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Triggering Investment in First-of-a-Kind and Early Near-Zero Emissions Industrial Facilities

By **Dr. Chris Bataille**, **Seton Stiebert**, **Jonas Algers**, **Dr. Francis Li**, and **Margaux Alfare**

July 2024

REPORT

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Executive Summary

Among the most significant challenges to achieving the Paris Agreement goal of global net-zero CO_2 emissions by 2055–2075 is addressing the so-called "hard-to-abate" heavy industrial sectors such as iron and steel, cement and concrete, ammonia, methanol, and high value feedstock chemicals like olefins. These sectors accounted for 7.5 Gt CO_2 or 20.4 percent of global emissions in 2021, and global demand for their products will only rise until broad development goals are met everywhere. Moreover, nearly all heavy industrial plants being planned or in construction today are fossil based, with the exception being a handful of small-scale pilot facilities. Given that plants tend to operate for at least 20 years before their first deep renovation, and 40–80+ years overall, these new ones will likely still be in operation by the time global CO_2 emissions must be net-zero (~2050–2060), after which heavy industry players that are still emitting will likely need to pay for CO_2 removal (CDR) from the atmosphere. The cumulative CO_2 emissions between now and then and the likely very high cost of CDR are driving society, governments, and firms to make near-zero emissions the default minimum standard for all new and retrofit facilities by the end of the 2020s.

However, fulfilling that standard is no easy task. The main bottleneck is less technological in nature than financial and market based. At the current state of the art, near-zero emissions plants simply cost more than fossil-based plants, and meanwhile, no demand pull or market exists for lower-emission industrial products. Given the urgency of the task at hand amid the global climate crisis and the current lack of a business case to undertake it, strong policy signals can be used to incentivize early investment in near-zero-carbon heavy industry.

This report, part of the Carbon Management Research Initiative at the Center on Global Energy Policy at Columbia University SIPA, explores financial policy instruments that can make first-of-a-kind (FOAK) near-zero emission industrial facilities viable. The report finds that such FOAKs can then be used as low-risk, replicable models for rapidly transforming the "hard-to-abate" sectors and ultimately facilitating a transition to full net-zero emissions for industry as a whole.

The takeaways of the report are as follows:

- There is no one-size-fits-all policy instrument to trigger FOAKs — policymakers seeking to encourage such projects may instead want to consider packages of policies at various stages of a project's lifetime that account for both the climate in which that project operates and any risks that could impinge on its success.
- Equitable financial support by governments across industrial sectors and products can be transformational for establishing FOAK projects and getting them off the ground at the lowest

possible cost, but in providing that support, governments will need to weigh relative emissions-reduction potential, technological readiness, and the cost premium above existing market prices to maximize effectiveness and efficiency.

- A clear and consistent long-term strategy and policy signal can provide the certainty needed to trigger broader investment in FOAK facilities.
- Long-term policy strategies to transform the most carbon-intense sectoral processes can be politically and economically maintained if: 1) those strategies are tailored to each sector; 2) participation by industry players is initially rewarded and then eventually mandatory; and 3) investment capital is raised privately by the sector, initially with guarantees from government, and full cycle costs are passed through to consumers.

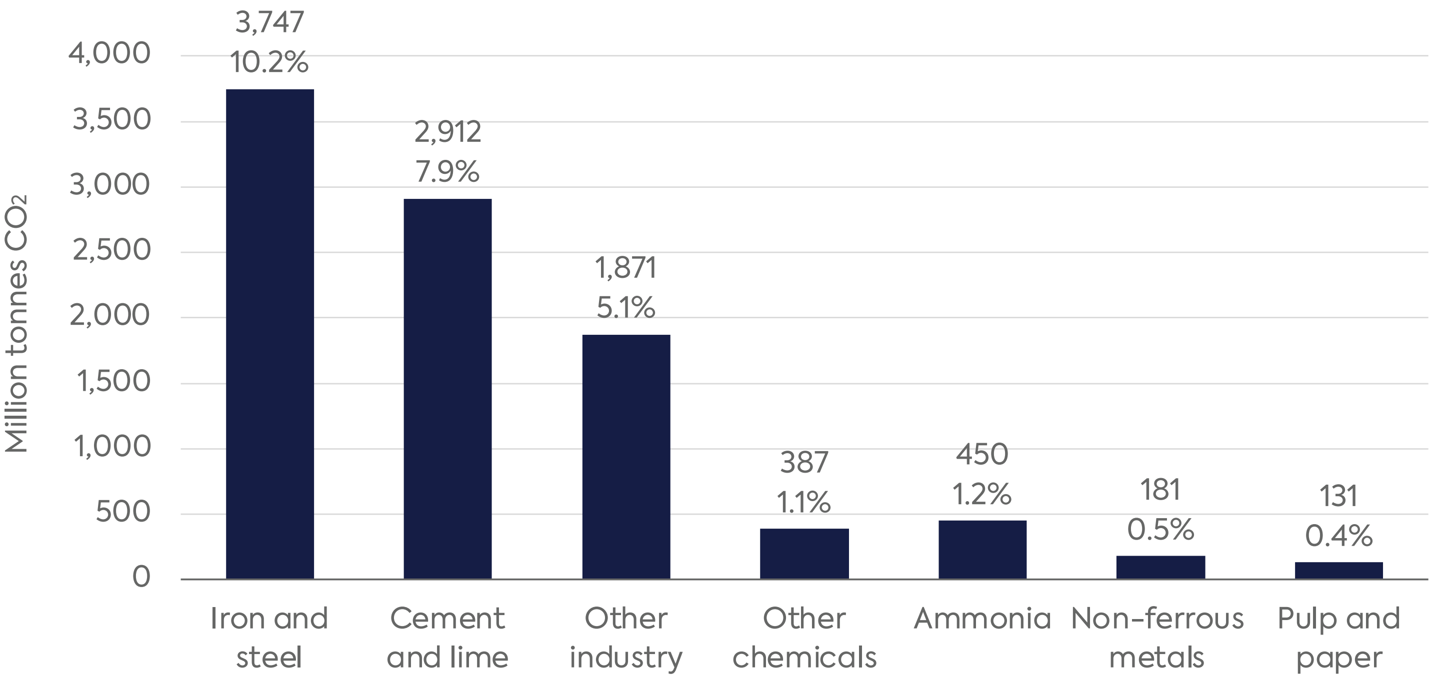
The authors recommend the following measures for getting near-zero-emitting projects to full deployment both in the US and in other developed countries:

- Reduce upfront and ongoing investment and operating risk associated with the first few plants, whether through a first round of direct pay product tax credits (in the US) or contract for difference reverse auction mechanisms (in the EU and other developed economies).
- Create a US federal level and EU-wide tradable zero emissions performance standard for near-zero emissions production, or ideally share one across the advanced economies, which can help maintain market value for green commodities until sufficiently strong and economy-wide carbon constraints (e.g., carbon pricing or near-zero emissions regulations) apply.
- More broadly, embrace an attitude of experimentation that understands failure as the necessary cost of learning.

Introduction

The Paris Agreement goal of maintaining average global temperatures "under +2°C and towards +1.5°C" from preindustrial temperatures requires net-zero CO_2 emissions globally by 2055-2075 (IPCC 2022; UNFCCC 2015). This means that all fossil fuel combustion needs to be fully abated, eliminated, or offset through CO_2 removal (CDR). The so-called "hard-to-abate" or "hard-to-transition" heavy industrial sectors such as iron and steel, cement and concrete, and ammonia and other chemicals pose one of the greatest obstacles to that goal. Not only are existing standard processes from these sectors' emissions intense and long lived, but they also represent 7.5 Gt CO_2 or 20.4 percent of global CO_2 emissions in 2021. In that same year, all heavy industrial sectors were responsible for 26.3% of direct emissions (9.7 Gt CO_2), and 33.6% (4.4 Gt CO_2) of total utility electricity was used to serve them (Figures 1 and 2).

