esha Chaudhuri, Michael Kremer, Alexandre Simoes Gomes and Christopher Snyder. 2022. “Expanding Capacity for Vaccines Against COVID-19 and Future Pandemics: A Review of Economic Issues”. NBER Working Paper 30192

[18] Castillo, Juan Camilo, Amrita Ahuja, Susan Athey, Arthur Baker, Eric Budish, Tasneem Chipty, Rachel Glennerster, and others. 2021. “Market Design to Accelerate COVID-19 Vaccine Supply.” Science 371 (6534): 1107–9.

Why are many challenges in climate innovation particularly appropriate for a pull mechanism, with the caveat that the precise mechanism varies based on the specific climate problem and the contours of the underlying market.

One major reason is the uncertainty about the precise technological pathway to reduce emissions. Consider the case of carbon dioxide removal (CDR). There are many methods by which CO_2 molecules could be permanently removed from the atmosphere. There are engineered solutions such as direct air capture (DAC), where large fans pull in air that contacts with a sorbent, which selectively removes the CO_2 from the rest of the air. Others have attempted to use natural-based processes such as enhanced rock weathering, which entails using basaltic rocks that naturally react and combine with CO_2 in the atmosphere. There are processes as diverse as ocean alkalinity enhancement, direct ocean capture, soil carbon methods, and more. Nor is CDR an outlier. For decarbonizing concrete, entrepreneurs have tried introducing waste materials to reduce the amount of polluting cement input that is required. Others are researching using cleaner heat sources, alternative binder chemistries, and even different cement chemistries themselves (such as using calcium silicate directly or magnesia instead of limestone). Within the green hydrogen space, there are a wide range of possible electrolyzer pathways (electrolyzers are machines that separate aqueous solutions into hydrogen and water), including simple alkaline electrolyzers, proton electron membrane electrolyzers, solid oxide electrolyser, thermoelectric water splitting, photoelectrochemical water splitting, and beyond. It remains unclear which, if any, of the above pathways will prove to be most cost-effective at scale. Push funding that rewards specific firms pursuing specific techniques risks not only choosing the wrong firm, but also directing industry resources towards techniques that ultimately prove less successful. In a worst case scenario, supportive infrastructure and industry familiarity evolves around these less successful approaches thanks to government subsidies, locking out more promising approaches from breaking into the market.

What distinguishes the vaccine case from some climate cases complicating the direct translation of the model from the pneumococcal AMC? Firstly, the right model depends on the ratio of fixed costs to marginal costs. Vaccines have high research and development costs, high fixed costs of putting in place large manufacturing capacity but then relatively low marginal costs once a vaccine candidate has been approved and a factory built. In contrast, Direct Air Capture for carbon dioxide removal or current electrolysis methods of producing hydrogen use a lot of energy for each marginal unit of production. While there is hope that these marginal costs will decline over time, this is not guaranteed. Second, unlike a novel vaccine, green products often produce end-products that are undifferentiated from their non-green competitors, limiting their ability to charge differentiated prices. If the green product has a higher marginal cost to produce than the non-green competitors it might need to be subsidized indefinitely, unlike the vaccine sample where an AMC that covers the fixed cost of innovation would be sufficient. For instance, ideally, hydrogen produced using renewable energy and electrolyzers produces the identical product (H_2) from hydrogen produced using steam methane reforming. As a result, if the marginal cost of the greener approach exceeds the standard, non-green approach, then some permanent supportive policy might be necessary to allow the green approach to remain cost competitive.

A third major differentiator is that one firm may not see innovation all the way from start to finish. In the pharmaceutical industry, financial structures exist such that firms can originate an idea (or take over a biotech company with an idea), examine its suitability, run clinical trials, and then manufacture and distribute the vaccine. For industrial decarbonization the process of identifying a low-carbon process and perfecting it to be produced at low cost at scale may require a series of multiple successive innovations and iterations. Solar is a good example of this: the first production of solar panels was expensive and only after hundreds or thousands of iterations of both product and manufacturing innovation have costs declined and the product became lighter and easier to use. Many different firms have been part of this process of innovation with each firm learning from the innovations of others. The initial innovators did not capture much of the final market. To achieve a cost-competitive net-zero cement, a firm may need to invent a novel cement chemistry, as well as new equipment and machinery to handle that new chemistry. They must then learn how to best optimize these complex plants to minimize cost. Under a simple pull design, a firm that achieves only one of these innovations may not be able to earn a return. For example, a firm that figures out how to make a novel cement chemistry work but cannot figure out how to optimize its manufacturing plant to approximate price parity with non-green cement would receive no reward. If one believes that the rewards of the early innovation (such as inventing the new cement chemistry) will ultimately spill over to another firm who refines the formula and optimizes other processes to ultimately take it over the finish line, then there will be little incentive to invest in that early innovation. A novel approach will be necessary to tailor optimal pull policy to climate change-specific problems: it is not enough to simply copy and paste the lessons from pull designs in other domains.

