MIT CEEPR

Center for Energy and Environmental Policy Research

Newsletter

SPRING 2025

Editorial.

"[T]he policy changes we can expect under the incoming administration ... are likely to slow down or reverse transformational trends induced by policy and regulation, and it will be an important task for research and analysis to distinguish these from disruption driven by evolving market forces and falling technology costs." Those words, contained in the editorial to the fall edition of this newsletter following Donald J. Trump's first election victory in 2016, remain relevant today. As the second Trump administration gets underway, the energy landscape once again faces deep uncertainty, with political volatility complicating long-term investment and planning.

During the first Trump presidency, federal policy retrenchment was offset by economic trends and subnational efforts that largely enabled the energy transition to continue. Market dynamics and technology cost declines continued to drive renewable energy deployment and emission reductions, even as policy reversals constrained federal support. But the present moment marks a more sweeping departure from previous policy trends. Within its first months, the current administration has already suspended or terminated programs supporting low-carbon technologies, delayed permitting processes for infrastructure projects, and adjusted funding priorities.

The resulting uncertainty has chilled private investment across the energy sector. Reductions in funding for research and development have raised concerns about potential long-term impacts on the innovation system that supports U.S. leadership in both conventional and emerging energy technologies. While markets continue to provide some counterweight – particularly through falling fossil fuel prices that deter investment in new supply – policy volatility and weakening institutional capacities could have a greater impact on the energy system than they did during the first Trump administration.

Globally, other economies are contending with their own political shifts. In Europe, rising electoral support for parties critical of the breakneck pace of decarbonization in recent years has prompted some governments and the European Union to streamline or delay specific climate policy initiatives. Still, despite these headwinds and a recalibration of priorities towards national security and competitiveness, Europe has reaffirmed its long-term climate commitments. The broader trajectory of decarbonization, though slowed in some areas, remains intact.

Against this backdrop, the upcoming United Nations climate summit – COP30 – in Belém, Brazil will serve as a bellwether for the prospects of global climate cooperation. With the United States once more stepping back from international climate engagement, the spotlight now shifts to other major emitters as these submit revised pledges under the Paris Agreement. Emerging economies – including, most notably, China – stand to influence the pace and direction of the global energy transition, possibly heralding an era in which they play a growing role in shaping international norms and cooperation.

In times of political uncertainty and turbulence, reliable analysis remains as important as ever to separate structural trends from short-term policy fluctuations. MIT CEEPR remains committed to providing robust, data-driven insights and a forum for informed debate. By engaging a broad network of scholars and practitioners, we aim to support durable decisions that transcend electoral cycles and contribute to a more affordable, secure, and sustainable energy future. As always, readers are invited to explore the research featured in this newsletter and join us in advancing a deeper understanding of the evolving global energy landscape.

Michael Mehling

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MIT CEEPR Newsletter is published twice yearly by the MIT Center for Energy and Environmental Policy Research.

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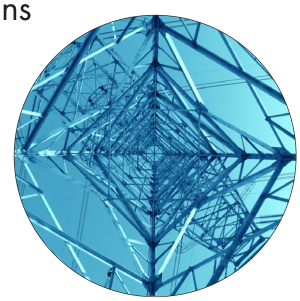
Contents.



Research.

Small Changes, Big Impact: Nudging Employees Toward Sustainable Behaviors

By: Laura Cappellucci, Lan Ha, Jeremy Honig, Christopher R. Knittel, Amy Vetter and Richard Wilner

In recent years, businesses have increasingly adopted aggressive sustainability goals such as reducing greenhouse gas emissions, reducing waste, and increasing recycling. The most popular strategy for reaching these goals is investing in cleaner technologies, with $1.7 trillion projected to be invested in sustainable energy in the United States in one year alone (IEA, 2023). Another complementary and more cost-effective strategy could be nudging employees to alter their behaviors to reduce waste. However, most of the literature related to this strategy focuses on altering behavior within the home, despite promising results. As such, the workplace is an under-explored setting for these kinds of sustainability interventions. We wanted to examine nudge strategies within the workplace in an effort to fill the research gap and identify cost-effective strategies for achieving sustainability goals.

To examine the workplace in this context, with the goal of promoting sustainable behaviors, we developed and facilitated three randomized control trials with biopharmaceutical company Takeda, which oversees over 160 plasma donation centers. Takeda has developed several sustainability goals, including a 5% reduction in water usage by 2025, zero waste-to-landfill by 2030, and net zero emissions of all direct and some indirect emissions by 2035, and the rest of their indirect emissions by 2040. Within Takeda's plasma donation centers, we identified three behaviors that we proposed contributed to operational errors that led to dropped collection materials, longer freezer door open times, and improper recycling practices that would negatively impact the company's sustainability goals.

The first behavior was the plasma collection itself, which uses sterile collection materials called "softgoods" that must be discarded if dropped on the floor. To promote handling these materials with greater care, we placed a clear plastic bin in an employee-only area with instructions to discard any softgoods into it, and also counted the number of dropped materials on boards within the centers, making the count visible to employees and serving as a constant and subtle reminder to be cautious when handling softgoods. The second behavior we identified concerned the freezing process for collected plasma in walk-in freezers at the centers, as each plasma donation must be frozen within a specific amount of time after collection. Excessive and elongated door openings can increase electricity consumption and direct emissions through leaking refrigerants. We chose to nudge employees to close the freezer doors within 50 seconds of opening (this is the maximum amount of time determined for a new employee to complete the task safely) by installing audible alarms that sounded every 30 seconds while the freezer doors were open to remind the

Laura Cappellucci, Lan Ha, Jeremy Honig, Christopher R. Knittel, Amy Vetter and Richard Wilner (2024), "Small Changes, Big Impact: Nudging Employees Toward Sustainable Behaviors", CEEPR WP-2024-17, MIT, October 2024. For references cited in this story, full bibliographical information can be found in the Working Paper.






staff, and again tracked outcomes on boards within the centers. The final behavior we identified was the inappropriate disposal of waste. A lack of ability to recycle due to improper disposal increases the rate of waste-to-landfill, negatively impacting sustainability goals. To encourage employees to correctly recycle materials, we worked with a third party provider to install AI-enabled in-dumpster cameras in each recycling bin. The cameras generated a weekly count of contaminants by type which were then translated into metrics that were again displayed on boards within the centers for the staff to see.

To evaluate the success of our attempts at altering employee behaviors to promote sustainability practices within the centers, we developed and ran three randomized control trials, with each experiment focusing on the aforementioned interventions for the three behaviors, over the course of about one year. Before each experiment/implementation of each intervention, we invited each treated center to a kick-off call to offer the center managers instructions and resources, and maintained weekly/monthly meetings to provide updated information and answer any questions. We compared the results of these trials to our estimated causal impact, which we calculated to account for several specifications using two methods; one that weighted our regressions with weights corresponding to the centers' average donation during the pre-experiment observation stage, and one that included donation-related variables in our control group variables. However, there were still some notable limitations within experiments. For instance, in experiment 2 (regarding freezer door openings) there was some imbalance between the control and treatment groups, and in experiment 3 (regarding recycling) the presence of a camera could have altered the staff's behavior. We should also note that any resulting sustainability benefits should be weighed against any burdens faced by employees within the workplace.

Ultimately, we found that our interventions related to softgoods translated to a decrease in softgood drops by at least 48% and by as much as 97%, which would decrease costs related to softgoods drops between 41% and 85%. In regards to our interventions related to the length and frequency of freezer door openings, we found that the interventions led to an average reduction of 44-48% in the duration of daily alarms as well as a reduction between 59% and 93% of the number of daily freezer door alarms. Finally, we found that our attempted interventions related to recycling practices in the centers aren't statistically significant, except with a small possible reduction by 20-41% of uncollapsed cardboard. However, these results are less confident due to an increase in uncollapsed cardboard within the treated centers just prior to the start of the experiment.

Essentially, though, our findings hold importance for any business looking for cost-effective ways to achieve their sustainability goals, and emphasizes the value and potential of behavioral nudges within the workplace as well as technological investments when it comes to meaningful sustainability efforts.

Ilenia Gaia Romani, Nicola Comincioli, and Sergio Vergalli (2024), "Climate Policy and Cartelization Risk for Critical Minerals: An Application to the Copper Market", CEEPR WP-2024-18, MIT, November 2024. For references cited in this story, full bibliographical information can be found in the Working Paper.

Research.

Climate Policy and Cartelization Risk for Critical Minerals: An Application to the Copper Market

By: Ilenia Gaia Romani, Nicola Comincioli, and Sergio Vergalli

Global demand for key minerals such as copper, nickel, cobalt, and Rare Earth Elements (REEs), crucial for advancing green technologies, has surged in recent years. These minerals are often found in geographically concentrated deposits, a feature that might facilitate the control by a restricted number of countries, limiting the competitiveness. Historically, mineral commodity markets have witnessed various cartels. For instance, the Organization of the Petroleum Exporting Countries (OPEC) has successfully controlled oil prices since its formation in 1960, thanks to the concentration of global oil reserves among its members. OPEC's market power is still ongoing, as it controls a significant portion of global oil production and reserves. Other examples include the Intergovernmental Council of Copper Exporting Countries (CIPEC) and the International Bauxite Association (IBA), which, despite some early accomplishments, eventually disbanded due to organizational challenges and geopolitical issues.

The geographical concentration of critical mineral reserves raises similar concerns. For example:

- The Democratic Republic of Congo (DRC) holds nearly half of the world's cobalt reserves;
- Mozambique dominates global graphite reserves;
- Argentina, Bolivia, and Chile (i.e., the "lithium triangle") hold half of global lithium reserves;
- China controls 34% of copper reserves, and Indonesia holds over 20% of nickel reserves.

These geographical concentrations might enable resource-rich nations to actively collaborate in controlling the market. Concerns were raised about the potential formation of an Organization of Metal-Exporting Countries (OMEC) or smaller cartels for specific metals like copper, nickel, and lithium. Such developments could allow countries to influence global prices and production, potentially impacting the downstream supply chain.

Historical examples like OPEC, CIPEC, and IBA demonstrate that while resource concentration is necessary for cartel formation, it is not sufficient. For a cartel to succeed, its members must:

- Coordinate production and enforce agreements;
- Ensure relevant additional gains from cartelization, to be likely outweighing the hard-to-estimate economic and political costs of collaboration.

This study assesses the potential for cartel formation in the copper market. This focus is motivated by copper's historical and technological significance, availability of data, and extensive research background. Our research uses a two-fold approach:

- Developing a comprehensive model of the copper market, incorporating demand, supply (both primary and secondary), reserves, and stock dynamics;
- Simulating two scenarios: a competitive and a cartelized market, where production quantity and market price are set endogenously, respectively.

By comparing potential price trajectories and the corresponding profits in these scenarios, the study evaluates whether the benefits of cartelization outweigh the associated costs.

Market price (Figure 1) is almost always higher in the cartelized scenario than in the competitive one, signaling the market power exerted by cartel members and the consequent allocative inefficiency. Moreover, despite the initial cartel volatility, in both cases the market price exhibits an upward trend. This dynamic is in line with the Hotelling's rule, according to which the price of an exhaustible resource rises as its depletion nears.

As for yearly profit (Figure 2), despite the initial price-induced volatility in the cartelized scenario, we observe that, for the first two decades, potential cartel members would make higher gains in the competitive scenario. Only around the midpoint of the depicted time frame, a flip occurs. Although profit is closely linked to market price, the dynamics of these two variables are different, as profit also depends on the quantity supplied to the market. Moreover, it is important to note that profits in the cartelized scenario exhibit fluctuations that cartel members would probably prefer to avoid, and that consuming countries could anticipate and counteract through stockpiling.

Another important information is provided by the cumulative profit over the considered time horizon. Specifically, over 45 years, the cumulative profit of potential cartel members is 3.47×10^{11} USD if they act as competitive players, compared to 5.41×10^{11} USD if they actually form a cartel. Given that the decision to form a cartel is a lengthy process based on long-term projections, the fact that cartelization yields higher gains than perfect competition in the long run might still provide valuable insights to potential cartel members. On one hand, if cartel members were to adopt a long-term perspective, they might find it worthwhile to wait decades to maximize their profits. This approach could be sustainable, particularly when reserves are abundant and won't be depleted for a long time. On the other hand, cartels might instead take a shorter-term view, due to the higher risks of external disruptions, especially when reserves are in less stable or less developed countries. Factors like political instability, challenges in maintaining cooperation among members, or even abrupt regime changes can shorten a cartel's expected lifespan and reduce its viability. As a result, it is difficult to predict with certainty whether a cartel might form in the global copper market. However, our findings highlight the presence of conditions that could support its formation, consistent with earlier studies that have observed oligopolistic tendencies in the copper market.

Addressing the risk of cartelization in the copper market requires proactive measures from governments and regulators. Strengthening supply chain resilience is one key strategy. This might involve developing new copper mining sites in diverse locations or forming strategic partnerships to reduce reliance on a few dominant suppliers. Trade diversification could also help counterbalance the influence of any potential cartel.