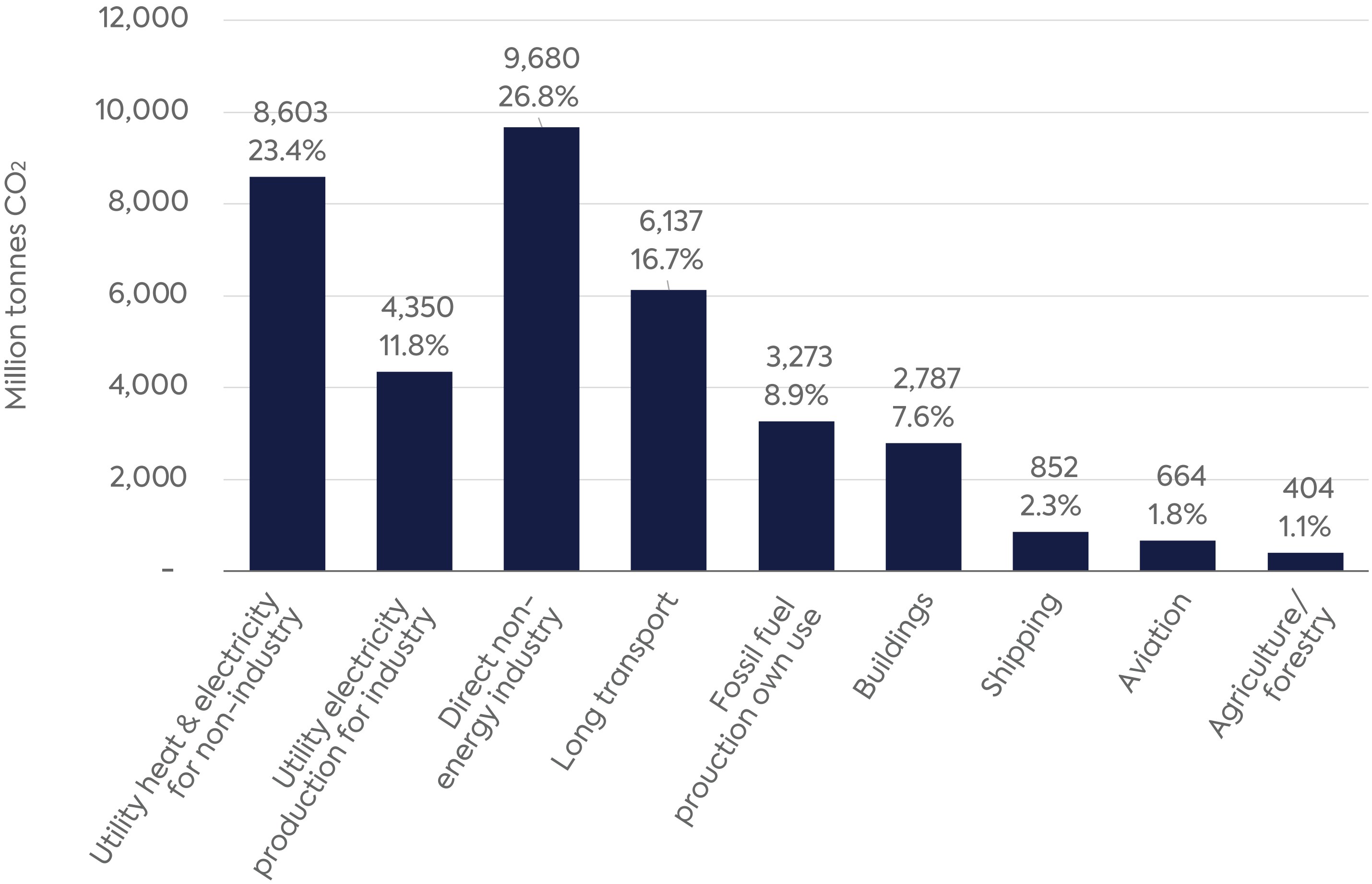
Figure 1: Global combustion and process CO_2 emissions by industrial sector in 2021, absolute and % of global total



Source: Constructed from IEA World Energy Balances (IEA, 2023b).

Note: The total volume for each sector reflects all dedicated onsite CO_2 emissions, including for heat and power.

Figure 2: Global combustion and process CO_2 emissions by broad sector in 2021, absolute and % of global total



Source: Constructed from IEA World Energy Balances (IEA, 2023b). All dedicated onsite CO_2 emissions, including for heat and power, counted to the sector.

Moreover, the products of heavy industry (e.g., steel,[1] cement, ammonia for fertilizers, and methanol and high value chemicals feedstocks such as olefins) will be required in the future global low-carbon economy; in fact, population growth and human development aspirations suggest that overall demand for them will only grow (Bataille 2020; IPCC et al. 2022).

Yet, at present, there are no full-scale, fully built and operating near-zero emissions steel, cement, or chemicals[2] plants anywhere in the world, and only a few such plants are near final investment decision or under construction.[3] The heavy industrial facilities being planned or built today are instead nearly all fossil based. Given that such plants tend to operate for at least 20 years from the time they are built before their first deep renovation, and for 40–80+ years overall, these upcoming facilities will likely still be operating at midcentury (~2050–2060), when global CO_2 emissions must be net-zero and then net-negative to hold global temperatures to the Paris Agreement goal. Heavy industry players still emitting at that point will likely need to pay for offsetting permanent, verifiable, additive, and traceable CDR at somewhere between $100–300+/tonne CO_2e (Bataille 2020; IPCC 2022). The cumulative CO_2 emissions between now and then, as well as the potential penalty CDR, are the underlying drivers for society, governments, and firms to make near-zero emissions the new default minimum standard for all new and retrofit facilities by the end of the 2020s, in accordance with the 2050 net zero goal. While zero or negative emissions would surely be more ideal, from a practical implementation standpoint, some level of residual emissions will likely occur until all processes can be electrified, run on low-carbon hydrogen or synthetic net-zero carbonaceous fuels, or be switched to utilize novel manufacturing processes where greenhouse gasses (GHGs) can be eliminated (e.g., innovative electrochemistry).[4]

This report explores the potential advantages, challenges, and policy means of encouraging first-of-a-kind (FOAK) near-zero emission industrial facilities as replicable, low-risk examples for transforming the "hard-to-bate" sectors and ultimately facilitating a transition to full net-zero emissions for industry as a whole. The first section explores why support for FOAK near-zero emissions facilities is needed, addressing in turn how to define this level of emissions, the state of play in green industrial and trade policy regarding FOAKs, and the broader benefits of their adoption. The following section analyzes the risks that FOAKs pose from an investor perspective and policies that could address those risks and ultimately facilitate FOAK investment. The penultimate section explores a case study of a real-world, near-zero emission FOAK industrial facility — a private-sector green steel plant in Sweden — to show how such FOAK projects are already being developed. The report concludes with a short list of policy recommendations for making full-commercial-scale FOAK plants a reality.

The Need for FOAK Near-Zero Emissions Facilities

FOAKs have proven helpful in the past to transform sectors by reducing perceived risk of investment and use, and they are standard practice for any transformative technology. When innovative technologies are successfully commercialized, they redefine what is considered commercially viable and technically possible, reduce perceived risk for investors, increase operating knowledge, and drive down costs for future generations of facilities. This was the case for commercial electric and hybrid vehicles; nickel-cadmium and then lithium batteries; onshore, fixed offshore, and now floating wind turbines; and solar panels. In terms of near-zero emissions facilities specifically, the first large-scale prototype zero-emissions steel plant has already been built in Sweden (Hybrit, discussed in detail below), and it completely transformed the conversation around steel decarbonization. Before fleshing out the potential benefits of a broader approach to FOAK policy, it will be useful to define what is meant by near-zero emissions in order to delineate clearly what the FOAK plants under discussion are meant to achieve.

Defining "near-zero" emission manufacturing

Defining near-zero emissions as a guide for investment, or more broadly a Paris Agreement-compliant use of fossil fuels in the context of economy-wide climate policy, is like aiming at a moving target (Bataille 2023a; Bataille, Al Khourdajie, et al. 2023). This is because neither the future natural CO_2 absorption capacity of the Earth nor the capabilities of future technological carbon dioxide removal options can be projected with any certainty. Any net-zero emissions analysis must therefore assume a certain level of carbon capture and sequestration (CCS) of atmospheric CO_2, often termed carbon dioxide removal (CDR). Based on the typical amount of CDR employed in the Intergovernmental Panel on Climate Change's (IPCC's) integrated assessment scenarios of 1.5–2°C pathways (IPCC 2022), this report assumes that by mid-century the remaining 5–10%[5] of CO_2 emitted after CCS and 0.2–0.5% of fugitive methane (CH4) remaining after reasonable and achievable fugitive control efforts can be reasonably compensated for with natural or technological CDR technologies. In other words, a near-zero-emitting industrial facility is one where: 1) > 90–95% of fossil fuel emissions are directly captured and stored using CCS, with low upstream fugitives; 2) all processes are electrified using less than 30 grams CO_2 per kWh of electricity; or 3) processes use synthetic net-zero fuels such as hydrogen or net-zero hydrocarbon or alcohol fuels with emission intensities less than or equal to the equivalent of 1.5 kg CO_2 per kilogram hydrogen (Bataille 2023b).

The state of play in green industrial policy

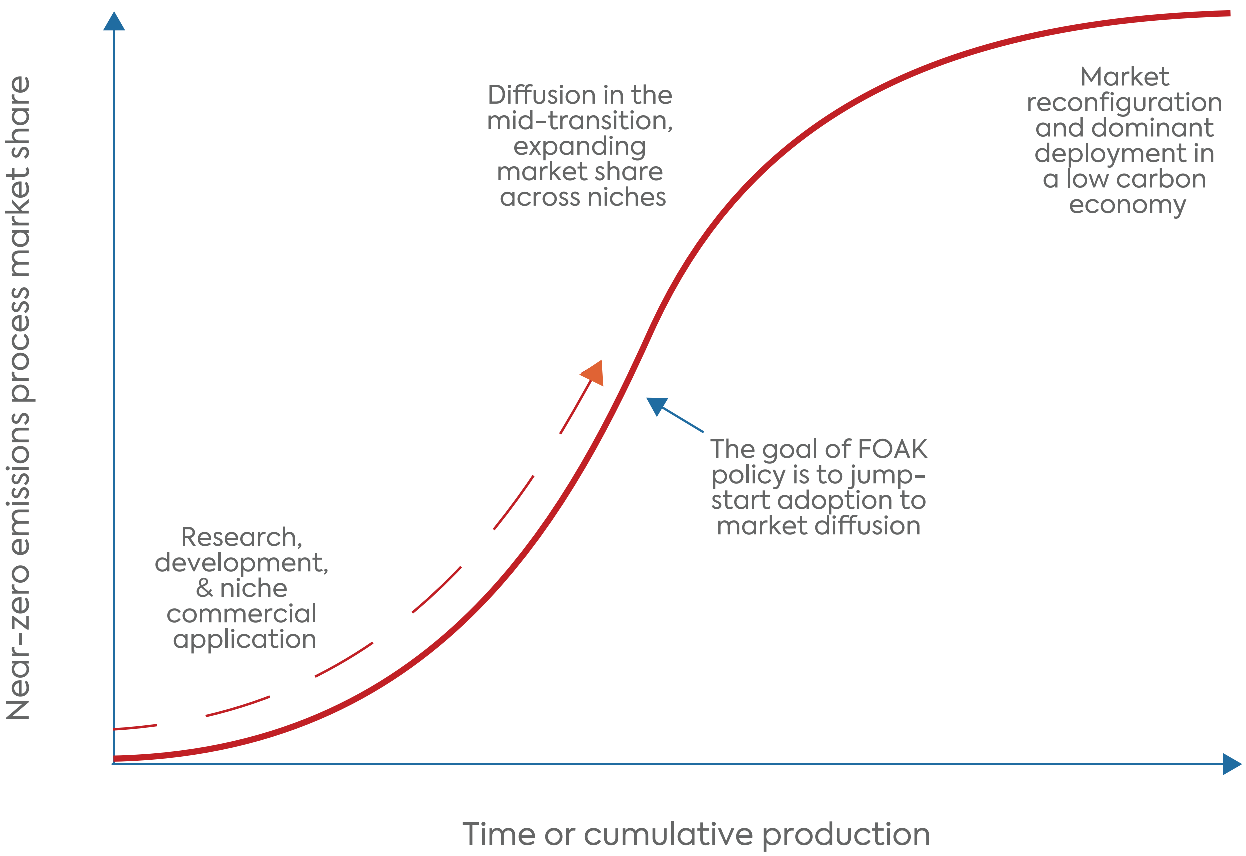
As mentioned, no full-scale, fully built and operating near-zero emissions steel, cement, or chemicals plants currently exist anywhere in the world, and only very few have passed full final investment decision and are under construction. One primary reason for this state of affairs is that while it is technically possible to make near-zero emissions versions of most of these commodities from a "lab bench" perspective, they would cost considerably more to produce with currently available technologies than their more carbon-intensive counterparts, and no specific market or other demand exists for them. Heavy industry products like reduced iron, clinker, ammonia, methanol, and high value chemical feedstocks like olefins (e.g., ethylene) are mostly homogeneously traded on world markets, with no distinctions made based on GHG intensity. Even if consumers were willing to pay a premium for less GHG-intense materials, dedicated market exchanges are not currently operating to meet such demand.