Application Example: Cement

Background

In this section we attempt to apply these general principles to a specific example, in this case, cement. Cement is the primary input into concrete, which is itself the second-most used material in the world after water. Concrete is used in everything from buildings to roads to dams and will all but certainly remain a critical part of the global economy for the near future.

However, cement is also highly pollutive, being responsible for roughly 7% of global emissions (Department of Energy 2023).[19] Cement comes from limestone rock, which is itself calcium carbonate. This rock is ground up and heated to form a substance called clinker, which is cooled and combined with other materials such as gypsum and raw limestone to form cement, which is in turn combined with water and other aggregates like sand to form concrete. Approximately 90% of the carbon intensity of concrete comes from the production of cement, hence the focus on cement itself in this section.

Only about half of the carbon intensity of cement comes from producing the heat and electricity involved in the clinker-making process. The other half comes from the *calcination* process, where the carbon embodied in the calcium carbonate is released as the rock is heated. This means specific policy measures need to be targeted that are unique to cement–it is not merely a case of decarbonizing the industrial heat and electrical sectors and applying those gains to the cement industry.

There are currently several technologies that can help reduce the carbon intensity of cement from its current level of 0.8-0.9 tons of CO_2 per ton of cement produced (in the US). One of the most common is to blend in supplementary cementitious materials (SCMs) into the cement, to reduce the amount of clinker used. These SCMs are often waste products, such as fly ash (a byproduct of coal production) or slag (a byproduct of steel production), or other common materials such as natural pozzolans. The performance of these blends tends to be very similar to standard cement (called Ordinary Portland Cement), with some blends having small differences such as higher strength but longer cure times. With little to no added costs, the Department of Energy estimates that this “low-hanging fruit” can reduce the carbon intensity of cement by up to 30-50%. However, achieving deeper decarbonization poses greater challenges still.

There are two other salient features of the cement industry that bear on its unique decarbonization challenges. First, cement is cheap by weight (~$130/ton) but highly expensive to transport. Combined with the extraordinarily high fixed costs in setting up a plant, this results in relatively few cement plants in any given area. There are currently only 96 cement plants in 34 US states (USGS 2023).[20] As a result, even measures that have low costs per abated ton of CO_2 may lead to a large percentage impact on the price of cement. Second, government procurement drives roughly 50% of all demand in the United States, meaning that demand signals and regulatory changes from the government may have outsized effects on the overall market (Department of Energy 2023).[21]

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[19] U.S. Department of Energy. 2023. “Pathways to Commercial Liftoff: Low-Carbon Cement”. https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Cement.pdf

[20] U.S. Geological Survey. 2023. “Cement”. https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-cement.pdf

[21] U.S. Department of Energy (2023) “Pathways to Commercial Liftoff: Low-Carbon Cement”. https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Cement.pdf

Unique Challenges

There are three further features of the cement industry that make decarbonization particularly challenging.

First, capital expenditures to build cement plants is high, up to $1 billion per plant (Department of Energy 2023)[22]. In order to recoup these large upfront expenditures despite thin margins, plants tend to last for on average 36 years.[23] Due to safety concerns and inertia in government procurement standards, customers and industry groups are often fairly reluctant to endorse the use of novel cement chemistries or processes.[24] The risk that government purchase subsidies may change over time adds to the challenge when plants are so long lived. Given these uncertainties cement innovators may face high borrowing costs to finance the construction of large plants which will be hard to repay given the low margins in the industry unless there are long term guaranteed market advantages for clean cement. One way to reduce uncertainties and potentially borrowing costs would be to first build a pilot and demonstration plants to demonstrate their product's safety and cost-competitiveness before progressing to full commercial scale.

Second, the overwhelming majority of cement production occurs overseas (~98%) in low- and middle-income countries (>95%) (United States Geologic Survey 2023)[25]. China alone produces over half the world's cement.[26] As a result, merely eliminating cement emissions in the US will have a limited impact on global emissions. The ideal end-state of market-shaping is to generate a process that can be cost-competitive enough with ordinary Portland cement that LMICs will ultimately choose to build the greener plants, rather than the OPC plants, even without external incentives. Processes, such as adding carbon capture and sequestration (CCS) to existing cement plants, may reduce the carbon intensity of that plant, but will necessarily be more expensive than cement without CCS, and are thus unlikely to be a cheap, exportable model for LMICs.

Third, because of the expense associated with transportation, demand for green cement needs to reach a critical mass in a sufficiently geographically small location to justify building a plant. It is not enough to have small amounts of distributed demand throughout the country. Even if the total demand is enough to be larger than the output of a single plant, if that demand is spread out through the 50 states then no one will find it worthwhile to build a plant in any specific location.