Another approach is to explore alternatives to copper where feasible. However, this is challenging because of copper's unique properties, which make it difficult to substitute in many critical applications. In some cases, copper itself is used as a lower-cost substitute for more expensive metals, like silver. For this reason, investing in technologies that reduce copper intensity or adopting alternative energy solutions, such as less copper-dependent sub-technologies, could be impactful.

Then, boosting the supply of recycled copper could also play a significant role. Expanding domestic smelting capacity for copper scrap and increasing recycling rates could help mitigate potential shortages. Tapping into existing unused copper stocks could also contribute to meeting demand more sustainably. Beyond addressing immediate supply concerns, these actions could finally also foster a more circular economy, reducing waste and enhancing sustainability.

Figure 1

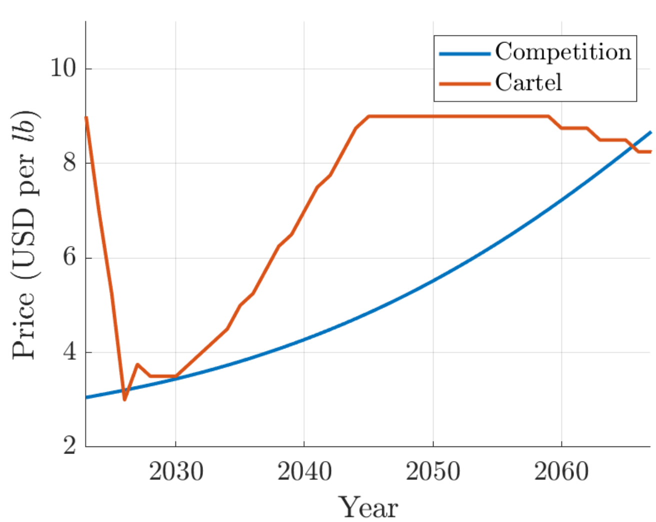
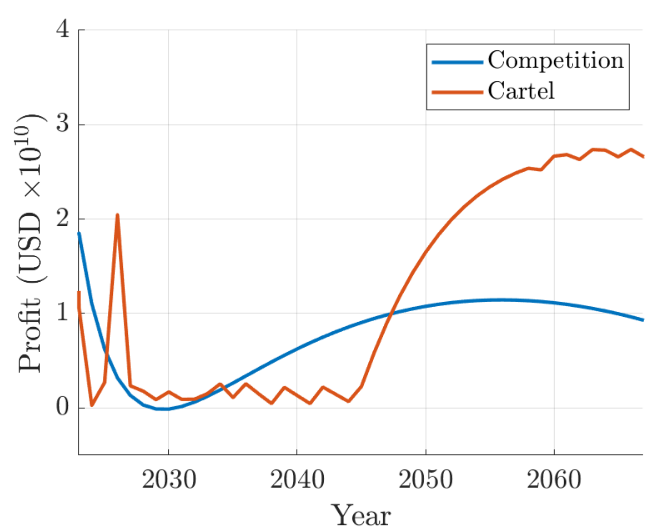


Figure 2



Notes: Figure 1 shows the optimal price trajectory, and Figure 2 the consequent profit dynamics, over a 45-year time horizon, for both the competitive and cartelized scenarios.

Michael A. Mehling (2025), "Good Spillover, Bad Spillover: Industrial Policy, Trade, and the Political Economy of Decarbonization", CEEPR WP-2025-01, MIT, January 2025.

Research.

Good Spillover, Bad Spillover: Industrial Policy, Trade, and the Political Economy of Decarbonization

By: Michael Mehling

Empirical research suggests that spillover effects frequently exceed the intended impacts of policy decisions. Knowledge and technology spillovers of early policies to promote renewable energy, for instance, precipitated the rapid cost decline and worldwide diffusion of solar photovoltaic energy, which has been identified by the Intergovernmental Panel on Climate Change as the largest near-term contribution to greenhouse gas emission reductions. Just as spillover effects have enabled past successes in climate change mitigation, however, they also threaten to undermine accelerating decarbonization efforts. While contested in its magnitude, emissions leakage — when emissions associated with production, consumption or investment patterns are displaced as a result of climate policies — could stall or reverse progress with decarbonization if emissions merely relocate rather than undergo an aggregate decline.

Because they are difficult to define and quantify, spillover effects have been neglected in the theoretical framing of climate policy instrument choice. Research on them remains fragmented, with no unifying definitions or methodological framework. Some spillover effects have been extensively studied, while others remain opaque, with scarcely understood causal mechanisms and interactions. That may now change, as influential actors and initiatives, such as the Inclusive Forum on Carbon Mitigation Approaches, the G7 Climate Club, and a task force of international organizations led by the World Trade Organization, have recently begun to feature spillover effects in their work. While a promising development, the initial outputs of these efforts reflect the lack of an overarching conceptual paradigm and reveal a disciplinary bias in the spillover effects selected for further exploration.

In common usage, the term 'spillover' refers to situations in which activities in one context generate effects in another context. Past research shows that spillover effects can be positive or negative, intended or unintended, and manifest themselves across a variety of dimensions: time horizons, geographies, markets, sectors, companies, technologies, functions, and behaviors. They share many features with the economic concept of externalities, but have also been studied in non-market settings. Geographic spillover effects mediated through international trade have received the greatest attention in the policy debate, and also feature in a growing number of policies aimed at mitigating transboundary spillover harm.

Spillover effects also have implications for the political economy of climate action. Spillover effects beneficial to climate action tend to correlate with policy interventions that socialize the cost of decarbonization, such as subsidies for the development and deployment of emission reduction technologies. Harmful spillover effects, by contrast, tend to accompany policy interventions that impose a private cost on emissions, such as carbon pricing. Research has consistently affirmed that this latter category of policy interventions faces greater political economy constraints, because it incurs immediate and concentrated costs while only yielding diffuse, long term benefits. A strategy emerging from this observation, the idea of 'policy sequencing', acquires new relevance in the presence of spillover effects, creating opportunities for staged interventions that initiate a virtuous policy cycle to build supportive constituencies and increase climate policy ambition.

Recent policy trajectories in the United States and the European Union present a case study for the rise of industrial policy and its ramifications for the spillover effects of climate action. Responding to the economic shocks of a global pandemic and escalating military conflicts in different regions of the world, as well as distributional consequences arising from decades of expanding trade liberalization, both sides of the Atlantic are increasingly resorting to market interventions to accelerate decarbonization while advancing economic, social and political priorities. Spillover effects — such as supply chain disruptions, surging energy costs, and erosion of the domestic industrial base — have prompted many of these industrial policies, which will in turn result in new and unanticipated spillover effects.

A shared feature of the current generation of industrial policies is their reliance on provisions that limit or condition access to markets and incentives, such as border carbon adjustments and product carbon requirements, anti-dumping tariffs, countervailing duties, local content requirements, and export controls. Not only are these measures regularly opposed by trade partners, threatening to destabilize international climate cooperation, but they also erect barriers to the international flow of goods, services, capital, and knowledge which enabled past spillover benefits. While the concerns these policies seek to address are valid, their implications — including spillover effects — need to be carefully understood. Unconsidered use of trade-related climate measures risks increasing the cost and time horizon of decarbonization, while also inciting diplomatic tensions. Long-term implications for innovation spillovers and learning rate effects, in particular, need to be better understood.

Strategic cooperation is needed to manage spillover effects for enhanced climate action. Cooperation can help leverage positive and limit negative spillovers while promoting a virtuous sequence of technology and policy diffusion. First, spillover effects need to be better understood in order to inform planning and policy decisions, using common metrics and improved tools to reflect them in economic modeling and regulatory impact assessments. Second, cooperation can help identify principles and best practices for domestic policy design to actively promote spillover benefits and limit spillover harm. Third, countries should expand existing partnerships on technological innovation and climate finance, deploying new collaborative mechanisms that align incentives for the diffusion of climate policies and emission reduction technologies. Strategic cooperation can help trade fulfill its potential as an enabler of — rather than threat to — enhanced climate action.

Context	Example	Description	Climate Implication
Time Horizons	Green Paradox	Increase emissions in the near term due to anticipated regulation	Harmful
Geographies	Emissions Leakage	Emission shifts across geographies due to policy interventions	Harmful
	Policy Diffusion	Adoption of mitigation policies across geographies	Beneficial
	Technology Diffusion	Adoption of clean technologies across geographies	Beneficial
Markets	Price Effects across Interconnected Energy Markets	Changes in value of renewable energy resources due to growing penetration across markets	Harmful
Sectors	Waterbed Effect	Emission shifts across sectors due to policy interventions	Harmful
Companies	Knowledge Spillovers	Innovation and learning by doing benefits shared across firms	Beneficial
Functions	Functional Spillovers	Political integration	Beneficial
Knowledge	Technology Spillovers	Innovation effects transmitting across different technologies	Beneficial
Behaviors	Peer Effect	Changes in social norms or motivation	Beneficial
	Rebound Effect	Efficiency gains stimulate higher energy use	Harmful

Table 1: Types of climate-related spillover effects described in the literature, across contexts and with observed climate implications.

Research.

In the Vortex of Great Power Competition: Climate, Trade, and Geostrategic Rivalry in U.S.–China–EU Relations

By: Michael Mehling

Geopolitical tensions increasingly threaten global climate cooperation. Great power competition between the United States, the European Union, and China complicates effective climate action by embedding it within broader geopolitical conflicts. International cooperation between these actors has been pivotal for past successes, such as U.S.-China coordination preceding adoption of the 2015 Paris Agreement. Current geopolitical tensions reveal how economic pressures, stakeholder interests, and electoral politics at the national level can overshadow climate diplomacy, preventing a global solution to a quintessential collective action problem. Nowhere are these tensions more evident than at the nexus of climate and trade policy.

Accordingly, recent climate policies of the U.S., EU, and China reflect divergent strategies shaped by domestic politics and economic priorities. Climate policy in the U.S. has oscillated dramatically across administrations, evidencing deeply partisan views and the influence of incumbent interests in what is now the world's largest oil and gas producer. Europe demonstrates policy continuity with ambitious decarbonization targets, yet faces growing headwinds from domestic electoral shifts, regional security risks, and persistent concerns about economic competitiveness. As the world's largest emitter, China embodies a paradox, simultaneously increasing fossil fuel consumption while expanding its dominant lead in low-carbon technology manufacturing, deployment, and innovation.

More recently, climate and trade policies have become increasingly intertwined with geopolitical strategy. Countries routinely deploy trade-related climate measures to secure competitive advantages and influence geopolitical dynamics. Concurrently, supply chains for low-carbon technologies and critical raw materials have emerged as strategic battlegrounds, highlighting security concerns and prompting efforts to reduce dependency on rivals, notably China's market leadership achieved through targeted state support, vertically integrated production, and economies of scale and agglomeration. Trade interventions can provoke retaliatory action, however, and interfere with efficient resource allocation in line with comparative advantage, threatening to increase the cost and timeline of decarbonization.

Scenario analysis offers useful insights into how geopolitical dynamics can shape future climate action. In a context of significant uncertainty, scenario analysis provides a structured approach for assessing multiple plausible trajectories and how strategic choices can shape future outcomes. As such, it can help explore alternative strategic equilibria, where tipping points in political or economic conditions may propel actors towards different responses. Employing a two-level game framework, which emphasizes the interplay between domestic politics and international cooperation, a new Working Paper examines three scenarios that illuminate how economic interests, political constraints, and strategic rivalries align or conflict with global climate objectives and international coordination.

The first scenario, competitive cooperation, envisions intensified competition that delays, but does not altogether derail, global climate action. While sectoral priorities diverge, great powers vie for technological leadership, stimulating innovation, cost declines, and market-driven deployment. U.S. subnational and private sector momentum, sustained EU policy ambition, and continued Chinese industrial strategy all contribute to emission reductions despite diplomatic tensions and fragmented markets. Cooperation on less sensitive issues, such as emissions reporting standards or non-CO_2 gases, allows limited but productive engagement at the international level, while efforts to expand spheres of influence and cooperate bilaterally accelerate decarbonization in the developing world.