Numerous policies have been used in the past to reduce emissions from heavy industry. These include but are not limited to research and development subsidies, direct process subsidies (e.g., for cleaner hydrogen and CCS in the US Inflation Reduction Act (IRA) [IEA 2023a]), carbon pricing (e.g., the EU Emissions Trading System), regulatory standards for motors, etc., investment tax credits (e.g., for wind and solar in the US [US DOE 2023]), technology capital expenditure (CAPEX) borrowing subsidies and grants, and green procurement. While existing policies stacked together are reducing emissions in heavy industry, most of the emissions reductions taking place are related to process efficiency improvements of existing technologies and not yet to the building and implementation of near-zero-emitting full-scale heavy industry facilities. With the exception of two significant, very recent developments — the US DOE Office of Clean Energy Demonstration's funding of 33 industrial decarbonization projects (US DOE 2023a) and the European Green Deal Industrial Plan (European Commission 2023a) — policy signals to date have simply not been strong enough to incentivize early near-zero-carbon production in heavy industry.[6]

Benefits of deploying FOAK near-zero emission manufacturing

Moving to near-zero emitting industry facilities requires speeding up the technological emergence, diffusion, and supply chain reconfiguration processes that can transform each of the industrial sectors (Geels et al. 2019; D. Saha et al. 2021) (Figure 3). Normally, the research, development, commercialization, and deployment (RDCD) that these processes require takes several decades — a window of time that the existing carbon budget and immaturity and cost of carbon dioxide removal (which has its own RDCD challenges) does not allow. Meeting the Paris Agreement goal means that as many new facilities as possible will need to be near-zero emitting by 2030. This in turn requires jumpstarting as soon as possible the movement of at least one and ideally several technological options for the main GHG-intense processes in each sector from research and development to broad commercial applicability and diffuse deployment — for which FOAK near-zero emissions facilities as replicable templates can be very useful.

Figure 3: Technology diffusions through time



Source: Modified from Geels et al. (2019) and D. Saha et al. (2021).

From a societal and specifically governmental perspective, FOAK plants are intended to overcome barriers to deployment with the promise of lower emissions, decreased production costs over time, and compensation in the form of replicable future investment, economic growth, and high-value employment. Strategies for economic growth and innovation are inherently challenging, as government must balance the goals of employment, productivity, global competitiveness, regional development, full-spectrum security, local air and water quality, conservation, and net revenues with the additional goal of net-zero GHG emissions. For that reason, support for research, development, and commercialization leading to FOAK plants must be firmly established in the context of all the above broad social goals (Waisman et al. 2019). Absent this guiding principle, there is a significant possibility that more and more overlapping policies with narrow or vague objectives will be created, leading to underwhelming results (Bataille 2023c).

It should be noted that some FOAKs are likely better than others at generating replicable knowledge; there must be spillovers across projects and probably across firms, builders, and operators for the payoffs to be realized.[7] A full "standard-sized plant" may not be fixed over time; a minimum-sized plant from which the right lessons can be learned might be more useful. In addition, intellectual property is a potentially valuable outcome for participants in various scales of FOAK projects, but a balancing act is required: sufficient benefit to draw participants but intellectual property (IP) rules that are not too tight to allow competitors to benefit. A focus on monetization through intellectual property protection may be myopic, however, as once it is shown that a given FOAK works, it may not be possible to prevent it from being reverse engineered and used without respect to intellectual property rights. It is for this reason that technology-leading firms often proactively seek out partners in new markets.

The UK Offshore Wind Accelerator methodology for solving key issues related to floating offshore wind is likely the gold standard in the public domain for creating maximum sharable lessons from FOAK projects beyond the ability of a single company (Carbon Trust 2017). Working together, the UK government and industry identified key blockages in the supply chain beyond the means of any one firm. UK government funds were then used to resolve these blockages with industry, after which the project was closed with all parties sharing the IP generated. The project was then returned to full competitive reverse auction mode.

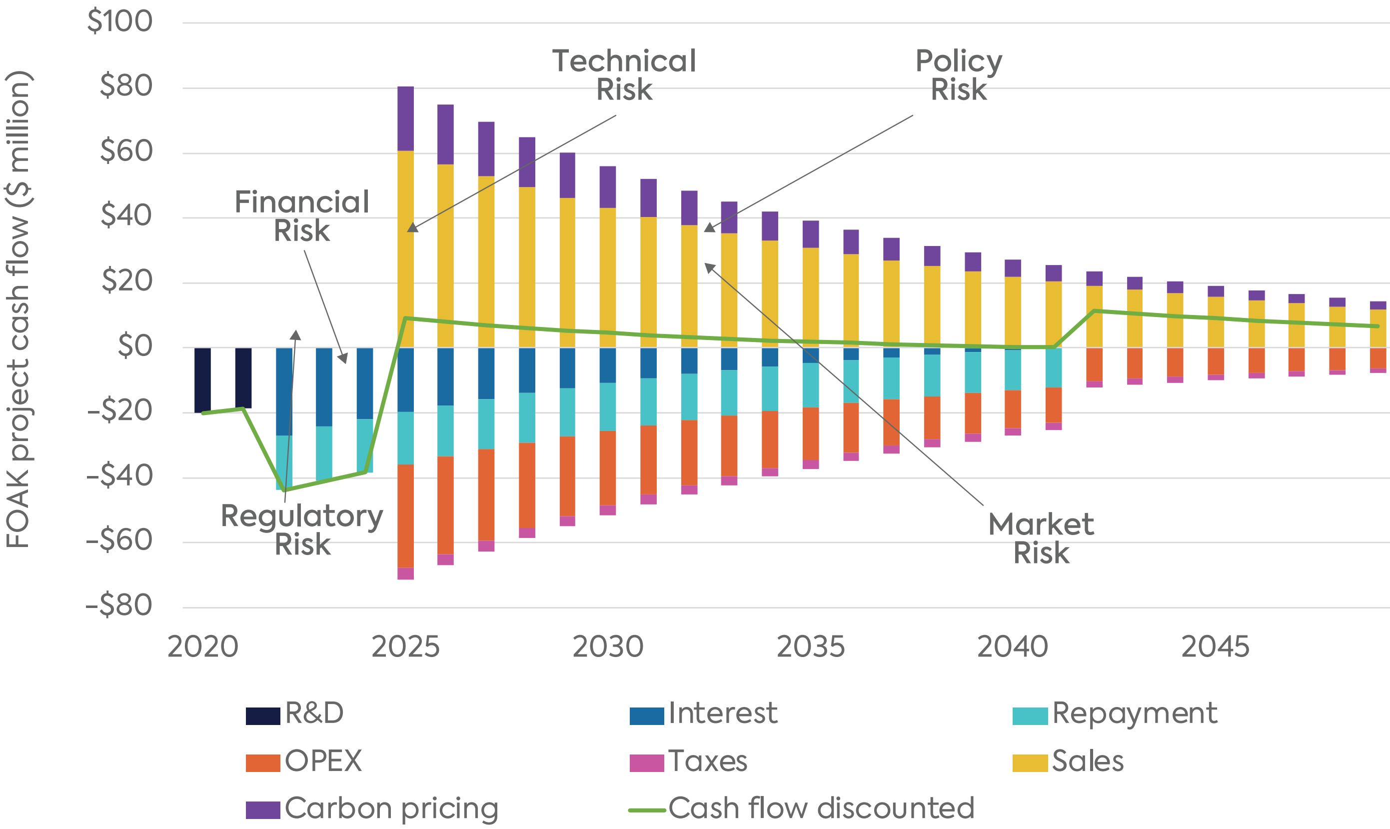
In the specific case of near-zero emissions industrial facilities, the successful construction of FOAK plants could reset regional and global definitions of what is considered "best available technology," with significant legal and broad sector perspective implications (Bataille and Stiebert 2022; Stiebert and Bataille 2022). While there is no shortage of some kinds of proposed near-zero emissions industrial projects (e.g., 134 gigawatts [GW] worth of green hydrogen projects by 2030 have been announced globally) (Collins 2022), most are currently stuck at the final investment decision (FID) stage because they are not considered "investable" or "bankable" as stand-alone projects (i.e., ones without perceived broader social benefits). Moreover, market prices for heavy industry products that are internationally traded and globally competitive are not currently high enough to convince investors that they will make an attractive return on investment. This is called the *investability gap*, or in the case of FOAK plants, the production *incentive gap*. Each FOAK project or product has its own unique production incentive gap, as different facilities in different market sectors face different pressures and risks. If policymakers wish to close the production incentive gap and make the first generation of near-zero emitting industrial facilities investable, it can be profitable for them to consider policies that address financial risk and provide greater certainty around returns.