Finally, it is worth flagging that standard off-take agreements largely do not exist in the cement industry, as the primary purchasers of cement (ready-mix concrete plants, or RMC) are generally small family businesses who face uncertain and volatile demand in a boom-and-bust construction

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[22] Ibid
[23] Ibid
[24] Ibid
[25] U.S. Geological Survey (2023). "Cement". https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-cement.pdf
[26] Ibid

industry (Department of Energy 2023).[27] These RMC plants are also largely not big enough to make large, credit-worthy commitments to prospective cement plants.

Appropriateness of Pull

Despite these challenges, there are several features that make pull particularly attractive.

First, as mentioned, the government purchases roughly half of all cement in the United States (Department of Energy 2023),[28] meaning that tweaks to government procurement rules could influence large market decisions.

Second, there is considerable uncertainty about which technological approach will ultimately be most successful. There are many different kinds of alternative cement chemistries–magnesia, calcium silicate–and other approaches that use traditional limestone but combine them with novel SCMs, energy efficiency measures, green feedstock and some CCS to eliminate emissions. It is unclear which approach will prove most promising.

Third, a market test is important. Billions of dollars could be spent on building pilot and demonstration plants, only to produce a cement that cannot be used at scale. Some of these provisions can be tested for–strength, performance under various weather conditions, etc.--but others are more subtle and cannot be evaluated without the overall market. As noted in the Push/Pull section, there are many intersecting factors that may make a cement mixture look good on paper but ultimately of little practical value to the actual market.

We want to end with two other considerations associated with designing a pull mechanism for cement.

First, small incentives are highly unlikely to yield positive results: the returns to prize or pull funding are unlikely to be linear. A demand signal to purchase $10 million worth of cement with embodied carbon 50% below current baseline measures are unlikely to result in any new green plants (which can cost up to $1 billion), let alone investments in R&D, pilot and demonstration plants as well. If that money is claimed at all, it is likely to be captured by those who would have taken these steps without the prize/pull funding. A demand signal needs to both be large enough

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[27] U.S. Department of Energy (2023) “Pathways to Commercial Liftoff: Low-Carbon Cement”. https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Cement.pdf

[28] U.S. Department of Energy (2023) “Pathways to Commercial Liftoff: Low-Carbon Cement”. https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Cement.pdf

and credibly long-term enough to justify building a ten-figure capex plant with a 30-year lifespan.

Second, how do we handle the challenge of needing complementary innovations? As identified above, developing a novel cement process or chemistry may require a series of successive innovations. A firm that achieves only one may not be able to claim the final reward from an AMC or a prize. It might be able to sell its innovation to another firm that has a complementary innovation. But when it sets out on the R&D investment it may be unclear whether a firm with a complementary innovation will appear. In addition, it may worry that once it has invented the new innovation it will face a holdup problem because the second firm knows the first innovation is worthless without the second innovation.

A program designer may be tempted to introduce intermediate targets: small rewards or prizes for reaching technical milestones that are on the path towards the end goal to solve this problem. While this might be the right approach in some situations, it comes with downsides. One challenge is identifying the correct intermediate targets. Suppose we want to optimize for two features: low-carbon and cost-competitiveness. Planners cannot merely give prizes to anyone who discovers a low-carbon cement blend, as many of those blends may be so expensive as to be wildly impractical. After all, the challenge is getting both of those factors at once, not merely achieving one of them. Identifying cost at the pilot stage, moreover, can be highly difficult: it is unclear at small size if the economics get worse or better as one scales. For instance, a novel plant reliant on new chemistries may seem relatively cheap, but it turns out that they are using a relatively rare and ill-used input whose price would skyrocket if it started being used in multiple major cement plants simultaneously. Another plant may seem rather expensive, but get much cheaper as economies of scale enable more efficient mining, milling, and processing. It is difficult at the intermediate stage to identify which plants will be economically feasible, and planners should be wary of prematurely rewarding firms with little path to future success.

Conclusion

The commercial incentive to produce innovations to combat climate change are generally incommensurate with the social returns of those innovations. This gap stems from several well-known market failures, including unpriced externalities, knowledge spillovers, and the hold-up problem. Existing mechanisms to correct those failures suffer from asymmetric information problems (push funding), monopoly problems (patents) and/or lack of incentives to do the detailed innovation for scale (small-scale prizes). Even the introduction of a carbon price, while correcting for some of the aforementioned market failures, would not, by itself, be sufficient to solve the market failures associated with innovation and the associated wedge between the social and commercial returns.

Pull funding–funding based on achieving identified results–may serve an important role in filling in some of these gaps. Many decarbonization tasks have sufficiently uncertain technological pathways that identifying a target to hit and rewarding those who achieve it may be easier than specifying which firm or pathway should receive funding in advance. Each industry will require its own unique solution, however. As we see with the cement industry, using the same AMC structure used to incentivize pneumococcal vaccine research and capacity may not produce the desired result. Market designers need to be particularly conscious of balancing between (a) rewarding sufficient early innovations that firms who do necessary early innovations are rewarded without (b) rewarding innovations that will ultimately be economically non-viable.

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