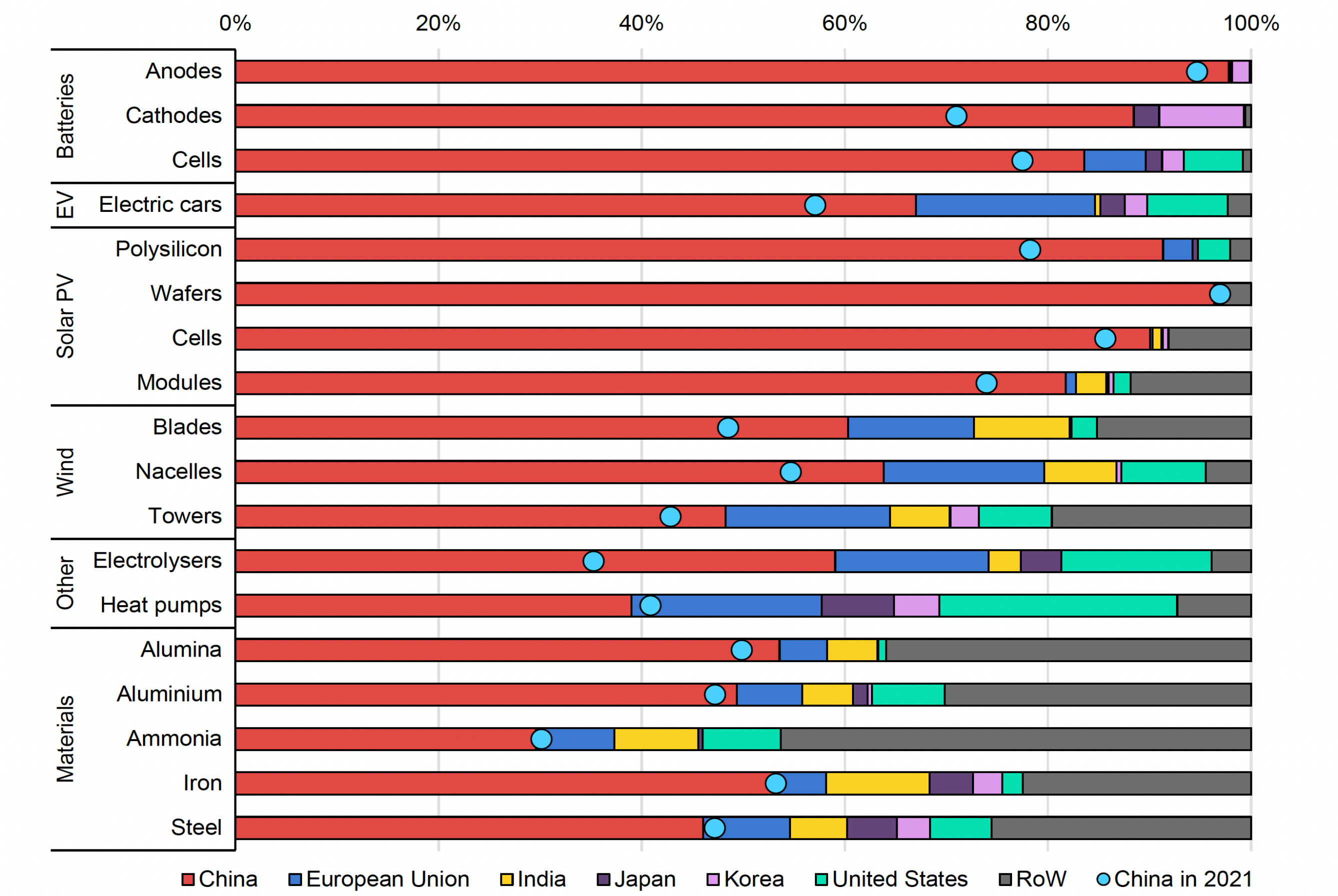


Figure 1. Installed Low-Carbon Technology Manufacturing Capacity by Country/Region, in % (2023).
Note: RoW = Rest of World. Source: IEA (2023).

In the second scenario, geopolitical fragmentation severely undermines climate action. Heightened nationalism, economic protectionism, and strategic hostilities dominate, with each power prioritizing domestic economic and political objectives over collaborative climate goals. The U.S. embraces its fossil fuel interests and joins forces with other petrostates to obstruct global climate progress; the EU is paralyzed by internal divisions and fraying security alliances; and China doubles down on economic and political nationalism, further alienating its trade partners around the world. Formerly integrated markets splinter into competing trade blocs, resources are diverted to a new global arms race, and emissions rise unchecked as climate action stagnates, leading to a vicious cycle.

A third scenario envisages a dramatic reversal of traditional climate leadership roles, with China assuming global leadership. Driven by economic self-interest, public pressure, and geostrategic ambitions, China substantially accelerates its decarbonization efforts at home and —through vehicles such as the Belt and Road Initiative—abroad. As domestic reforms and international investments bolster China's global status, the U.S. cedes influence in a world that has moved beyond peak fossil fuel demand. Striving to lower its traditional dependence on the U.S. for military security and increasingly for energy, Europe cautiously turns to China as a pragmatic partner in building renewed support for multilateral cooperation. A new world order emerges.

As the foregoing scenarios demonstrate, navigating the evolving geopolitical landscape requires a delicate balancing act to create space for climate action. The fraught interplay of competition and cooperation between the U.S., the EU, and China presents significant challenges, but also harbors new opportunities for decarbonization. Despite the risks posed by current economic and political trends, confidence building measures and policy alignment remain possible. Rebuilding bilateral and multilateral communication channels, insulating climate cooperation from broader geopolitical disputes, and enhancing domestic policy continuity can all be constructive ways forward, but in the end climate goals need to align with national interests for decisive and sustained progress.

Michael A. Mehling (2025), "In the Vortex of Great Power Competition: Climate, Trade, and Geostrategic Rivalry in U.S.–China–EU Relations", CEEPR WP-2025-11, MIT, June 2025.

Diego S. Cardoso, Stephen W. Salant, and Julien Daubanes (2025), "The Dynamics of Evasion: The Price Cap on Russian Oil Exports and the Amassing of the Shadow Fleet", CEEPR WP-2025-05, MIT, March 2025. For references cited in this story, full bibliographical information can be found in the Working Paper.



Research.

The Dynamics of Evasion: The Price Cap on Russian Oil Exports and the Amassing of the Shadow Fleet

By: Diego S. Cardoso, Stephen W. Salant, and Julien Daubanes

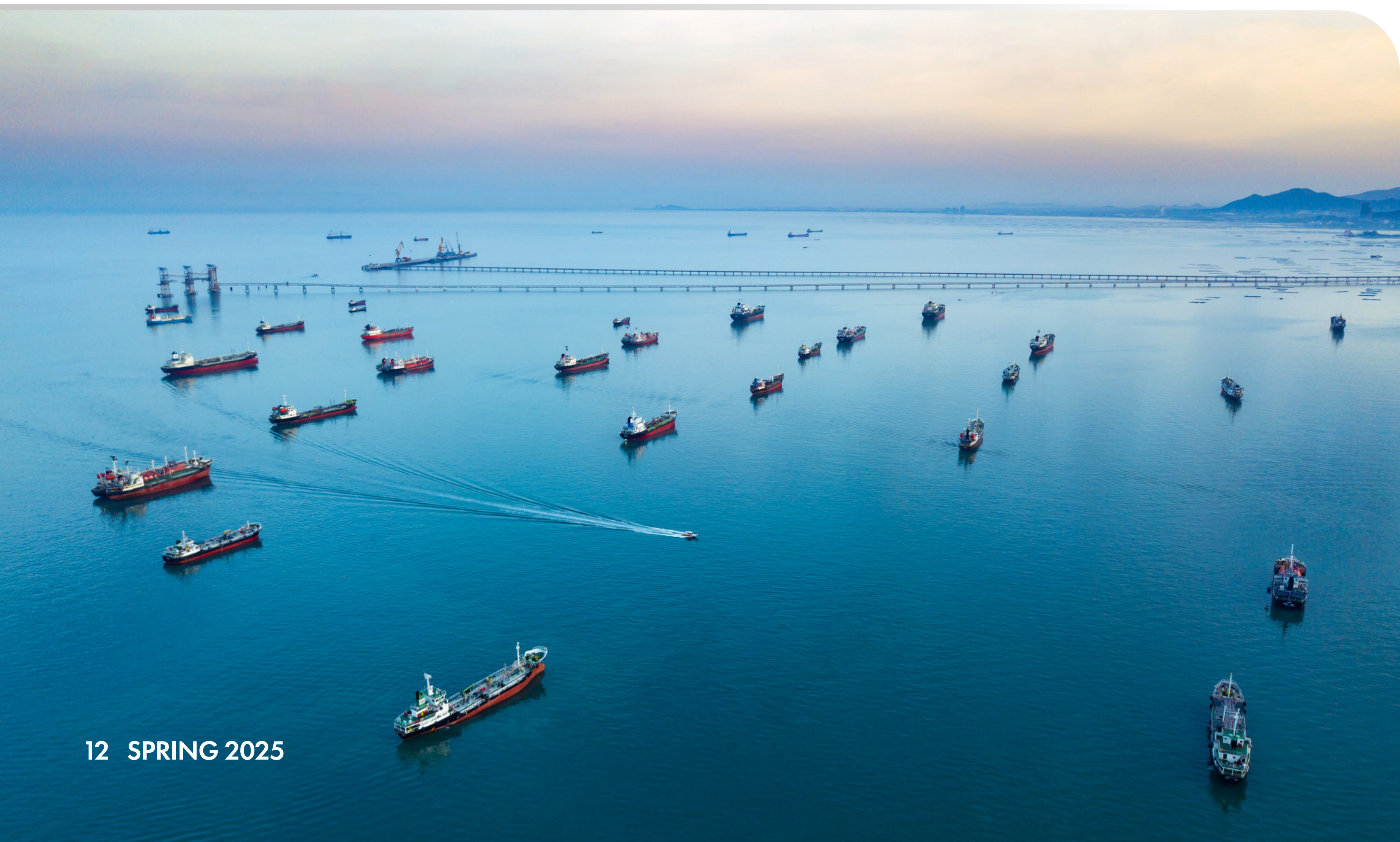
In response to Russia's invasion of Ukraine in February 2022, the EU, the US, and other G-7 countries (hereafter the West) ceased their imports of Russian oil, leading Russia to export more to India, Turkey, and China instead. In addition, the West imposed sanctions on oil exports from Russia, whose profits are instrumental in supporting its war.

Since more than 80% of Russia's seaborne oil exports relied on the provision of Western services (CREA, 2023)—financial, operational, and commercial—the EU suggested banning the use of these Western services on all Russian seaborne exports. Yet governments feared that this would have caused a spike in the world oil price. As an alternative, the US suggested a price cap, which the West ultimately imposed in December 2022, limiting Russian revenues from oil shipped using Western services to $60 per barrel.

Oil transported without Western services is exempt from the cap. Therefore, Russia gradually assembled a "shadow" fleet that uses non-Western services in order to sell oil at prices above the cap.

The price cap on Russian oil is a new, untested economic sanction, currently a subject of active discussion. In their pioneering contribution to this literature, Johnson, Rachel, and Wolfram (2025) provide a rich analysis of the effects of the price cap, albeit under the assumption that the shadow fleet has a fixed capacity.

In this MIT CEEPR working paper, Cardoso, Salant, and Daubanes (2025) present a new dynamic equilibrium model that accounts for the expansion of the Russian shadow fleet. The model is calibrated to reproduce observed facts and used to simulate the effects of (1) various levels of the price cap, including the extreme case of a complete ban, of (2) enforcement stringency, and of (3) policies targeting the shadow fleet.



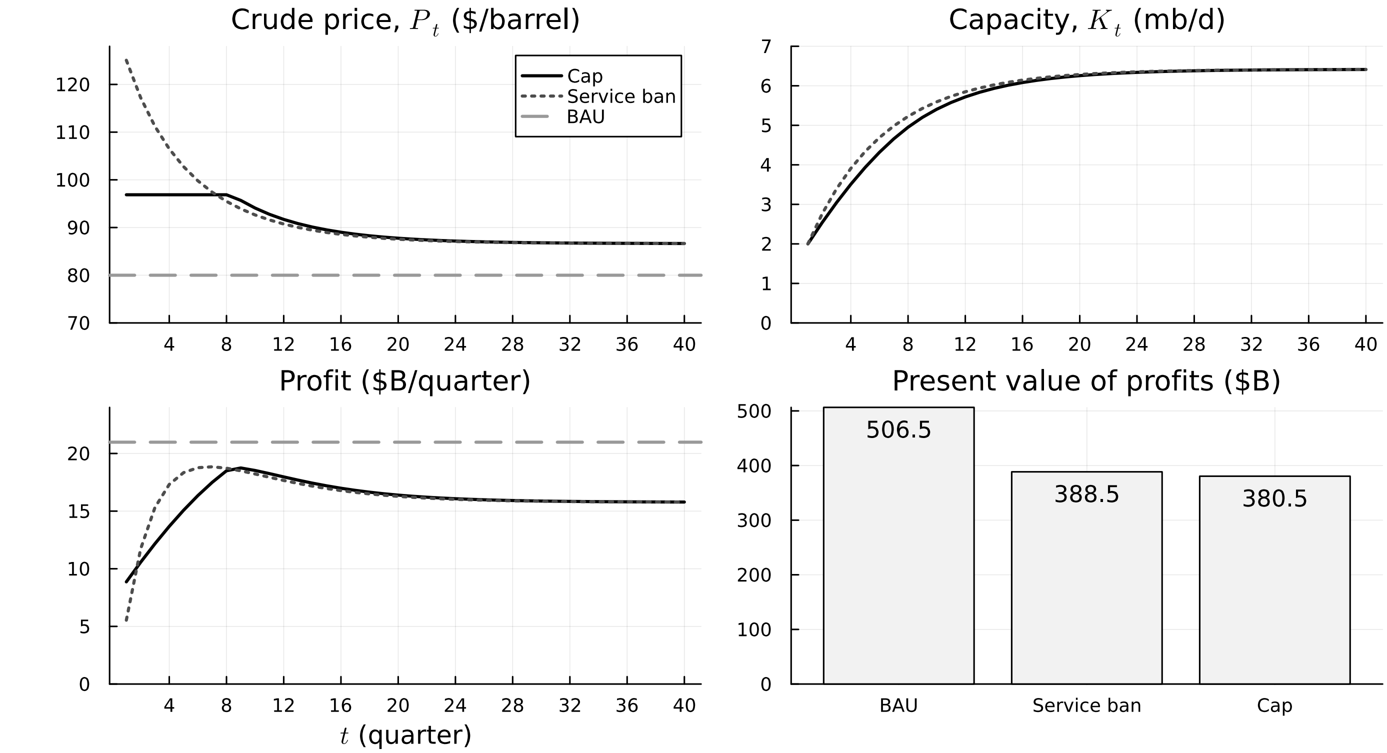


Figure 1: A comparison of prices, capacity, and profits under a price cap sanction (solid lines) and a service ban (dotted lines). The line graphs display only the first 40 quarters of the 80-quarter simulation.