Analyzing Investor Perspectives on the Risk Associated with FOAK Plants

Industrial firms and the investment firms that provide the capital for industrial firms to build their facilities are the key decision-making agents for determining whether FOAK plants get built, so understanding how they think about these investments is critical. Given that capital owners are always balancing returns against risk, their perception of an investment's risk profile is often the determinative factor in any investment decision.

Figure 4 and Table 1 describe the normal risks associated with a capital investment, like an industrial facility and the particular risks associated with a new FOAK facility, respectively. At the outset, there is a risk that a facility will not be approved by regulators (Table 1a) or, owing to its novel nature, will encounter delays in planning and permitting that scare off investors. If and when an FID is made, there is a financing cost-of-capital borrowing risk as well as project execution risk. These two risks are linked in that the greater the project execution risk, the higher the financing costs to compensate for it, beyond the normal cost of borrowing for a project paid back over 10–20 years (Table 1b). On top of this is the technical risk of the facility not working as designed (Table 1c), which could require significant redesign or face process failures. This type of risk is reduced dramatically with subsequent plants. Once a facility is operating normally, there is the normal market price risk (Table 1d) as well as the "stroke of pen" policy risk (i.e., the risk that the government will remove, weaken, or otherwise change climate policy in a way that devalues the committed mitigation investments) (Table 1e). For figurative purposes only, "climate policy" is valued as salable credits earning positive cash flow, based on an archetype decarbonization project developed by Stiebert and Bataille (2022). The latter project used $28 per tonne CO_2e, discounted at 2% through time, which could take several practical forms (e.g., tradable emissions permits, subsidies, contracts for difference, tradable material performance standards), as discussed in more detail in later sections. The focus of this report is on execution risk (i.e., building FOAK heavy industry plants), while still considering demand, regulatory, and policy risks. It should be noted that the higher the expected carbon price factored in as a penalty or credits, the less the other risks matter, but this depends completely on firms' expectations of long-term government action, which can be difficult to predict and are often discounted.

Figure 4: Typical discounted FOAK cash flow and investment risks – $28 per tonne CO_2e



Source: Based on analysis from Stiebert and Bataille (2022).

Table 1: Risks associated with FOAK near-zero emissions plants

Risk Category	Description of Investment Risks
Upfront risks	
(1a) Regulatory	FOAK industry plants face greater risk of delays in planning and permitting as well as issues related to integrating with existing infrastructure.
(1b) Early development (TRL 1–7) and early commercial financing (TRL 8+)	Given that FOAK industry plants are inherently risky, investors may require higher financing rates or weighted average returns to capital compared with traditional investments in the industry sector. The higher financing rates are a form of insurance to cover project risks such as construction delays and cost overruns as well as operating issues.
Operating risks	
(1c) Long-term technical	FOAK industry plants generally rely on new technologies that, though proven to work in pilot plants, are untested over long time periods and subject to greater risk of pitfalls that can affect output consistency, quality, and volume as well as supply chain resilience. Processes may also be less efficient than expected, need unexpected maintenance (e.g., the need to regularly replace expensive amine solutions in first-generation flue gas CCS plants), or require new inputs that are subject to unusual supply chain constraints.
(1d) Market	While global market prices for products are a risk for any new production plant that is expected to operate 20 to 40 years into the future, FOAK low-carbon plants typically require expectation of a premium, and there is a risk this premium disappears due to market forces. In related fashion, FOAK projects also carry the significant risk that another low-carbon technology pathway with significantly lower costs comes along, potentially stranding the asset (e.g., if direct electrolysis-based iron reduction came to market much faster than expected, stranding green hydrogen direct reduced iron [DRI] facilities).
(1e) Climate policy	Existing and planned policies may be in place that provide financial incentives for low-carbon production (e.g., carbon pricing); however, these policies may be vulnerable to political headwinds that cause them to be canceled or reduced in a way that negatively impacts revenues. Many low-carbon plants may rely on carbon credit generation for revenue, and that is subject to separate carbon market valuation.

Policy Instruments to Trigger FOAK Investment

In light of these significant investment risks, this section provides an overview of policy instruments that could help to render investment in FOAK near-zero emitting industrial facilities more attractive to investors. It is rare that a single incentive or instrument is used to address all the different types of project risks (e.g., regulatory, technical, financing, and operational). Coordinated efforts by investors, technology providers, regulators, and government are typically required, especially if the goal is to accelerate investments to reach net-zero and to nurture innovative and competitive companies with long-term export potential and technology rights. For example, a large-scale FOAK plant may require a combination of financial guarantees from investors, permitting guarantees from regulators, and investment and production tax credits and project grants from various levels of government before sufficient confidence is established to make an FID and put shovels in the ground. In most cases, it takes the cumulative positive effects of multiple incentives to overcome inertia and tip the overall appeal of a project past an investment threshold, as shown by the case study of the H2 Green Steel (H2GS) start-up in Sweden discussed at the end of this report.

Upfront regulatory risk support

Before large industrial facilities are constructed, they typically undergo a permitting process conducted by national, state/provincial, and municipal regulatory authorities that provides authorizations for construction, electricity, water, waste disposal, transport and energy infrastructure upgrades, and, ultimately, operation. This process can be very slow, requiring years of lead time, and it does not even include the permissions required to support infrastructure like transport links and connections to energy and water utilities, which themselves can become mired in slow permitting processes. All of this contributes to project uncertainty, especially in the case of FOAKs. Given their quasi-experimental nature, FOAK projects are subject to even greater regulatory scrutiny — indeed, navigating the different layers of state, provincial, and federal approvals and policies often significantly delays FOAK projects or even leads to their cancellation.

The urgency of reaching net-zero climate goals demands a more efficient and predictable process that will likely need to involve coordination between all levels of government and utilities. Such a process can deliver global benefits in terms of reduced GHG pollution, and in the case of FOAKs, many local benefits that could be taken into consideration in the permitting process. Many near-zero emitting industrial projects, for instance, help improve local air and water quality because they replace local unabated fossil fuel use with electricity or hydrogen (Wang et al. 2024).

Given how challenging permitting has been for new renewables projects and transmission siting, pre-approval for generic construction as well as infrastructure for set cumulative amounts of energy, transport, water, and waste disposal where possible in clean industrial zones or clusters could help minimize permitting times. Beyond the issue of permitting, agreements by the appropriate levels of government to provide directly or indirectly (through public-private partnerships) infrastructure and services at specified long-term rates (e.g., through tolling) in pre-approved clean industrial clusters can provide critical support to FOAK plants.

Upfront technical development and project financing risk support

As summarized in Table 2, numerous financial mechanisms can be used to address technical and financing risks associated with FOAK near-zero emission industrial facilities, including funding for research and development as well as for scaling production from small to large pilot plants. This can propel technologies from low technology readiness levels (TRLs, Table 3) of 1–7 to near commercially viable, deserving of investment in private industry (TRL 8+), and, critically, capable of generating product sales revenue in niche and broader markets (UNFCCC-TEC et al. 2021). The main options for de-risking investment for the private sector currently include: direct project grants from government; below-market interest rates and financing from government or development banks; investment tax credits that reduce the tax burden of investors; and buyer equity participation that enables product buyers to obtain an ownership stake in the project.

Table 2: Financial instruments to address the upfront technical and financing risks for FOAK near-zero GHG industrial facilities

Investment Risk Type	Financial Instrument for FOAK Plants	Description
Early development technical risk (TRL 1–7)	Funding/grants for research, development, and scaling from small to large pilot plants	Government-supported research, development, and commercialization funding, ranging from simple primary research to more goal-oriented innovation programs like the US DOE's Advanced Research Projects Agency-Energy (ARPA-E) and US DOE Industrial Decarbonization Roadmap and Liftoff reports (US DOE et al. 2022; US DOE 2023b).
First and early commercial financing risk (late TRL 7 and TRL 8 onward)	Project grants/loans	Early funding transfer payments for FOAK near-zero-carbon plants that meet eligibility requirements. Example: the US Industrial Demonstrations Program Office of Clean Energy Development (OCED) (US DOE 2023a).
	Below-market interest rates and financing	Government or development bank loan supports and guarantees. A risk-absorbing instrument to mobilize private sector investments for development. Provide investors with assurances to invest capital in FOAK projects. Example: The US DOE Loan Programs Office (USDOE 2024, p. 202).
	Investment tax credits	Tax incentive for project investment that enables the deduction of a percentage of investment costs from taxes. Additional to normal allowances for depreciation. Requires deductible expenses or transferability to another entity.
	Buyer equity participation	Shared stock or other security representing ownership interest shared between government, public agencies, final customers, and/or competitors for FOAK plants (e.g., H2 Green Steel).