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Perhaps surprisingly, our research shows that lowering the cap below $60 would not hurt Russia further unless a robust expansion in non-Russian oil supply occurred in response; in fact, lowering the cap could even moderately increase Russian profits. More generally, the model reveals that a lower cap would have two opposite static effects on Russia: On the one hand, it would reduce its profit (i.e. revenues net of production costs) from sales at the cap. On the other hand, since a lower cap would reduce Russia's oil exports, it would increase the oil price and, therefore, Russia's profit from sales through its shadow fleet. The paper's model links shadow fleet capacity to sales at the ceiling price. When sanctions were imposed, Russia's relative shadow fleet capacity was already sufficiently high for Russia to benefit from higher oil prices. Moreover, dynamic simulations indicate that these higher oil prices would have prompted Russia to rapidly further expand this fleet. As a result, Russia's discounted profits would have been slightly larger if a service ban or a lower-than-$60 cap were imposed.

All these sanctions quantitatively impact Russian discounted profits (i.e., export revenues net of production and investment costs) in a similar way. For example, the $60 cap reduces Russian profits by about 25% with respect to the absence of sanctions and the complete ban would have impacted Russia only slightly less.

The figure above shows a comparison of prices, shadow fleet capacity, and profits under a price cap sanction (solid lines), a service ban (dotted lines), and the absence of sanctions (grey dashed lines). The simulations assume no supply response from non-Russian producers (none occurred when the cap was first implemented). A lower cap cuts Russian exports and raises the global oil price, raising Russian profits on its fleet sales. A non-Russian supply response would dampen this oil price spike and would, therefore, diminish the resulting revenue increase in Russian fleet sales.

Russia sometimes uses Western services to ship oil at a price above the cap, taking the risk that its shipments get sanctioned. Increasing the probability that cheating is punished lowers the expected price for Russia, with consequences formally identical to a reduction in the cap level: Tighter enforcement would increase Russia's discounted oil profits.

By contrast, policies that sideline part of the shadow fleet may harm Russia, even though they prompt Russia to rebuild its fleet rapidly. This happens, for example, if the neutralization of the fleet occurs while oil is also being sold at the ceiling, so that ceiling sales replace the lost fleet sales.

Overall, these results justify using the price cap instead of the service ban and maintaining the cap at its current level instead of a lower one. They also call for attention to complementary energy policies that would facilitate the response of non-Russian oil production to higher global prices.

Research.

Addressing Uncertainty in the Joint Production of Energy Transition Metals

By: Mahelet G. Fikru, Adrienne Ohler, and Ilenia G. Romani

The global shift towards clean energy and decarbonization has led to a significant increase in demand for critical raw materials such as copper, cobalt, and nickel. These metals are essential components of energy transition technologies, including batteries, electric vehicles, and renewable energy infrastructure. However, their production is subject to significant uncertainties related to costs, market demand, regulatory policies, and technological developments, that make planning and investment decisions more complex. Unexpected cost increases can affect how companies allocate resources, while shifting environmental policies can influence decisions about waste management and sustainability efforts. In addition, metal prices can be highly volatile, with fluctuations leading to significant increases in the cost of producing clean energy technologies. Some estimates suggest that metal price changes alone could raise the costs of renewable energy production by 13% to 41%, making it more difficult to meet sustainability goals. These price shifts often stem from uncertainties in mining and supply chains, which can delay investments as companies struggle to predict future profitability. Moreover, the rapid pace of technological change in mineral extraction and processing adds another layer of uncertainty. Environmental regulations further complicate the picture, as governments introduce new policies on waste management and ecological restoration that affect mining operations.

While recent studies have explored how market uncertainties affect green investments, there is still limited understanding of what drives fluctuations in metal production costs, ore extraction, and waste management. These challenges become even more complex when multiple metals are extracted from the same ore at a single mining site. When two or more metals are produced together, changes in the market conditions, costs, or regulatory policies for one metal can have ripple effects on the production and cost structure of all co-produced metals. These interdependencies introduce operational complexities and amplify uncertainties in investment and production decisions. This is particularly true for critical minerals such as cobalt, which face greater technological uncertainties compared to base metals like copper.

Although there is increasing research on the demand for energy transition metals, few studies have examined how technical, economic, and policy factors interact to shape production costs and environmental outcomes, particularly in cases where multiple metals are produced from a single ore. In addition, the relationships between primary and secondary metals in joint production remain poorly understood. This study aims to fill that gap by introducing an economic model that accounts for multiple sources of uncertainty in joint metal production, i.e., cost parameters, total factor productivity, output elasticity, waste intensity, and regulatory fees.

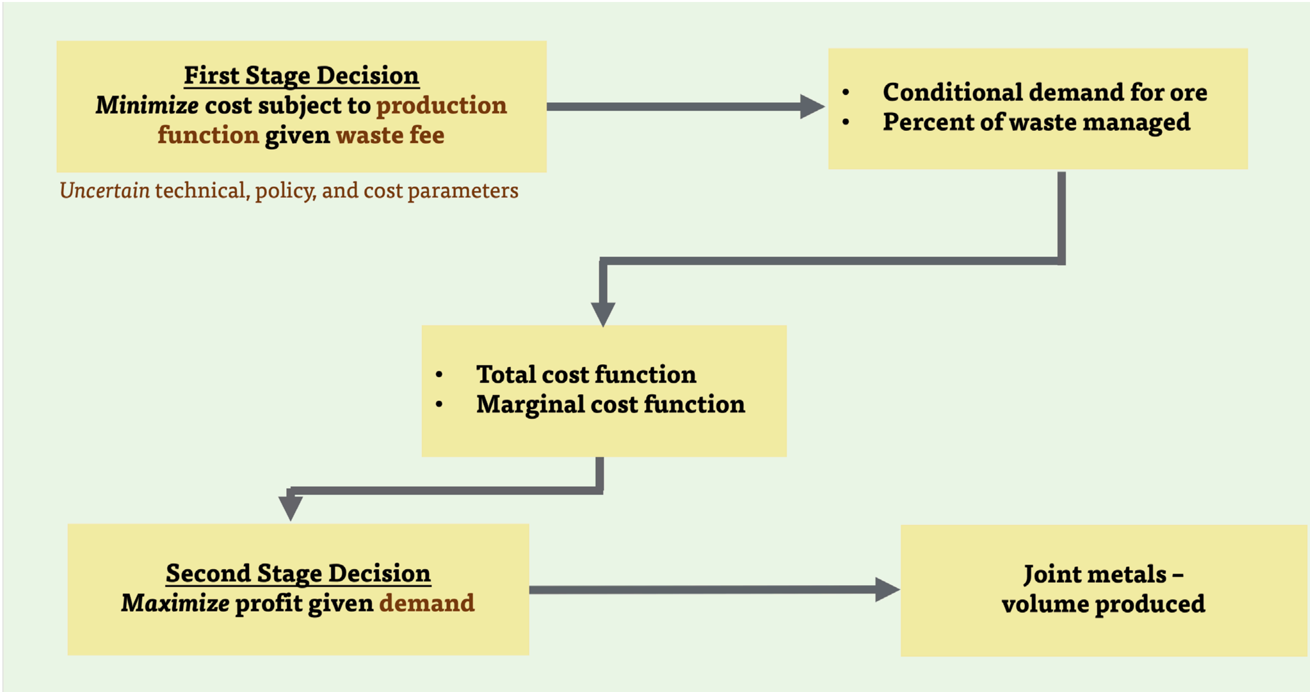


Figure 1: Double optimization framework used in the working paper.

To understand the dynamics behind the variations of costs and ore processed, we analyze data from 114 mining projects worldwide. These empirical insights are then used to develop an economic optimization model of joint metal production, which is described graphically in Figure 1. The model analyzes the effects of key parameters, i.e., cost, technical (technology, output elasticity, waste intensity) and policy parameters (waste regulation fees), on the marginal costs of metal production, the volume of ore processed, and the percentage of waste managed. Finally, we apply Monte Carlo simulations to visualize the variation in model outputs and identify key factors contributing to this variability. Through this comprehensive approach, our work aims to clarify the complex dynamics that affect joint metal production, offering valuable insights for stakeholders in the mining sector.

The analysis reveals several critical insights regarding the cost dynamics of joint metal production.

First, marginal production costs are most sensitive to output elasticity rather than waste intensities or fees. This suggests that improving production efficiency through technological advancements can significantly reduce costs.

Second, ore demand is driven primarily by output elasticity, waste fees, and processing costs, rather than total factor productivity alone. This highlights the importance of regulatory policies and technological innovations in shaping ore extraction decisions.

Third, the proportion of waste managed is more responsive to waste fees and abatement costs than to production parameters, underscoring the role of regulatory frameworks in driving environmental outcomes.

These results suggest that improving production parameters can significantly enhance the economic viability of joint metal production by lowering marginal costs. This also emphasizes the need for mining firms to prioritize investments in technology and innovations to better navigate uncertainties and improve overall production outcomes in the rapidly evolving landscape of energy transition metals. Finally, the fact that the percentage of waste managed is more sensitive to the waste fee than to cost and production parameters underscores the need for ongoing investment in technological advancements and robust environmental policy frameworks to optimize production while minimizing environmental impacts.

Mahelet G. Fikru, Adrienne Ohler, and Ilenia G. Romani (2025), "Addressing Uncertainty in the Joint Production of Energy Transition Metals", CEEPR WP-2025-07, MIT, April 2025. Full bibliographical information can be found in the Working Paper.

Research.

Firm Presence, Pollution, and Agglomeration: Evidence from a Randomized Environmental Place-Based Policy

By: Michael Gechter and Namrata Kala

Firm location decisions are one of the most important choices managers make, optimizing factors such as proximity to customers, suppliers, and useful information. At the same time, these decisions may have spillover effects on local neighbourhoods, by impacting environmental quality and contributing to local economic activity. For this reason, numerous policies attempt to change location choices of firms. The fact that firms can choose their locations based on factors we don't measure makes estimating the impact of firm presence on the local economy difficult. Policies that shock firm location decisions are typically implemented with additional components and across metropolitan areas, making it difficult to find an appropriate comparison group and to isolate the specific effect of firm presence.

In this project we examine the effects of a policy which relocated over 20,000 firms from high-population-density areas in central Delhi to industrial areas on the outskirts of the metro area, with a main stated goal of reducing aggregate exposure to air pollution. A unique feature of this policy is that, due to a shortage of industrial plots when relocation began, plot allotment was done via a series of lotteries between 2000 and 2005, with firms actually moving between 2006 and 2010. This generates random variation in firm presence over the time period, between neighbourhoods with a greater number of firms receiving a plot earlier in the process, and those with a greater number of firms receiving a plot later in the process (conditional on the total number of firms relocated from a neighbourhood). It also generates random variation within the industrial area on who a firm's neighbours are since, conditional on plot size and lottery year, the allocation of firms to plots was also random. We study how the policy impacted the relocated firms, and whether the effects of firm interactions revealed by its design imply that the design could have been improved. We also evaluate whether the policy achieved its desired goal of improved air quality.

Location restrictions that seek to limit pollution exposure have a long history, starting with the first zoning laws introduced in the early 20th century in New York in part to improve environmental quality (Wilson et al 2008). Harrison et al (2019) study how Indian Supreme Court-ordered Action Plans for 17 cities affected firm decisions in corresponding districts to exit or invest in pollution abatement. A primary means to reduce pollution mentioned in these action plans was relocation of polluting industries to certain designated areas. 14 of 17 Action Plans in major cities mention industrial relocation. Industrial relocation policies to combat pollution are also an increasingly popular policy tool across the developing world, such as China's industrial relocation policy to move polluting industries outside of Beijing city limits by 2017.

Policy and Research Design

Since each plot in the industrial areas was assigned a random firm, a relocated firm's distance from its original location is random when compared to other firms from the same location. To take advantage of this historical randomized experiment, we combine administrative data from the Delhi State Industrial and Infrastructure Development Corporation Ltd. (DSIIDC) and digitized maps of the industrial areas to identify each firm's precise location and neighbours. Using a combination of natural language processing and manual assignment, we determine each firm's industry based on a free text description the owner provided to DSIIDC.

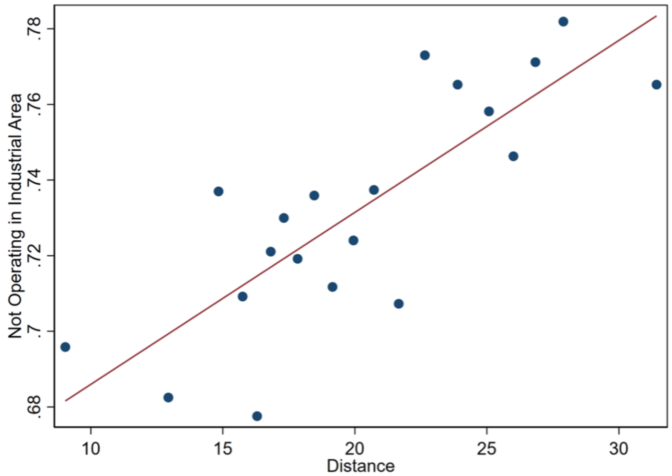
The lotteries also mean that different concentrations of eligible firms left neighbourhoods throughout Delhi at different (random) times, creating variation in polluting firm presence by neighbourhood. To identify a firm's origin location we geocoded the addresses they provided to DSIIDC, making on-the-ground visits to roughly half to validate our approach.

Effects on Relocated Firms

DSIIDC data from 2018 shows that 74% of firms in the largest industrial area were no longer operating in their assigned plot, roughly 10 years after firms first set up shop there. The probability of exiting is increasing in the distance between a firm's original address and their location in the industrial area, as shown in Figure 1. Using the random variation in distance relocated, we can attribute 28 percentage points of the 74% exit rate to relocation alone.

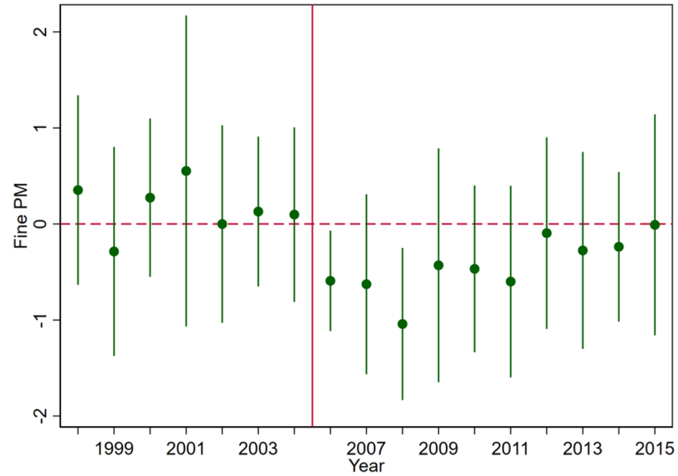
Given that firms typically form geographic clusters by industry, how damaging was the policy's random assignment of plots to firms, which spread all industries evenly across industrial areas? We take advantage of the random assignment of firms to neighbourhoods to identify the impact of different neighbourhood industrial compositions on a firm of any industry. We find that the large majority of neighbourhood composition effects on firm survival are driven by the fraction of firms in the neighbourhood with upstream and downstream linkages, and the fraction of firms producing the same product. Upstream linkages having the strongest impact, with a substantial positive effect on survival.

We then use our estimated neighbourhood composition effects to arrive at an optimal industrial area neighbourhood composition, with the goal of maximizing firm survival. We find that the optimal neighbourhood composition would have cut the effect of relocation on exit roughly in half, increasing firm survival by about 14 percentage points.



Note: binscatter of relocated firm exit rates as a function of the distance between assigned plot in the Bawana industrial area and original location, along with a best-fit regression line. Source: DSIIDC (2018), Authors' calculations.

Figure 1: The majority of relocated firms were not operating in the industrial area 10 years later.



Note: points show the effect on fine particulate matter (PM 2.5, micrograms per cubic meter) of 1% more polluting firms in a neighborhood having won a plot by 2004. 2005 is Omitted. Bars represent 90% confidence intervals.

Figure 2: Firm relocation decreased pollution.

Effects on the Neighbourhoods Firms Departed

We use the random timing of firm removal to estimate the causal impact of firm presence on neighbourhood environmental quality, specifically air pollution. We use a relatively fine definition of neighbourhood, a 1km by 1km grid-cell, which is the level at which air pollution measurements from van Donkelaar et al. (2021) are available. This allows us to test whether the relocation policy achieved its environmental objectives. A reduction in air pollution should not ex ante be taken for granted because India, like most developing countries has limited regulatory capacity. The relocated firms might move back, be replaced by other polluting firms, or pollution may increase due to, for example, the policy's enabling growing vehicular emissions.

Accounting for the total number of firms that were relocated in a neighbourhood, we compare neighbourhoods that on average relocated a higher number of these firms earlier vs. later, with the timing randomly generated by the allotment of plots to firms via lottery. We find that the average neighbourhood impacted by relocation experiences a 1.7 microgram per meter cubed drop in particulate matter (PM) levels. This is a drop of about 1.6% of the mean fine PM concentration for the average neighbourhood. Since industrial pollution contributes about 20% to Delhi's PM 2.5 (Sharma et. al. 2018), relocation reduced industrial pollution in Delhi by 8% for the average neighbourhood. Figure 2 breaks out the effect by year of having one percent more lottery winners in a neighbourhood by 2004.

Cost-Benefit Analysis

Finally, we conduct a back of the envelope cost-benefit exercise for the policy. We've seen that relocation reduces air pollution in the sending regions, but is costly for the relocated firms. In our cost-benefit analysis, we convert the reduction in PM levels to the statistical value of lives lost and compare this to costs associated with firm death, finding that the benefits outweigh the costs. Notably, optimal assignment of firms to plots in the industrial area taking into account neighbourhood composition effects would cut the cost of relocation roughly in half.

Michael Gechter and Namrata Kala (2025), "Firm Presence, Pollution, and Agglomeration: Evidence from a Randomized Environmental Place-Based Policy", CEEPR WP-2025-09, MIT, May 2025. For references cited in this story, full bibliographical information can be found in the Working Paper.

Lassi Ahlvik, Tuomas Kaariaho, Matti Liski and Iivo Vehviläinen (2025), "Household-Level Responses to the European Energy Crisis", CEEPR WP-2025-08, MIT, April 2025.




Research.

Household-Level Responses to the European Energy Crisis

By: Lassi Ahlvik, Tuomas Kaariaho, Matti Liski and Iivo Vehviläinen

High energy prices—driven by supply disruptions, renewable energy intermittency, and climate policies—have become central to policy discussions. A key concern is the financial burden that high energy prices impose on households. Assessing whether this concern is justified requires understanding households' capacity to adjust to elevated energy costs. The European Energy Crisis created a natural experiment to study how households respond when energy prices rise unexpectedly. To identify causal effects of high energy prices, we exploit a natural experiment based on the quasi-random expiration dates of two-year, fixed-price electricity contracts. Households whose contracts expire during the peak of the crisis suddenly faced large, overnight price increases (the "treated" group), while those with contracts ending later still paid their lower, pre-crisis rates (the "control" group). Using a stacked difference-in-differences research design, the study identifies significant differences in households' ability to respond. When energy prices double, the households respond as follows:

Electricity Use: Households reduce their electricity consumption by about 18.4% in response to a doubling of the electricity price. Higher-income households are more responsive, likely because they can afford efficiency upgrades or have more discretionary usage to cut back.

Labor Earnings: Households overall increase labor earnings by about 1.4% in response to doubling electricity costs. This effect is strongest among middle-income groups. Low-income households often have weaker labor-market attachments, limiting their ability to earn more.

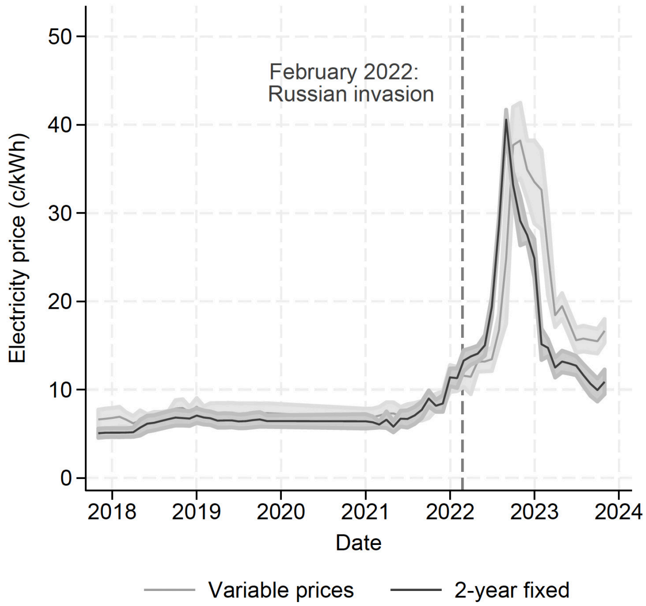


Figure 1: Mean electricity contract prices in Finland.

Financial Distress: We find about a 0.4 percentage-point rise in default probability (roughly a 4% overall increase) follows a price doubling. Low-income and heavily indebted households are at the highest risk, while high-income households avoid serious financial distress.

Residual Consumption: Using the administrative data, we can impute households' residual consumption and savings. On average, we find that households reduce residual consumption by 4.5%. Low-income lack other adjustment channels and must cut back spending more, amplifying inequality.

Beyond the direct effects, our setting allows us to study anticipation effects. By observing behavior in the months leading up to contract expiration, we find that households are forward-looking and reduce electricity consumption several months before their contracts expire. We do not find similar effects for households whose electricity retailer abruptly goes bankrupt during the crisis. Also, similar anticipation effects are not observed for earnings. A longer anticipation period alleviates some negative effects of the energy price increase, but does not completely remove them.

Beyond the energy crisis, the estimated household-level responses teach us about impacts of other policies that influence energy prices, such as climate policies. We use the estimated behavioral effects to simulate household-level responses to a hypothetical €100/tCO_2 carbon price; shown in Figure 2. Our results identify three channels through which low-income households are affected by carbon pricing: (i) they spend a larger share of disposable income on electricity, (ii) they have lower demand elasticity, and (iii) they are less able to increase earnings. These response channels help medium- and high-income households to reduce their cost burden by around one half, but low-income households only by less than one fourth. As a result, the low-income households face a higher risk of default, and they are forced to reduce their already low residual consumption further.

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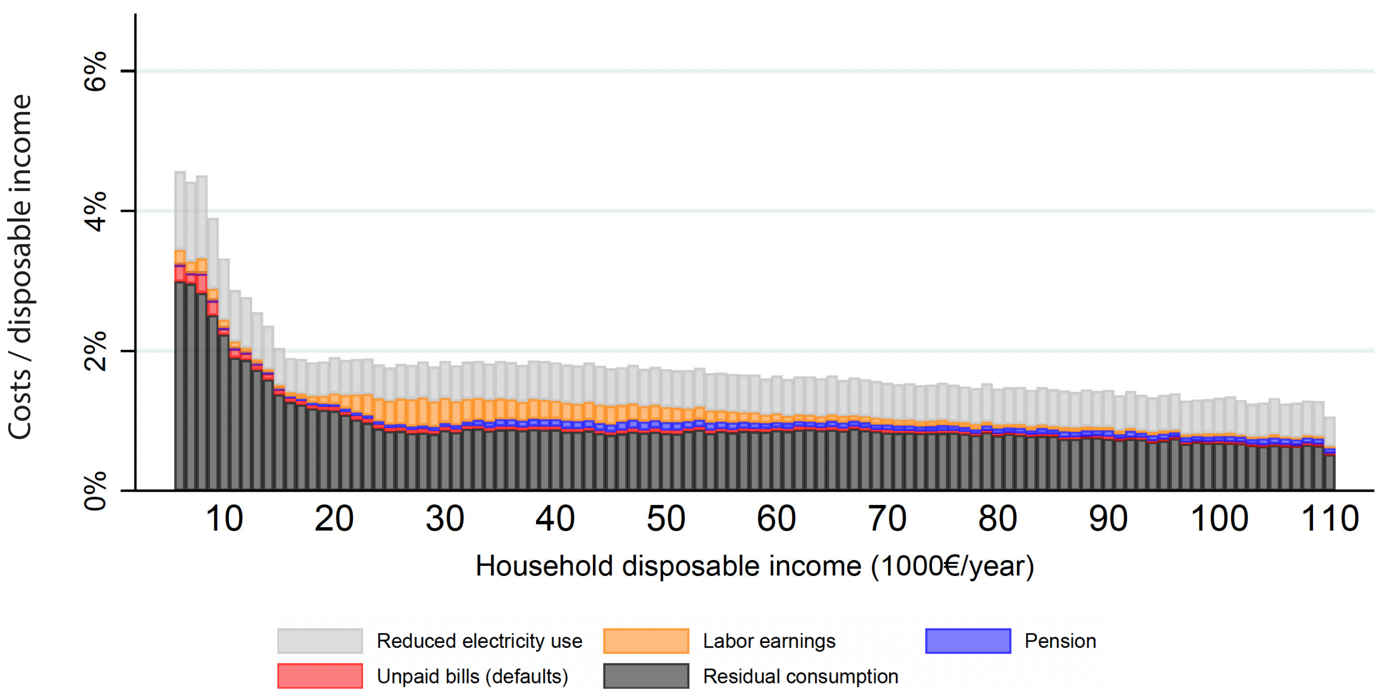

Figure 2: Incidence and response channel to a hypothetical €100/tCO_2 carbon price.