Table 3: TRLs and policy implications, using IEA and NASA definitions

Broad Stage	TRL	Narrow Stage	Policy and Financial Requirement Implications
Conceptual or research phase	1	Initial idea, basic principles observed	Conducted at scale of researcher or small company, with low capital needs. Broad R&D support is sufficient.
	2	Application formulated, technology concept formulated	See TRL 1. Broad R&D support is sufficient.
	3	Concept needs validation, experimental proof of concept	Moderate funds may be needed.
Small prototype (development phase)	4	Early prototype, technology validated in lab	Funding needs increase but are not beyond the capacity of research institutes or small firms. Entering realm of ARPA-style funding.
Large prototype (development phase)	5	Large prototype, technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)	Moderate costs, no revenue, significant support needed. Realm of ARPA-style funding.
	6	Full prototype at scale, technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)	Large costs, no revenue, significant support needed. Realm of ARPA-style funding, but moving toward Office of Clean Energy Demonstrations (OCED) funding.
Demonstra-tion (deployment phase)	7	Pre-commercial demonstration, system prototype demonstration in operational environment	Very large costs, no revenue, significant support needed. Funding needed beyond typical ARPA-style funding, firmly into OCED territory, broadly large firm, venture or state capital investment required.
	8	FOAK commercial, system complete, and qualified	Strong natural or created lead market necessary, makes compensating revenue generation to balance costs possible.
	9	Commercial operation in relevant environment, actual system proven in operational environment	Strong natural or created lead market necessary.
Early adoption	10	Integration needed at scale	Moderate natural or lead market support necessary.
Mature	11	Proof of stability reached	Natural or created lead market normally no longer necessary.

Source: UNFCCC-TEC et al. (2021).

Ongoing operational market and policy risk support

The same instruments are used to address operational market and climate policy risks, but market risk support can be more certain than policy risk support, as climate-orientated policies have sometimes proven vulnerable to reversal depending on the government involved. However, the more legally binding the climate policy risk support (e.g., as a contract where firms can sue governments for reneging, or in the US context as part of a Congressional act rather than an executive order), the stronger the risk reduction effect will be.

Table 4 lists financial instruments that have been used to address operational risks — process subsidies, public and private lead premium product markets, contracts for difference, and Zero Emission Performance Standards — each of which will be addressed in turn.

Table 4: Financial instruments to address the operational market and climate policy risks for FOAK near-zero GHG industrial facilities

Investment Risk Type	Financial Instrument for FOAK Plants	Description
Operating risk (market risk)	Process subsidies (e.g., production tax credits)	Credits or subsidies based on unit production of FOAK plants. For example, the IRA CCS 45Q credit (per unit of CO_2 sequestered [$85/t CO_2] or utilized [$60/t CO_2]) and IRA ~$0.026/kWh production tax credits (PTCs) for wind and solar, and long-term $0.015/kWh for all clean electricity.
Operating risk (market and policy risk)	Creating premium product markets	Markets for green products from FOAK plants that pay a premium over baseline production or are otherwise preferred. Can be flexible and use reverse auction to find willingness to supply at least cost. Several European car makers have agreed to buy the early production of green steel plants in the EU on a private bilateral contract basis. Ideally, in the medium to longer term, willingness to pay will be transparent on some form of green commodities exchange, but this is not possible until there are several producers, which is the purpose of FOAK plants.

continued on next page

Investment Risk Type	Financial Instrument for FOAK Plants	Description
Operating risk (market risk) cont'd	Contracts for difference (CfDs)	A type of contract where a government or other agency guarantees a minimum product price (can be based on physical unit of production or carbon price). It can use reverse auctions to reveal supplier willingness to supply at the least cost. The UK uses reverse auction derived CfDs to fund offshore wind, and Germany has instigated a CfD program for heavy industry.
	Tradable zero emission performance standard (ZEMPS)	The ZEMPS concept is based on the Zero Emissions Vehicle (ZEV) standard used by the California Air Resources Board. A ZEMPS can be set for a sector within a specified jurisdiction (e.g., the California cement sector). Firms must hold a ZEMPS credit for all units sold (e.g., one for every 10 units given a 10% market standard). Over-complying firms can sell their excess credits to under-complying firms, providing a financing source for FOAK plant investment and market uptake. While normally thought of as a market uptake policy, a ZEMPS can be used to trigger investment in a FOAK facility when the means to build a FOAK facility are well understood but much more expensive than a conventional plant (e.g., CCS for modern cement plants).

Source: Detailed references for each instrument are provided in the following explanatory sections.

Process subsidies

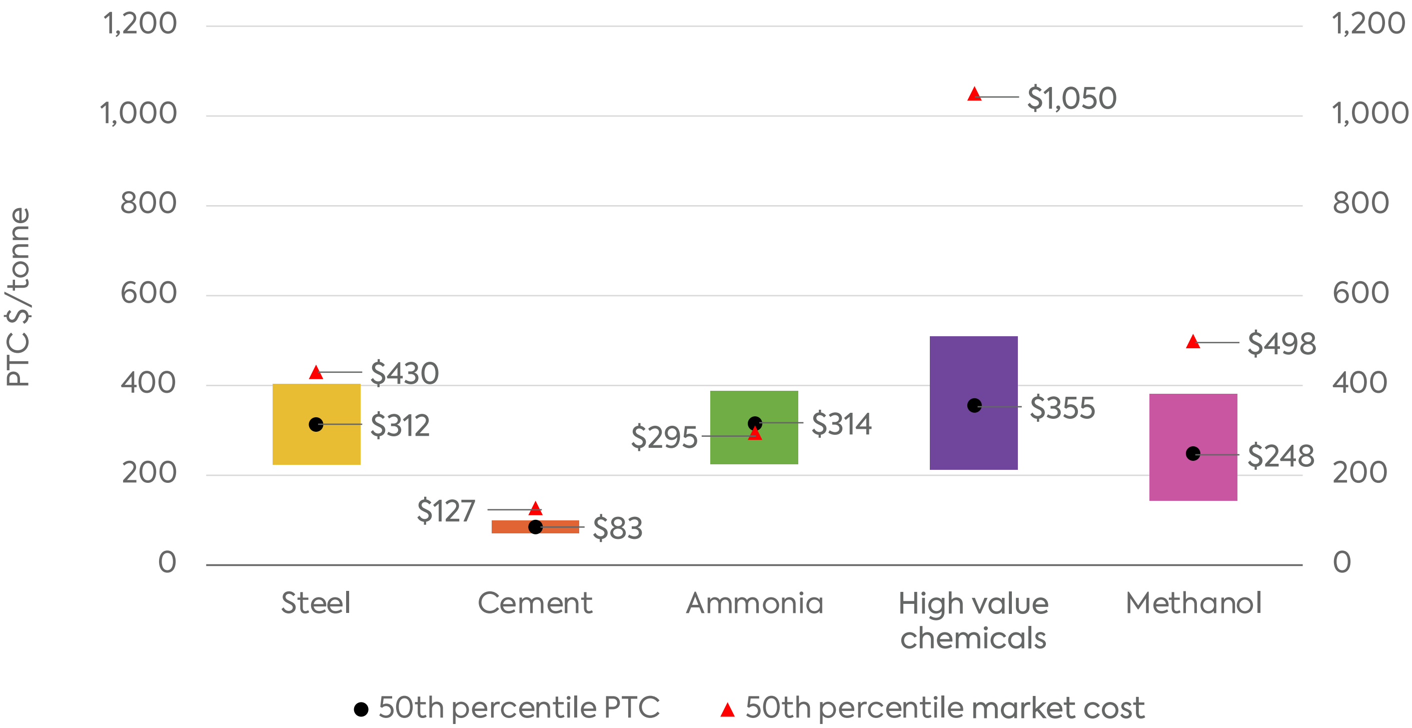
Process subsidies have been used extensively in many countries since the early 1990s for electricity generated from renewables (e.g., wind and solar). The amount of the subsidy is typically linked to the physical quantity of production (e.g., kWh of electricity produced, tonnes of steel produced, tonnes of hydrogen produced), which makes the potential credits earnings from the subsidy scheme straightforward to forecast. Process subsidies are a relatively predictable source of revenue and act to reduce uncertainty about future cash flow, which in turn reduces the perception of risk by investors. Provision of the subsidies is often tied to local production requirements (e.g., to protect local labor) and performance standards (e.g., the level of emission intensity desired by the policy) such that credits are only earned when these conditions are met.

The IRA's tradable investment and production tax credits (US Congress 2022) and the European Green Deal Investment Plan (EGDIP) (European Parliament 2020) are the most recent examples of process subsidies in action. The IRA already offers production tax credits (PTCs) for clean electricity,[8] green hydrogen,[9] advanced manufacturing components (e.g., solar modules, wind turbines, battery cells and modules, and critical minerals), efficient hybrid and electric vehicles, clean biofuels and sustainable aviation fuels, and carbon capture and sequestration or utilization.

Future policies to support the near-zero emissions industry could apply IRA-style credits to the production of zero-emissions industrial commodities such as reduced iron for green steel and clinker for cement. At the time of writing, the available evidence indicates that FOAK projects intended to produce near-zero emission versions of several key intermediate inputs do not become investable unless the expected carbon price on all emissions or premia (e.g., as a PTC) are estimated as follows (see also Figure 5):

- **Reduced iron for steel:** Median $312 per tonne (~+73% increase in production cost), with a range of $224–403 from the 10th to 90th percentile, excluding all other inducements. This is equal to $129–301 per tonne CO_2e.
- **Clinker for cement to make concrete:** Median $83 per tonne (~+66% increase in production cost), with a range of $69–98 per tonne excluding all other inducements. This is equal to $94–118 per tonne CO_2e.
- **Green ammonia (i.e., where electrolysis is used to make the necessary hydrogen):** Median $314 per tonne (~+106% increase in production cost), with a range of $224–388 per tonne excluding all other inducements. This is equal to $296–314 per tonne CO_2e.
- **Bio-methanol:** Median $248 per tonne (~+50% increase in production cost), with a range of $144–381 per tonne excluding all other inducements. This is equivalent to $147–247 per tonne CO_2e.
- **High value chemicals (HVCs, olefins)[10]:** Median $355 per tonne (~+34% increase in production cost), with a range of $212-509 per tonne excluding all other inducements. This is equivalent to $386-638 per tonne CO_2e.