Research.

From Tank to Odometer: Winners and Losers from a Gas-to-VMT Tax Shift

By: Christopher R. Knittel, Gilbert E. Metcalf, and Shereein Saraf

The design of transportation taxation has long been a critical issue in public finance, with policymakers seeking systems that are both efficient and equitable. In the United States, the federal gas tax—a longstanding mechanism for funding transportation infrastructure—has faced increasing scrutiny due to its declining revenues and concerns about fairness. This decline is largely driven by improvements in fuel efficiency and the accelerating adoption of electric vehicles (EVs), which do not contribute to gas tax revenues. As EV adoption grows, particularly in urban areas and coastal states, federal gas tax revenues are falling and are projected to continue falling. By law, revenues from this tax are earmarked for the Federal Highway Trust Fund, which finances a major portion of state and federal roadwork in the United States. This has led policymakers and analysts to explore options for replacing the gas tax. One option gaining traction is a vehicle miles traveled (VMT) tax, which charges drivers based on the distance they travel rather than the fuel they consume. Our research examines the winners and losers from transitioning the federal gas tax to a revenue-equivalent VMT tax, focusing on the distributional impacts across geography and political affiliation. The analysis is done at the census tract level.

For the highly disaggregated geographic analysis we undertake, we need to generate a prediction of household travel at the census tract level. There are about 80,000 census tracts in the United States with an average of 4,000 households per tract. Unfortunately, a measure of vehicle miles traveled at the census tract level does not exist. Instead, we predict household level annual vehicle miles at the census tract level using data from the 2017 National Household Transportation Survey (NHTS 2017), a nationally representative household travel survey, that provides household-level data on annual vehicle miles traveled and other household demographic characteristics, such as income, age, race, education, and employment for about 7,000 households. The survey also includes information on the number of vehicles owned by the household, the type of vehicles, and the use of public transport to travel to work.

The 2017 NHTS only provides geographic information at the nine Census division levels. Using household-level variables common to the NHTS and to the American Community Survey (ACS 2022), we construct a best-fit model from the 2017 NHTS and use that model to predict average household vehicle miles traveled at the tract level in the 2022 ACS.

Given the large number of possible variables available to us to predict household-level vehicle miles traveled, we use machine learning techniques to identify a best-fit model to apply to the ACS data.

Our first result is that the shift is modestly progressive in terms of income.

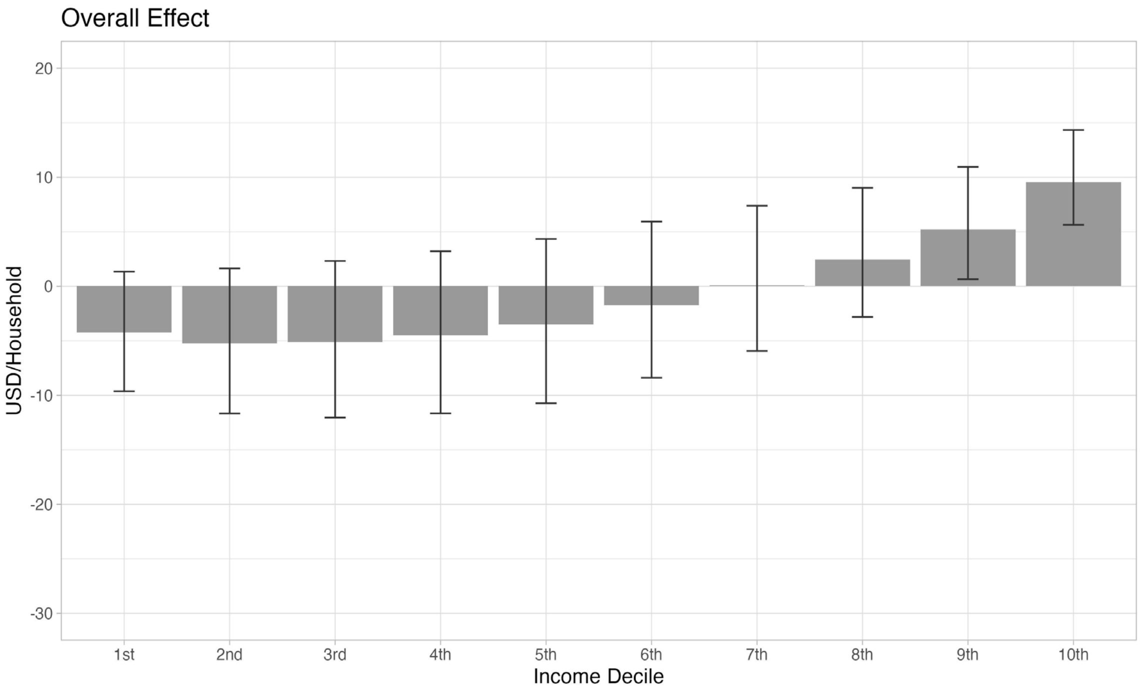

Figure 1: Change in tax payments by income decile.

The bars in the figure above report the average change from the tax swap and show that lower income groups (measured in deciles) on average gain from the tax swap while upper income groups in general pay more taxes. The whiskers report the range from the 25th to the 75th percentiles and demonstrate considerable heterogeneity within deciles while preserving the trend in negative burdens for lower-income households and positive burdens for higher-income households.

Our disaggregated analysis finds striking disparities emerge across geography. Rural areas and the center of the United States, which tend to experience lower average fuel efficiency, experience substantial benefits from a revenue-neutral VMT-Gas Tax swap. This effect is closely tied to the uneven geographic distribution of EV adoption: urban areas and coastal regions, where EV penetration is highest, are less reliant on the gas tax and benefit less from a shift to VMT-based taxation.

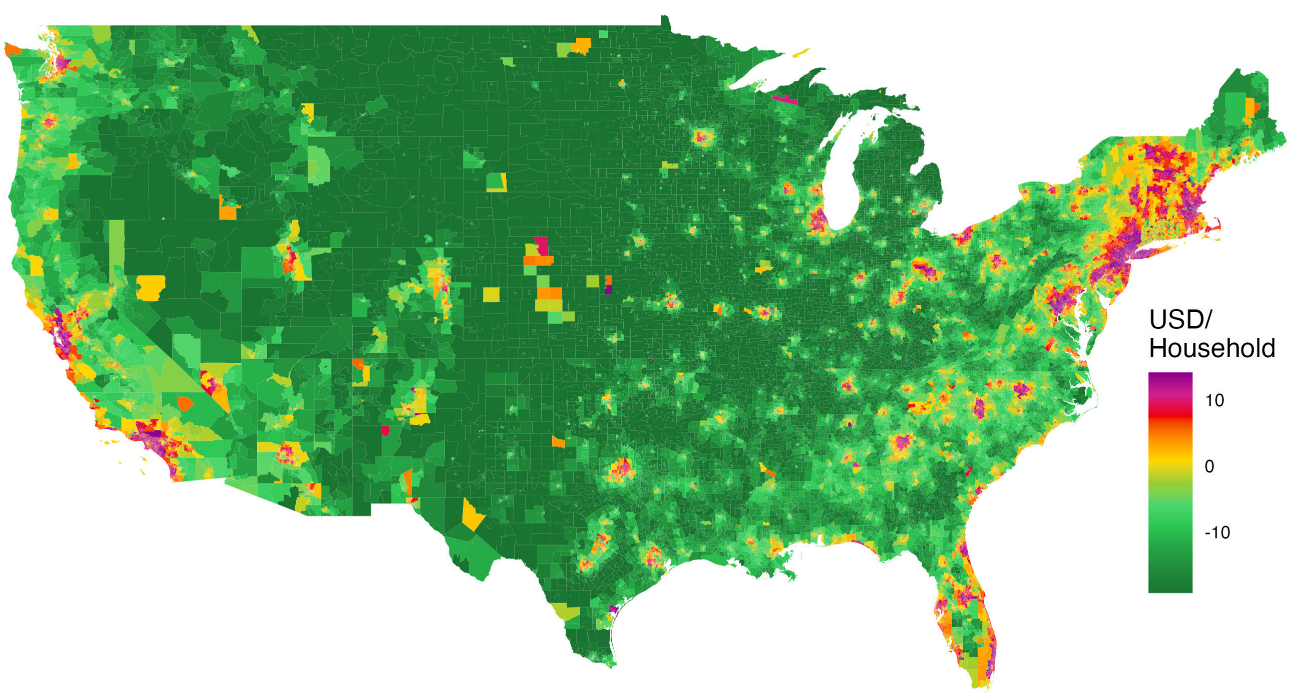

Figure 2: Changes in tax collections from Gas-VMT Swap.
Note: Census tract average data are winsorized at 95%.

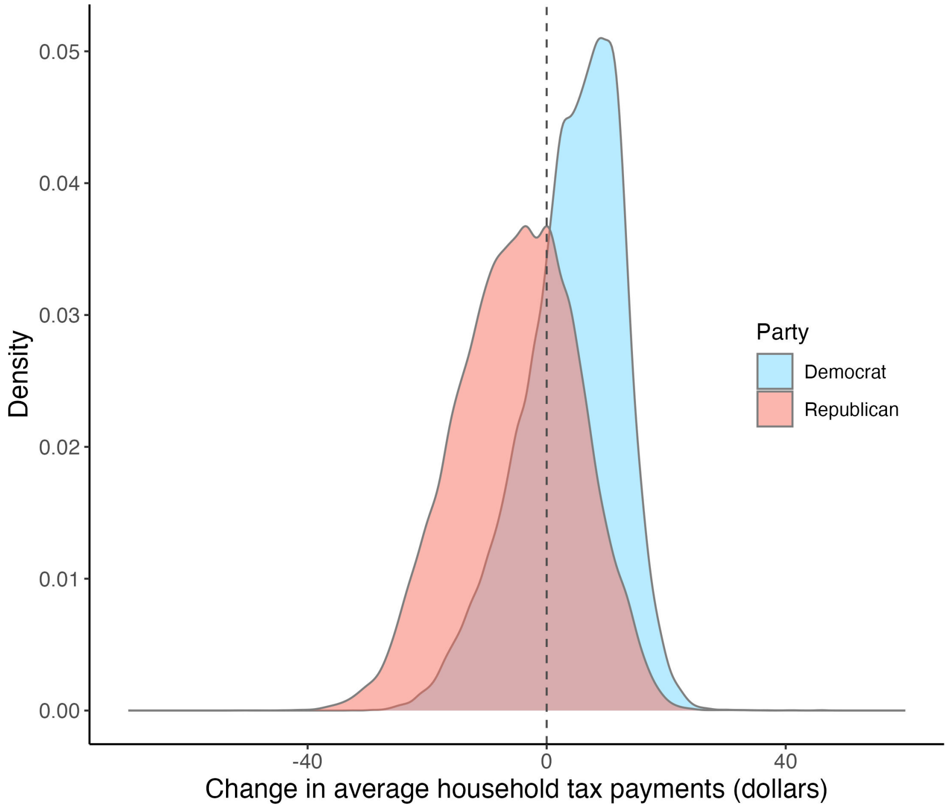

Figure 3: Change in tax collections from gas-VMT tax swap by political party affiliation.
Note: Party affiliation based on affiliation of the House Members in the 118th Congress.

Additionally, Republican-leaning districts, which overlap significantly with rural areas, see marked advantages compared to Democratic districts. The results highlight the potential for a VMT tax to address longstanding inequities in transportation funding while offering a politically salient narrative. By documenting the geographic and political implications of this policy shift, this study contributes to the broader debate on how to design equitable and effective transportation taxation systems in a rapidly evolving mobility landscape.

Our focus here has been on the distributional implications of a tax swap to address the ongoing erosion of the tax base of the motor vehicle fuel excise tax. We should emphasize that we have not made a case on theoretical grounds for efficiency improvements from such a tax swap. Whether we should think of the gas (or VMT) tax as a benefit tax or as an externality-correcting tax, there are a number of factors to take into consideration. A benefits perspective argues for a VMT tax on the grounds that those using roads should bear the cost of their upkeep (as financed through the Highway Trust Fund). But this begs the question of the appropriate sharing of costs between personal and commercial transportation, and especially long-haul trucking in the latter category. From an externalities perspective, considerations of local pollution, road wear, congestion, and accidents all come into play. Innovation and network failures that impede the penetration of electric vehicles are also a consideration. An ideal set of policies likely combines a VMT tax with a subsidy for EVs to address pollution, innovation, and network failures.

Christopher R. Knittel, Gilbert E. Metcalf, and Shereein Saraf (2025), "From Tank to Odometer: Winners and Losers from a Gas-to-VMT Tax Shift", CEEPR WP-2025-10, MIT, May 2025.
For references cited in this story, full bibliographical information can be found in the Working Paper.

Beyond the Hype: The Rainbow of Hydrogen Technologies and Policies

By: Christopher R. Knittel and Jiwoo Oh

Decarbonizing all sectors of the economy and achieving climate goals will require alternative energy carriers that reduce carbon emissions while meeting global energy demands. Among these, hydrogen is often considered a leading candidate due to its versatility in replacing fossil fuels in industrial processes, heavy-duty transportation, and electricity generation. The method of hydrogen production significantly impacts its environmental benefits and economic feasibility, however, leading to classification into several 'color codes' based on feedstocks and production processes: gray, blue, turquoise, green, pink, and gold/white hydrogen. Each method is described in greater detail in the next section.

Hydrogen Production Pathways and Their Implications

Currently, gray hydrogen, produced predominantly through the thermochemical process of steam methane reforming (SMR) of natural gas, accounts for the majority of hydrogen production worldwide. While economically advantageous due to established infrastructure and technology, this method generates substantial carbon emissions, approximately 9 to 13 kilograms (kg) of CO_2-eq per kg of hydrogen produced when accounting for upstream and downstream emissions. In a decarbonizing world, this high carbon intensity necessitates exploring and adopting alternative methods that reduce the carbon footprint of production.

Blue hydrogen, similar in production to gray hydrogen but incorporating a variety of Carbon Capture, Utilization, and Storage (CCUS) technologies to abate carbon emissions, offers significant emission reductions. By capturing and storing emitted CO_2, this method reduces lifecycle emissions to between 1.5 and 6.2 kg of CO_2-eq per kg of hydrogen. While this reduces the carbon intensity of blue hydrogen, achieving consistently high capture rates (above 90%) remains challenging, and more robust technology supply chains as well as substantial infrastructure investments will be required for large-scale CCUS deployment.

Turquoise hydrogen, produced through methane pyrolysis, offers an innovative approach by decomposing methane into hydrogen and solid carbon with thermal and catalytic methods. This process drastically reduces gaseous emissions, potentially achieving near-zero CO_2 emissions. However, significant technological hurdles remain. Currently assessed at Technology Readiness Levels (TRL) 3 to 4, it requires

substantial thermal energy inputs and advancements in catalytic materials for practical scalability and economic feasibility.

Green hydrogen, obtained via electrolytic separation of deionized water into hydrogen and oxygen molecules using renewable energy sources such as wind and solar, represents the cleanest production pathway with essentially zero direct emissions. Although potentially the least impactful on the environment, green hydrogen currently faces considerable economic challenges, primarily due to high capital and operational costs. Furthermore, the supply chains for critical minerals required for electrolyzers are highly vulnerable and geographically concentrated, raising concerns about long-term scalability and security of supply. In many regions, the high rate of water consumption to produce green hydrogen can also pose challenges.

Pink hydrogen uses nuclear power to perform water electrolysis. Similar in environmental benefits to green hydrogen, pink hydrogen produces minimal lifecycle emissions—around 0.1 to 0.3 kg of CO_2-eq per kg of hydrogen—and offers competitive production costs due to the relatively stable and continuous power output of nuclear plants. Despite these benefits, broader acceptance remains limited by significant societal concerns about nuclear safety, waste management, and regulatory hurdles. Conventional reactors are often situated far from urban centers, potentially necessitating additional infrastructure development.

A category of hydrogen production that has only been defined relatively recently is gold/white hydrogen, sourced naturally from geological formations. This pathway could offer exceptionally low production costs—estimates suggest 50 to 70 cents per kg of hydrogen—and minimal environmental impacts, rendering it a potentially impactful option. While global reserves of natural hydrogen are estimated to be considerable, the viability of their extraction at scale remains speculative, contingent on successful exploration and technological advancements in drilling and commercialization.

Economic and environmental analysis of these hydrogen production pathways reveals distinct trade-offs. Gray hydrogen remains the most economically competitive method, but carries significant environmental costs. Blue hydrogen provides an intermediate solution with moderate economic and considerable environmental benefits, but depends critically on CCUS advancement and infrastructure development. Green and pink hydrogen offer the greatest environmental advantages, but require significant cost reductions and technological improvements to become widely viable. Turquoise and natural hydrogen pathways hold potential, pending substantial research, technological innovation, and infrastructure development. Importantly, continued technological innovation means that the foregoing costs and benefits will evolve over time. Likewise, policies can significantly influence the viability of alternative hydrogen production pathways.

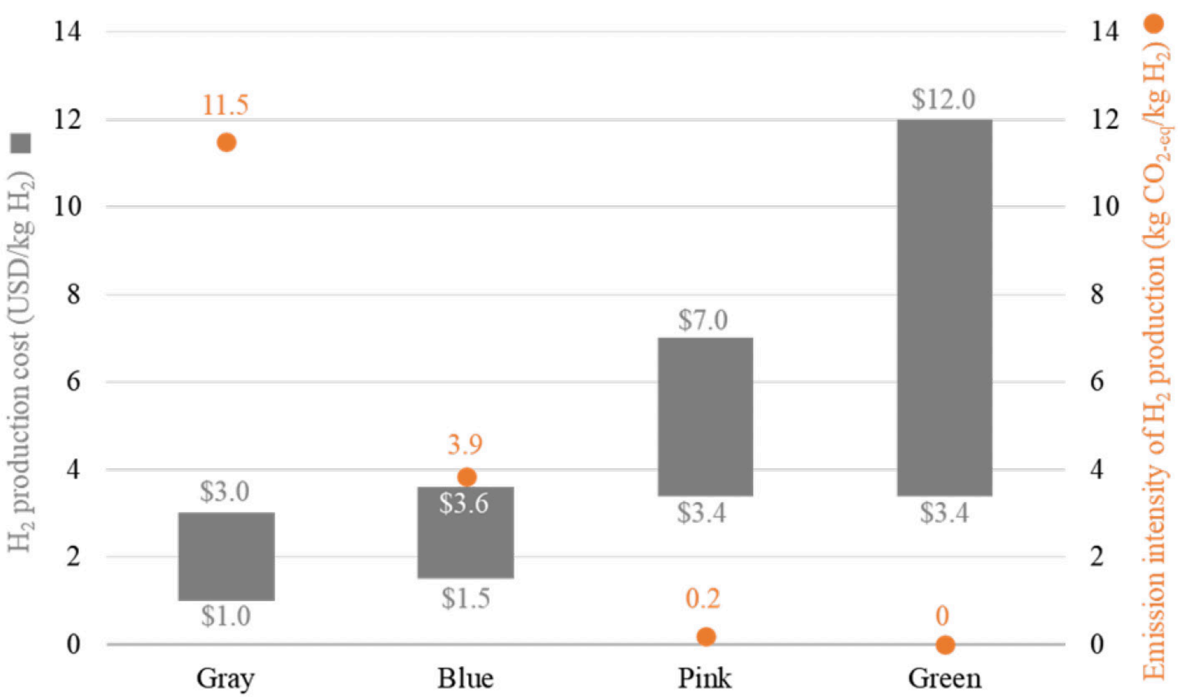

Figure 1. Production cost and emissions comparison of each hydrogen production pathways.
Source: IEA (2023).

U.S. Policy Landscape

Recognizing hydrogen's potential role in achieving climate goals, the United States has advanced a variety of policies and roadmaps across successive administrations aimed at increasing production of hydrogen. Arguably the most impactful among these are the various tax credits introduced under the Inflation Reduction Act (IRA), including the Section 45V Clean Hydrogen Production Tax Credit providing tiered incentives directly linked to lifecycle emissions reductions. Under optimal conditions, blue and pink hydrogen production can achieve competitive costs comparable to or even below gray hydrogen through these tax credits, which green hydrogen production costs are reduced by more than 50%. Additionally, the Infrastructure Investment and Jobs Act (IIJA) allocated nearly $10 billion to various initiatives related to hydrogen supply and demand, with the largest share dedicated to the establishment of regional hydrogen hubs across the country. These hubs aim to produce over three million tons of clean hydrogen annually, significantly contributing to national decarbonization efforts.

Further supporting these initiatives, significant funding has also been allocated to creating a demand-pull for clean hydrogen and address the critical issue of demand uncertainty. As part of these efforts, a project led by the Energy Futures Initiative Foundation (EFIF) and involving the MIT Energy Initiative (MITei) was launched in January 2024: the Hydrogen Demand Initiative (H2DI). By developing foundational market policies, financial incentives, and trading mechanisms, H2DI seeks to stimulate early market adoption and ensure long-term viability of the hydrogen market.

International Policy Perspectives

Internationally, hydrogen policies are evolving rapidly, complementing and sometimes leading U.S. initiatives. The European Union (EU) has notably pursued aggressive hydrogen strategies through the European Clean Hydrogen Alliance and subsequent policy initiatives, setting ambitious targets for renewable hydrogen production and infrastructure development. By 2030, the EU plans to install at least 40 GW of electrolyzer capacity, producing 10 million tonnes of renewable hydrogen annually. This strategy aligns with broader European objectives of energy independence and decarbonization, and is flanked by renewable energy deployment targets and financial support mechanisms.

Similarly, China has recently introduced a comprehensive national roadmap for hydrogen, targeting significant expansions in green hydrogen production and electrolyzer capacity. By leveraging state-owned enterprises and abundant critical mineral resources, China seeks to assert global leadership in hydrogen technologies and markets. Concurrently, China's policies emphasize the development of a robust domestic market and extensive infrastructure to facilitate hydrogen utilization across multiple sectors.

Australia presents a unique model in global hydrogen policy, strategically positioning itself as a major global hydrogen exporter. Utilizing its abundant renewable energy resources, particularly solar, Australia's national strategy includes substantial investment in hydrogen production facilities and infrastructure aimed at international markets. Strategic partnerships with hydrogen-importing countries further enhance its global influence and market reach, and have prompted other regions to emulate Australia's policy model and approaches.

Policy Issues Going Forward

Interviews with several experts at MIT served to gain insights into future hydrogen policy design. Generally, the substantial policy support and ambitious initiatives that have emerged in the U.S. in recent years were seen by the experts as important first steps in launching a domestic hydrogen economy.

Still, the experts also noted that the hydrogen industry continues to face several critical challenges. Regulatory complexity and ambiguity, in particular, complicate investment decisions. Detailed and stringent requirements embedded in policies such as the IRA 45V tax credit, particularly hourly electricity matching standards and reliance on the GREET-45VH2 lifecycle emissions model, contribute to investment risks and uncertainties. Policymakers should therefore carefully balance regulatory strictness with practical investment considerations, aiming for clarity and stability in policy implementation.

Policy design and support should also consider the entire hydrogen value chain, and provide improved assurances of robust demand for clean hydrogen both in the short and in the longer term. Finally, the experts also admonished keeping global markets in mind: given very different resource endowments and policy contexts, different regions will either tend to be net exporters or importers of clean hydrogen. Enhancing global coordination and adopting support measures to leverage the comparative advantage of the United States can help it achieve net zero while also enhancing its competitiveness in the global market.

Christopher R. Knittel and Jiwoo Oh (2025), "Beyond the Hype: The Rainbow of Hydrogen Technologies and Policies", CEEPR WP-2025-02, MIT, January 2025.

For references cited in this story, full bibliographical information can be found in the Working Paper.

Catherine Wolfram: High-Energy Scholar

By: Peter Dizikes | MIT News

Cambridge, MA, November 22, 2024 —

In the mid 2000s, Catherine Wolfram PhD '96 reached what she calls "an inflection point" in her career. After about a decade of studying U.S. electricity markets, she had come to recognize that "you couldn't study the energy industries without thinking about climate mitigation," as she puts it.

At the same time, Wolfram understood that the trajectory of energy use in the developing world was a massively important part of the climate picture. To get a comprehensive grasp on global dynamics, she says, "I realized I needed to start thinking about the rest of the world."

An accomplished scholar and policy expert, Wolfram has been on the faculty at Harvard University, the University of California at Berkeley — and now MIT, where she is the William Barton Rogers Professor in Energy. She has also served as deputy assistant secretary for climate and energy economics at the U.S. Treasury.

Yet even leading experts want to keep learning. So, when she hit that inflection point, Wolfram started carving out a new phase of her research career.

"One of the things I love about being an academic is, I could just decide to do that," Wolfram says. "I didn't need to check with a boss. I could just pivot my career to being more focused to thinking about energy in the developing world."