Figure 5: Estimated FOAK near-zero emissions product premia or production tax credit (PTC) over current average market price before other inducements



Source: Authors' calculations; see the appendix for more explanation.

In exploring the range of market prices for these products, a key finding was that the lower estimates of the cost of producing clean versions of some of the commodities and the higher range of historic market prices often reduced the necessary premia or carbon prices substantially, especially in the case of ammonia, methanol, and HVCs. Explanations of these values can be found in the Appendix.

If these premia were to be translated into PTCs similar to the IRA hydrogen PTCs, either a single or declining ladder of dollar or percentage amounts must be specified (e.g., the IRA specifies hydrogen subsidy "buckets" of $0.60 for 4-2.5 kg CO_2e per kg H2, $0.75 for 2.5–1.5, $1 for 1–0.45, and $3 for < 0.45, etc. [DOE 2023a]). For example, in terms of the appropriate ladder for reduced iron, while evidence exists that $312 ($224–403) per tonne in support may be appropriate for achieving reductions on the order of 95% for the first plant, minus all other inducements, the situation becomes more complicated for partial reductions if they are included as a policy goal. The question of whether $100 per tonne is appropriate for -80% is potentially important for the design of detailed policy, but is beyond the scope of the present project. The authors plan to tackle it in future research.

The carbon prices associated with the above PTC values far exceed expected values for the coming decade, indicating carbon pricing cannot be expected to drive down investment in these FOAK and early follow-on facilities. These values may also differ across markets and national contexts. One useful means of avoiding overpaying or underpaying subsidies is to conduct premia price discovery using reverse auctions for tranches of production. Under a reverse auction, price support is offered periodically or in batches for a fixed amount of production, and industry must submit competitive tenders to obtain the subsidy. This approach incentivizes competition to drive down prices and has already successfully stimulated large-scale deployment of offshore wind energy in markets like the UK, Germany, Denmark, and the Netherlands (Rubio-Domingo and Linares 2021).

Premium product markets (PPMs)

The concept of creating markets offering a premium for near-zero emissions industrial products is in a very early phase of development. Niche markets for products like clean iron, steel, cement, ammonia, methanol, or HVCs, with transparent and verifiable low-emission credentials, would allow buyers willing to pay a premium for clean materials and chemicals to identify producers efficiently (i.e., at least cost). At the time of writing, there are no listed exchanges offering near-zero industrial products at premium prices. Instead, there are a few limited premium markets that are part of either government procurement programs or private company-to-company bilateral agreements guaranteeing higher long-term price purchases, with cost recovery from final consumers accompanied by enhanced green branding (see the end of this section for examples).

Governments can support the creation of premium markets through public procurement. Public entities often have sizable buying power for industrial products, making them an influential driver of demand. For example, public procurement accounts for an average of 12% of GDP in OECD countries and 30% in many developing countries (OECD 2023). The Netherlands is perhaps the most advanced country in terms of the practice of sustainable procurement. In 2010, the Dutch House of Commons ruled that Dutch public authorities had to implement 100% sustainable procurement by 2015 (OECD 2014). In the US, California adopted AB262 or the "Buy Clean California Act" in 2017 (Government of California 2023).[11] Green procurement arrived at the US federal level with US Federal Executive order 14057 (OFCSO 2021), which mandated the establishment of standards for clean procurement for all products procured by the US federal government. At the global level, the United Nations Industrial Development Organization (UNIDO) Industrial Deep Decarbonization Initiative (IDDI 2023), part of the Clean Energy Ministerial, brings together national jurisdictions willing to embark on various stringencies of Buy Clean policies. Currently co-led by India and the UK, the coalition comprises Sweden, the US, Canada, the UAE, Germany, Japan, and Saudi Arabia. Governments can also impose minimum content regulations or preferential buying obligations for the industrial products that are most important to decarbonize (e.g., cement, steel, fuels, chemicals). Examples of bilateral premium markets include the following:

Green steel

Some automotive companies have committed to ambitious end-to-end value chain decarbonization targets that require them to procure near-zero steel and other industrial products as they become available (SIEMENS 2023). In European automotive markets, demand for near-zero steel has been steadily increasing, resulting in bilateral contracts between several European steel and auto makers — H2 Green Steel, for example, had signed over 20 customers for its steel by January 2024.[12] Price tracking suggests that premiums for physical steel with low embodied (Scope 1, 2, and 3) emissions are currently in the range of €200–300 per tonne (Fastmarkets 2023). As an example of one of these bilateral contracts, Thyssenkrupp Steel and Mercedes-Benz have signed a memorandum of understanding under which the automaker will receive CO_2-reduced steel products from Thyssenkrupp from the second half of 2026 onward (ThyssenKrupp 2023). The German car company also has an equity stake in Swedish steelmaker H2 Green Steel and an offtake agreement for a 50,000 Mt/y supply of lower CO_2 emission steel.

Green methanol

Offtake agreements for low-emission-intensity fuels such as green methanol are emerging in the global shipping chain. For example, OCI Global, the world's largest green methanol producer, and X-Press Feeders, the world's largest common feeder operator, signed a green methanol offtake agreement in 2023 that guarantees demand and supply (OCI 2023). OCI global also has a partnership with the Danish shipping company Maersk, which is currently building 20 methanol-fueled container ships that will need fuel to serve them, which will be partly provided by OCI.

Sustainable aviation fuel

Current prices for sustainable aviation fuel (SAF), which is normally made from agricultural oils, are estimated to range in cost from 1.5 to 6 times the price of fossil-based jet fuel. Eventually, SAF based on CO_2 captured from the air combined with low-GHG hydrogen and oxygen is expected to cost around 1.5–2 times current fossil fuel prices (ICAO 2023). SAF producers around the world contract with airlines seeking to buy sustainable fuel to power their planes. In the EU, this occurs using a tradable credit system similar to a carbon offset system, wherein the airline purchases SAF credits to count against their consumption of fossil-based fuel, but the physical SAF is consumed at the local airport where it was supplied for other flights.

Contracts for difference (CfDs)

CfDs are a financial tool derived from futures markets where a contractual agreement is established to pay a specified price if a product or policy price index reaches a certain level — they are, in effect, a form of conditional insurance based on an independent price or value index. This tool has been successfully applied in several jurisdictions to increase market uptake of clean electricity technologies (Rubio-Domingo and Linares 2021; Welisch and Poudineh 2020) by guaranteeing a minimum price for wind and solar power. If the market price for electricity is lower than the contract price agreed upon at auction (often called the "strike price"), the electricity authority or another supporting institution pays the difference to the producer. If the price is higher, the supporting institution can keep the extra amount to help fund the program, as has typically occurred in the UK with its wind CfDs when the UK government sought to accelerate wind uptake (DECC 2012).

CfDs could also be considered a support mechanism for important emission-intensive industrial products like iron and steel; clinker and cement; ammonia, methanol, and other feedstock chemicals; and end-use synthetic fuels and fertilizers (Sartor and Bataille 2019). They can be designed to address carbon price uncertainty (i.e., carbon contracts for difference [CCfDs]) or market price uncertainty (i.e., product contracts for difference [PCfDs]). In a CCfD, the payment is indexed to a carbon price, providing insurance to protect mitigation investments (Richstein and Neuhoff 2022). In this case, the CfD would apply to the difference between the CCfD strike price and the carbon price realized during the period in question. In a PCfD, any payments would apply to the difference between the PCfD product strike price and the actual market price during the period in question. Table 5 and the next section on "CfDs in practice" provide further detail on the design and implementation of this policy instrument.

Table 5: Design elements for contracts for difference employed for FOAK low-GHG industrial plants

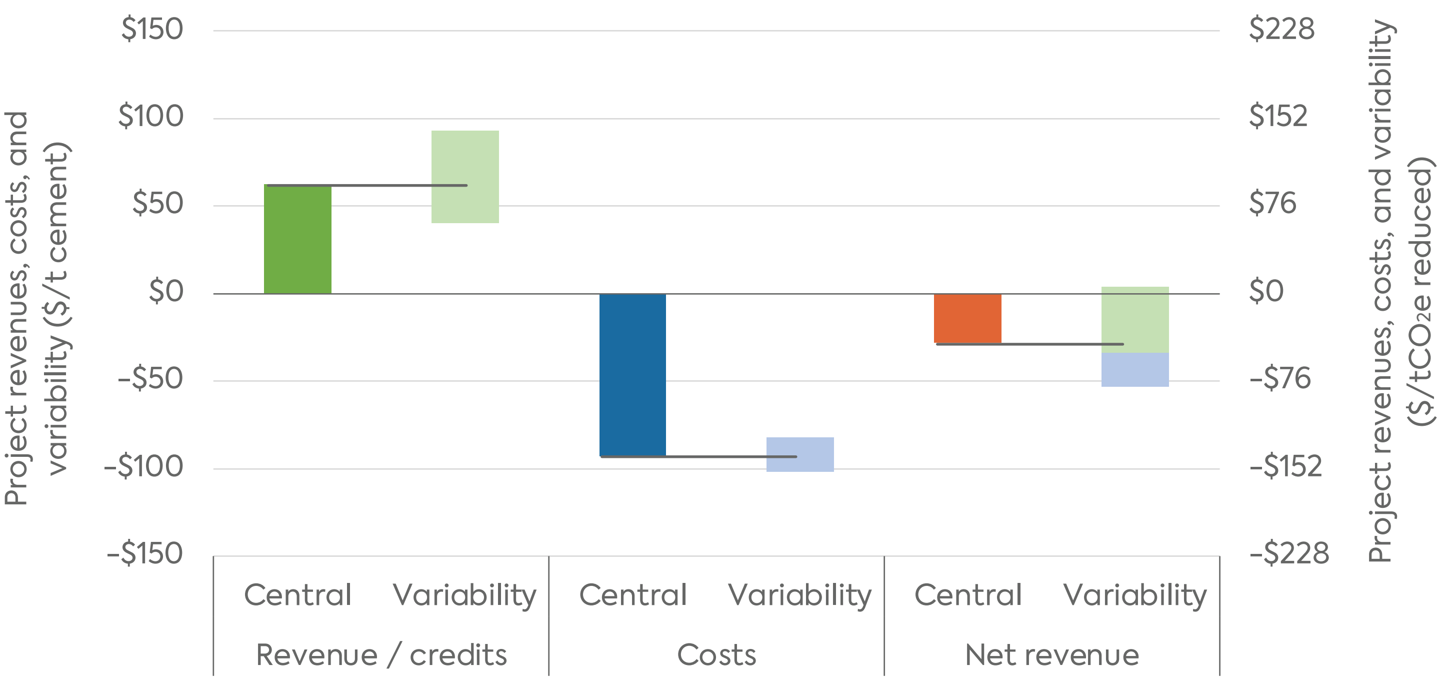
Instrument Design	Description
Eligibility considerations and ease of implementation	The concept applies to FOAK net-zero-compliant plants with technology, infrastructure, financial, or market risk that would otherwise delay their investment. The plants need to represent large-scale industrial facilities with relatively homogenous emission-intensive products where global benchmark market value (i.e., prices) can be established. Audit and verification of emission reductions is required.
Costs (terms and adjustments)	Multiple options are available to set the contract price, including simple granting through a criteria application process and more sophisticated reverse auctions. Terms are likely to be between 10 and 20 years; companies are very much focused on early capital returns on investment due to the costs of financing. Government liabilities could be high depending on the agreed upon price and volume achieved, and they need to be evaluated and pre-limited if necessary to preserve budget integrity. On the other hand, the UK notably set the maximum clearing price too low in its 2023 wind auction, and there were no successful bids. Funding could come from carbon pricing revenue.
Role of actors and governance	A national/federal/regional (state/province) organization with significant taxation and borrowing powers is required to implement CfDs. This could be a government department or an arm's length organization such as a development bank or fund.
Regulatory considerations	Many government programs and regulations have mandatory regulatory impact assessments, against which the regulation's legal acceptability and short-term impact may be measured. CfDs may not fit the standard measurements of effectiveness and cost efficiency.
Policy stacking considerations and interactions	An evaluation of the net effect of carbon policies and incentives related to other stacked policies is critical to avoid over-subsidization when determining the strike price without competitive auction.
Equity and distributional effects	CCfDs may be difficult to apply selectively for only a few sectors or for only a limited number of FOAK facilities and technologies, as the goal of carbon pricing is to establish a national, economy-wide price signal for industry. CfDs offer advantages over direct government subsidies, as they are designed to pay out only when verified emission reductions and low-carbon production occurs. In the case of PCfDs, they also hedge whether market prices reflect carbon or "green" product premiums.

Source: Authors' calculations; see the appendix for more explanation.

CfDs in practice

Previous research (Stiebert and Bataille 2022) developed a financial model for a hypothetical low-GHG cement production plant in Canada. The model considered cash flow outcomes based on ranges of expected operating expenses (OPEX), CAPEX, revenues, and carbon credit values as well as the contribution of existing carbon pricing policies and investment tax credits. Figure 6 shows the net present value of the project on a per tonne of cement and per tonne of CO_2e reduced basis without any additional financial instruments in place, given the estimated $28 per tonne carbon credit price used in Stiebert and Bataille (2022). The first bar for each element represents the absolute value of the central estimate, while the second represents its reasonable variability given known risks.

Figure 6: Expected profitability of a net-zero cement facility without additional financial instruments



Source: Stiebert and Bataille (2022).

Figure 6 indicates that in the central case the project (as is) would be expected to lose an average $26 per tonne of cement produced, but with a range extending from slightly above breakeven (in the best case) to a loss of more than $50 per tonne of cement (in the worst case). With such a project, a CfD could be designed to increase the likelihood that the investment is profitable. For example, if a product CfD set a strike price that was $30/tonne product greater than the expected market price, investors may be persuaded that the plant is likely to be profitable to operate and worth investing in. Ideally, CfDs would be set through reverse auctions because competition can help in identifying the price at which suppliers are willing to engage. CfD reverse auctions for electricity have been very successful in this regard by supporting the development of offshore renewable power markets in the UK, with substantial drops in price in Rounds 1–4 (ORE Catapult 2023). Interestingly, Round 5 failed because the maximum price was set too low, sending clear signals globally that the post-COVID interest rate increases had fundamentally changed the near-term cost of offshore wind in particular (Ambrose 2023).

Zero Emission Material Performance Standard (ZEMPS)

A ZEMPS to trigger investment in FOAK plants, initially suggested as a Zero Emissions Cement (ZEC) standard for clinker in Bataille, Stiebert, et al., (2023), is a means of creating and sustaining a premium market for near-zero GHG industrial materials (e.g., iron, clinker, ammonia, urea, finished fertilizers, or high value chemicals like olefins) using funding from existing producers in that market. Instead of subsidies originating from taxpayer revenue being used as direct payments to industry, a ZEMPS policy encourages regulators to create conditions where industry itself is incentivized to compete and fund innovation.

ZEMPS policies would employ a mandatory compliance credit system modeled on the Zero Emissions Vehicle (ZEV) standard administered by the California Air Resources Board (CARB), which is largely credited with helping to bring about the mass deployment of EVs many decades earlier than might otherwise have occurred. Early certificates traded at very high prices, providing EVs manufacturers significant income to offset early technology investment costs and risks, as conventional internal combustion engine (ICE) manufacturers had to purchase a mandated portion of credits for each thousand vehicles sold, while incurring only a small incremental cost per ICE vehicle sold. In this way, the policy achieved both short- and long-term goals. There is substantial evidence that the sales of overcompliance CARB ZEV credits to other automakers significantly contributed to net revenue and therefore to Tesla's survival from 2013 through 2020, when the company became structurally profitable (Statista 2023; Stock Dividend Screener 2023). Over the long term, the lessons Tesla learned have been largely transferred to other global EV producers, enabling economies of numeric scale and innovation, declining costs of production, and replicability. Traditional automakers have responded to the success of Tesla and other EV manufacturers by making enormous investments in their own EV programs to remain competitive amid the long-term rising expectation of the ZEV and declining costs.

The purpose of a ZEMPS modeled on the ZEV would be to transform industrial production by spreading the cost of building FOAK near-zero emission industrial facilities across all the existing producers covered by the policy (e.g., all the cement or iron produced in a given jurisdiction, whether a state, province, or country). A ZEMPS would require all industrial production of a homogenous and standardizable product (e.g., a tonne of clinker, cement, iron, steel, ammonia, methanol, or cracker usable output) to hold an accompanying Zero Emission Certificate, indicating that a specified portion (e.g., 1/10th) of the product was produced with near-zero emissions. The need to purchase the compliance credits from somewhere is the signal for rapid development of FOAK near-zero emission plants if they are ready to be built. The scheme anticipates the sale of credits from over-complying zero-emissions facilities to companies operating non-compliant plants.

The number and size of FOAK near-zero emission plants that the policy is designed to stimulate is a function of the policy stringency in the scheme design — particularly the ratio of near-zero emission production to conventional production required to earn each credit. To trigger the building of a first near-zero emissions plant in a given region, the initial ratio used to define the size of a Zero Emissions Certificate would need to be computed using the value of one standard-sized plant (e.g., producing X tonnes per annum) divided by a region's total production including net imports, which would also be required to hold a ZEC. The ZEMPS could then prescribe a rising portion of zero-emission production into the future, increasing in increments that fit standard plant sizes with the expectation of reaching close to 100 percent zero emission by 2050. The greater the coverage of production (i.e., jurisdictions and facilities), the lower the specified portion of near-zero emission production can be to trigger the building of the first, second, and third near-zero FOAK facilities — thus creating relatively inexpensive compliance costs for existing producers and allowing for effective cost sharing of the transition across the whole jurisdiction. To prevent leakage, importers of the commodity in question would be required to surrender ZEMPS credits with the sale of their products. The initial expected benefits of the ZEMPS have less to do with reducing absolute GHG emissions in the near term, and more to do with reducing the mid- and long-term costs of decarbonizing production, developing technology, and intellectual property benefits for participating companies and improving global competitiveness. In the longer run, the ZEMPS could be progressively tightened to include more of the producing fleet in a given jurisdiction, whereupon it would begin to act more like a minimum performance standard. More information on the design of ZEMPS is provided in Table 6 as well as in the discussion of the California ZEV program example below.