Over the last decade, Wolfram has published a wide array of original studies about energy consumption in the developing world. From Kenya to Mexico to South Asia, she has shed light on the dynamics of economics growth and energy consumption — while spending some of that time serving the government too. Last year, Wolfram joined the faculty of the MIT Sloan School of Management, where her work bolsters the Institute's growing effort to combat climate change.

Studying at MIT

Wolfram largely grew up in Minnesota, where her father was a legal scholar, although he moved to Cornell University around the time she started high school. As an undergraduate, she majored in economics at Harvard University, and after graduation she worked first for a consultant, then for the Massachusetts Department of Public Utilities, the agency regulating energy rates.

"One of the things that pleasantly surprised me is how tight-knit and friendly the MIT faculty all are," says Catherine Wolfram.

Photo Credit: Jared Charney

In the latter job, Wolfram kept noticing that people were often citing the research of an MIT scholar named Paul Joskow (who is now the Elizabeth and James Killian Professor of Economics Emeritus in MIT's Department of Economics and a former MIT CEEPR faculty director) and Richard Schmalensee (a former dean of the MIT Sloan School of Management, a former MIT CEEPR faculty director, and now the Howard W. Johnson Professor of Management Emeritus). Seeing how consequential economics research could be for policymaking, Wolfram decided to get a PhD in the field and was accepted into MIT's doctoral program.

"I went into graduate school with an unusually specific view of what I wanted to do," Wolfram says. "I wanted to work with Paul Joskow and Dick Schmalensee on electricity markets, and that's how I wound up here."

At MIT, Wolfram also ended up working extensively with Nancy Rose, the Charles P. Kindleberger Professor of Applied Economics and a former head of the Department of Economics, who helped oversee Wolfram's thesis; Rose has extensively studied market regulation as well.

Wolfram's dissertation research largely focused on price-setting behavior in the U.K.'s newly deregulated electricity markets, which, it turned out, applied handily to the U.S., where a similar process was taking place. "I was fortunate because this was around the time California was thinking about restructuring, as it was known," Wolfram says. She spent four years on the faculty at Harvard, then moved to UC Berkeley. Wolfram's studies have shown that deregulation has had some medium-term benefits, for instance in making power plants operate more efficiently.

Turning on the AC

By around 2010, though, Wolfram began shifting her scholarly focus in earnest, conducting innovative studies about energy in the developing world. One strand of her research has centered on Kenya, to better understand how more energy access for people without electricity might fit into growth in the developing world.

In this case, Wolfram's perhaps surprising conclusion is that electrification itself is not a magic ticket to prosperity; people without electricity are more eager to adopt it when they have a practical economic need for it. Meanwhile, they have other essential needs that are not necessarily being addressed.

"The 800 million people in the world who don't have electricity also don't have access to good health care or running water," Wolfram says. "Giving them better housing infrastructure is important, and harder to tackle. It's not clear that bringing people electricity alone is the single most useful thing from a development perspective. Although electricity is a super-important component of modern living."

Wolfram has even delved into topics such as air conditioner use in the developing world — an important driver of energy use. As her research shows, many countries, with a combined population far bigger than the U.S., are among the fastest-growing adopters of air conditioners and have an even greater need for them, based on their climates. Adoption of air conditioning within those countries also is characterized by marked economic inequality.

From early 2021 until late 2022, Wolfram also served in the administration of President Joe Biden, where her work also centered on global energy issues. Among other things, Wolfram was part of the team working out a price-cap policy for Russian oil exports, a concept that she thinks could be applied to many other products globally. Although, she notes, working with countries heavily dependent on exporting energy materials will always require careful engagement.

"We need to be mindful of that dependence and importance as we go through this massive effort to decarbonize the energy sector and shift it to a whole new paradigm," Wolfram says.

At MIT Again

Still, she notes, the world does need a whole new energy paradigm, and fast. Her arrival at MIT overlaps with the emergence of a new Institute-wide effort, the Climate Project at MIT, that aims to accelerate and scale climate solutions and good climate policy, including through the new Climate Policy Center at MIT Sloan. That kind of effort, Wolfram says, matters to her.

"It's part of why I've come to MIT," Wolfram says. "Technology will be one part of the climate solution, but I do think an innovative mindset, how can we think about doing things better, can be productively applied to climate policy." On being at MIT, she adds: "It's great, it's awesome. One of the things that pleasantly surprised me is how tight-knit and friendly the MIT faculty all are, and how many interactions I've had with people from other departments."

Wolfram has also been enjoying her teaching at MIT, and will be offering a large class in spring 2025, 15.016 (Climate and Energy in the Global Economy), that she debuted this past academic year.

"It's super fun to have students from around the world, who have personal stories and knowledge of energy systems in their countries and can contribute to our discussions," she says.

When it comes to tackling climate change, many things seem daunting. But there is still a world of knowledge to be acquired while we try to keep the planet from overheating, and Wolfram has a can-do attitude about learning more and applying those lessons.

"We've made a lot of progress," Wolfram says. "But we still have a lot more to do."

—This article originally appeared on the MIT News website at https://news.mit.edu/2024/catherine-wolfram-high-energy-scholar-1122

News.

What Business Needs to Know About Carbon Border Adjustments

By: Dylan Walsh | MIT Sloan School of Management

"I've been studying climate policy for about 20 years, and [CBAM] is the thing that has made me most optimistic."

Catherine Wolfram
Professor, Energy Economics, MIT Sloan

Cambridge, MA, February 18, 2025 —

There is an urgent need for businesses worldwide to reduce greenhouse gas emissions while remaining profitable.

In 2005, to address this challenge, the European Union launched its Emissions Trading System, a cap-and-trade program that requires companies in the most heavily polluting sectors to either reduce their emissions below a decreasing threshold or pay for them.

The system has worked relatively well over the past two decades, but it has given an unfair advantage to importers, since goods produced beyond EU borders may not be subject to a tax on their emissions.

The EU aims to address that imbalance with the implementation of its Carbon Border Adjustment Mechanism, or CBAM, starting in 2026; the United Kingdom plans to do the same in 2027.

"It's a complicated topic with a kind of funny name, but this is something that could have pretty profound implications for carbon emissions around the world," said Catherine Wolfram, a professor of energy economics at MIT Sloan and a former deputy assistant secretary for climate and energy economics at the U.S. Treasury. "I've been studying climate policy for about 20 years, and this is the thing that has made me most optimistic."

In a recent Q&A, Wolfram, co-author of a report titled "How Carbon Border Adjustments Might Drive Global Climate Policy Momentum," explained the mechanics of the CBAM, discussed why businesses outside the EU need to pay attention, and offered predictions on the future of carbon pricing. The conversation has been edited for length and clarity.

—This article originally appeared on the MIT Sloan Ideas Made to Matter website: https://mitsloan.mit.edu/ideas-made-to-matter

What do businesses need to understand about CBAMs? How do they help level the playing field?

Climate change is global problem. A ton of carbon emitted in one place affects the whole world, and so, in the language of economics, this creates a free-rider problem. If any individual country takes steps to reduce its carbon emissions, that country bears all the costs, but the whole world reaps the benefits.

The CBAM is the first climate policy that tackles this free-rider problem head-on.

If a country from outside the EU exports its products into the EU, then they're going to be subjected to the same level of regulatory scrutiny that countries within the EU face, specifically when it comes to carbon emissions and the Emissions Trading System. Those imported goods are going to have an equivalent carbon price imposed on them.

At the same time, companies outside of the EU get credit for any carbon price that they've paid domestically, which basically reduces the incentive for any individual country to free-ride.

Without this adjustment, if you're a German car manufacturer, then steel manufactured in Malaysia, with no carbon pricing factored in, is going to be a lot more economically attractive than German steel.

Credit: Stephen Sauer

How is a CBAM different from a tariff?

A CBAM adjusts for domestic policy, whereas a carbon tariff does not.

As we said, the U.K. and EU have carbon prices domestically, which means [that], under a CBAM, if you're a Malaysian steel manufacturer and you send steel to the EU, then you have to pay as though your steel factory were located in the same regulatory jurisdiction. You have to pay the carbon price — unless you've already paid for your carbon emissions in Malaysia.

Carbon tariffs don't adjust for carbon prices charged domestically. A country just makes the tariff proportional to the carbon emitted.

The CBAM is fundamentally designed to level the playing field and push for broader carbon markets.

What sectors will be affected first?

In the beginning, the EU CBAM only applies to a few pretty carbon-intensive sectors: cement, iron, steel, aluminum, fertilizer, electricity, and hydrogen. The U.K. CBAM won't cover electricity, but it does include glass and ceramics. There's no specific schedule to bring in other sectors, but that's the plan over time.

How are other countries responding to the prospect of the CBAM?

It's been successful beyond what any economic theory would predict. Since the EU started talking about this in 2019, 44 other jurisdictions around the world have either implemented or are in the process of debating, at a formal level, carbon prices.

China, which is a big deal in the climate world, previously had a carbon price that only applied to the power sector, but it has expanded this carbon price to cover CBAM sectors such as iron, steel, and cement. To me, that seems like a pretty impressive impact.

In other countries, like Pakistan, Thailand, and Taiwan, we've also seen a real run-up in the use of words like "decarbonization," "green energy," "clean energy," and so on in the English language press. It has not been ignored. I would say this has started global conversation about decarbonization and carbon pricing, which is one of the things it's designed to do.

What should businesses be paying attention to as the EU and U.K. CBAMs get underway?

All businesses should be paying attention to this. It seems, for one, to be an effective way to make some headway on confronting climate change. If the momentum behind carbon pricing and CBAMs really gets going, U.S. businesses will need to pay for their emissions when they export to [other] countries in addition to the EU and U.K.

It's worth emphasizing that the CBAM is mainly trying to address the issue of competitiveness. The EU has this emissions trading system. If a domestic carbon-intensive industry just leaves a market like Europe, then the world doesn't get the emissions benefits — and we might even get an increase in emissions if production moves to a place with less regulation. The EU also loses the economic benefits of the company.

This is where we can really see the value of the CBAM: It [disincentivizes] companies from leaving countries that are taking on climate change, and it generates policy spillovers, where other jurisdictions adopt prices themselves. It's something businesses will need to start thinking about, depending on their export markets.

Are there big questions that remain unanswered about implementation or efficacy?

There are lots and lots of details that people are fighting over, and it remains to be seen how these fights get resolved and whether they delay implementation. I've certainly painted the rosy picture; that's easy to do before you have to deal with messy details on the ground.

Questions remain about how other countries will report emissions, at what level reporting takes place, what exactly that means, and so on. There are also big questions about what, precisely, it means for other countries to have a carbon price and what kinds of activities will and won't be credited by the EU and U.K. This needs to be worked out.

Finally, there's some concern that countries will object to the CBAM as a whole and bring complaints to the World Trade Organization. I don't think that would actually delay the policy. But, in general, the broad question remains about how much other countries will go along with this or how much they might put up a fight. All that is to be decided this year, before the policy takes hold in 2026.

Where does the U.S. sit in all of this, and what does the new administration imply?

There are two ways to think about that. In terms of exports, I don't see this as an issue between the U.S. and the EU, as we export so little to the EU in the specific sectors covered by the CBAM. This protection is likely temporary as the EU and U.K. expand coverage to new sectors and as other countries around the world start to enact their own CBAMs, but for now, there are bigger fish to fry in U.S.-EU trade debates.

At the same time, some Republicans are talking about imposing a carbon tariff on U.S. imports. A bill has already been introduced on this last Congress, and it's part of the conversation with the current Congress. Where that goes remains to be seen. Some think it'll die; others think it has legs. But this would not have any direct effect on the CBAM, which ultimately remains an elegant solution to a tricky problem.

"It's worth emphasizing that the CBAM is mainly trying to address the issue of competitiveness."

Catherine Wolfram
Professor, Energy Economics, MIT Sloan

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Events.

Recent and Upcoming Conferences:

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2025 Spring MIT CEEPR Research Workshop

June 10-11, 2025
Royal Sonesta
Cambridge, Massachusetts

2025 European Energy Policy Conference

June 23-24, 2025
Warsaw, Poland
in partnership with the University of Cambridge, and Orlen S.A.

2025 Fall MIT CEEPR Research Workshop

October 23-24, 2025
Hilton Washington DC Capitol Hill
Washington, D.C.

Publications.

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WP-2024-17
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Laura Cappellucci, Lan Ha, Jeremy Honig, Christopher R. Knittel, Amy Vetter, and Richard Wilner, October 2024

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MIT CEEPR and MIT CS3 graduate research assistants at the MIT Technology and Policy Program thesis signing ceremony held at the MIT Museum. CEEPR students Adam Ali and Chris Colcord completed their degree requirements and graduated during MIT's 2025 Commencement. Chris Colcord also received one of two MIT TPP Thesis Awards granted to this year's cohort.

Pictured from left to right starting from the top row: Adam Ali, Grant Lee, Eli Duggan, Luke Heeney, Khyati Garg, Clara Park, Kevin Lin Yang, Chris Colcord, and Karikari Achireko.
Photo Credit: Ethan Kita

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