Table 6: Design elements for zero emission material performance standards employed for FOAK low carbon industrial plants

Instrument Design	Description
Eligibility considerations and ease of implementation	The more facilities that are covered, the more likely a ZEMPS can properly function, in terms of both the solvency of trading credits and not imposing a high unit cost on production that risks damaging overall competitiveness. The more traded a product is (outside the regulated jurisdiction), the more difficult it can be to design an effective ZEMPS. This is because the jurisdiction must have the legal and administrative capacity and political will to enforce a ZEMPS ZEC requirement for all large-scale imports. Where imported products arrive in large quantities at a few ports of entry, the requirement of ZEMPS credits may be enforceable. The point of enforcement must be clearly defined and may require monitoring and checking of traded commodities as well as other border measures. The more integrated the industrial product is with the secondary manufacturing of other products and the more heterogeneous the product, the more difficult it may be to track and enforce a ZEMPS. This enforcement and tracking can be tested with industry stakeholders to maximize efficacy. A ZEMPS needs to be consistent with a net-zero pathway appropriate for the jurisdiction (e.g., by 2045 in California and other early mover jurisdictions, 2050 in most OECD jurisdictions, 2060 in China, 2070 in India, and 2055 globally [IPCC 2022]). This implies that qualifying products will be near net-zero on a lifecycle emissions basis, e.g., by 2050 in most OECD jurisdictions. The ZEMPS is intended to provide "bankability" for large capital investments, and therefore requires a long-term schedule for stringency. If used as a long-term market uptake and not just FOAK policy concept, the policy would sunset when the goal of making new near-zero plants standard is achieved.
Costs (terms and adjustments)	In order to be effective, stringency, or the percentage of total production that needs to be covered by a ZEMPS, should be low enough that it does not impose significant cost increases to consumers (e.g., a 5% increase in cost), while still incentivizing the construction of the first, second, and third large scale near-zero plants. Typically, a ZEMPS will allow for banking and compliance flexibility. ZEMPS credits would be registered with the enforcement body, but prices may or may not be tracked on an exchange.

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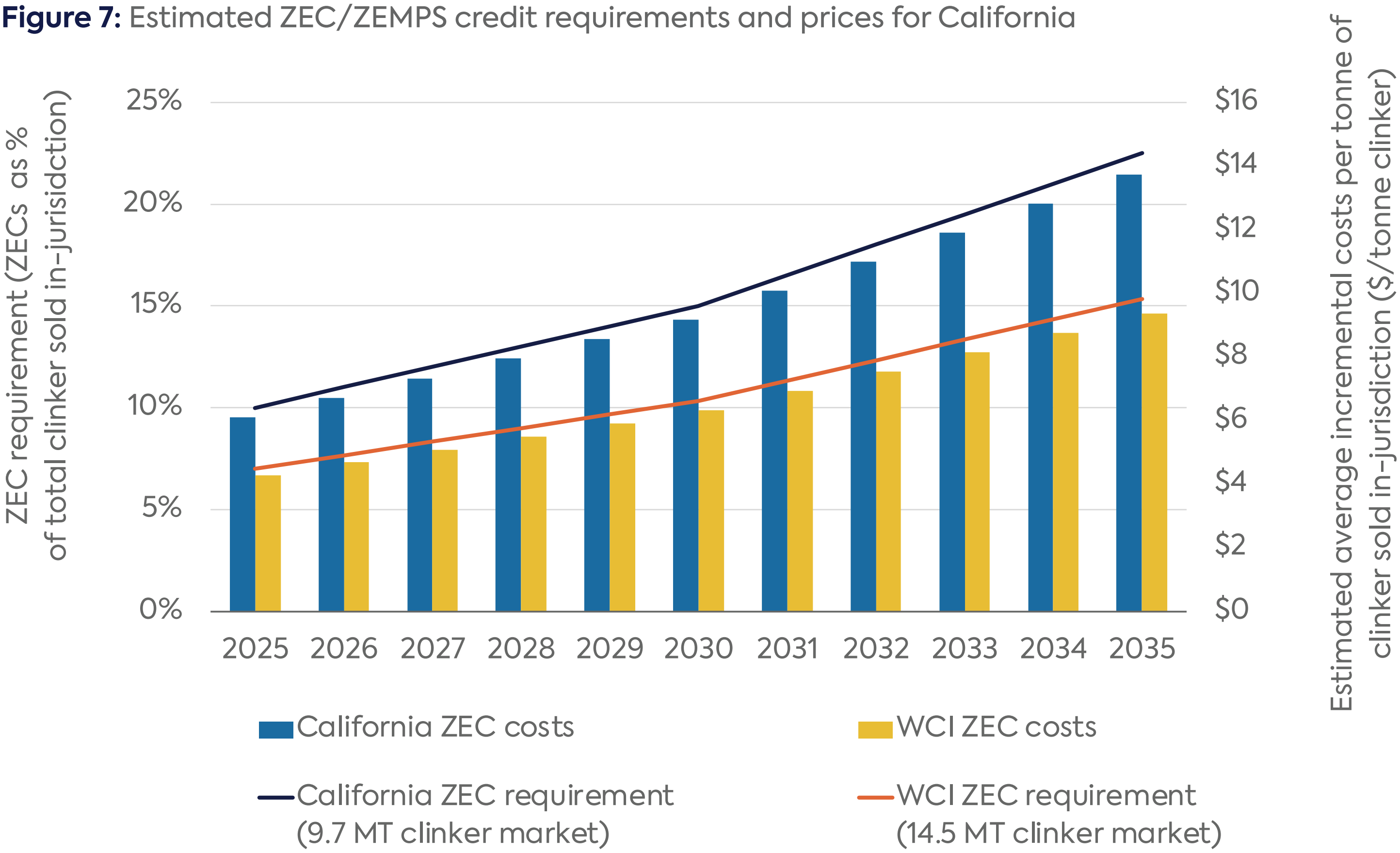
Instrument Design	Description
Role of actors and governance	Data collection, verification, and monitoring are key to enforcement and successful implementation. While a regulatory agency can design and implement the ZEMPS, it will need to work with the appropriate customs and trade authorities to ensure an effective system of tracking and compliance. If the government raises funds through non-compliance penalties, most jurisdictions will legally require that the policy specifies what happens to these funds, (i.e. kept in general revenues, used to self-fund operations, banked, etc.).
Regulatory considerations	Historically, trade rules from the World Trade Organization and General Agreement on Tariffs and Trade typically require equal treatment of in-jurisdiction and out-of-jurisdiction companies. If a company in the latter category sells near-zero product within the ZEMPS market, it would therefore in theory be eligible to sell ZEMPS credits. But in practice, it remains an open question how producers outside a jurisdictional area should be treated when it comes to ZEMPS credits. One advantage of permitting extra-jurisdictional facilities to receive these credits is that the facility gets built — and presumably at least cost. But on the downside, the investment is outside the jurisdiction, possibly reducing the political acceptability of the policy. If the relevant governing authority were nevertheless to permit such activity, then mechanisms for ensuring that the facility opts in to all requirements and monitoring to maintain the salability of its credits within the ZEMPS jurisdiction would need to be negotiated to avoid leakage and devaluation of ZEMP credits.
Policy stacking and trade considerations and interactions	A ZEMPS may be a complementary policy to carbon pricing or a jurisdictional cap and trade. Given that it is requiring the building of FOAK facilities instead of simply charging for tonnes emitted, typically at a lower cost per tonne avoided, its costs will be incremental to the complementary policy.

A proposed ZEMPS for cement (or ZEC standard [based on the CARB ZEV])

As a concrete example of a proposed ZEMPS based on the CARB ZEV principle, we turn to the needs of California Bill SB 596, in which CARB must provide a plan to reach a 40% emissions intensity reduction by 2030 and net zero by 2045. Bataille, Stiebert, et al., (2023) analyzed a potential Zero Emission Cement Standard for California and a larger market that also included the participants of the Western Climate Initiative (WCI). Based on the expected incremental costs of production for at least two FOAK near-zero clinker plants, the study estimated incremental costs per tonne of clinker sold within the jurisdiction (Figure 7

Figure 7: Estimated ZEC/ZEMPS credit requirements and prices for California



Source: Bataille, Stiebert, et al (2023).

As detailed in the figure, the ZEC requirement (percent of cement that must be near-zero clinker) for California to build two full-scale FOAK clinker plants by 2030 rises from 10 percent in 2026 to 22 percent in 2035, which corresponds to rising estimated average incremental costs of approximately $6 to $14 per tonne of clinker sold in California. This represents an increased premium for clinker of about 10 percent (clinker at US$125/tonne). If the ZEC applied to the whole WCI (which has 50% more clinker production than California), the ZEC requirement for building the same two full-scale FOAK plants by 2030 would start at only 7 percent in 2026 and rise to 15 percent in 2035. The incremental costs would be decreased by a third. The key lesson is that a ZEMPS for a major industrial product is possible at the scale of an economy the size of California, which pioneered the highly effective ZEV by itself, and it becomes progressively more acceptable economically and politically the larger the jurisdiction sharing the policy.

Case Study: H2 Green Steel

The report now turns to a case study of a real-world FOAK project to provide context for the discussions of investment risk and risk mitigation policies. H2 Green Steel (H2GS) in Boden, Sweden represents a rare phenomenon: a start-up heavy industry company. Building on knowledge gained from the HYBRIT project at Luleå nearby, HSGS has attempted to disrupt the global steel sector by using hydrogen rather than coal as the reductant in the ironmaking step of the steel-production process, thus cutting emissions by 95 percent relative to conventional steelmaking. Another novel feature of H2GS is that its investors are also early buyers of its produced steel — so in addition to providing investment equity and loans, these investors have pledged to purchase 1.5 Mt per year of H2GS's initial 2.5 Mt per annum production target (H2GS aims to be producing 5.0 Mt per year by 2030). H2GS will employ up to 10,000 people during construction and then 1,500 annually. The technology it deploys is direct reduction of iron using hydrogen (H2-DRI), with the hydrogen coming from low-carbon electricity (the project is anticipated to use around 4 TWh per Mt of production). Although H2GS was founded only in 2020, it aims to start production in 2025 — this would make it one of the fastest industrial set-ups in recent history. This case study attempts to explain how H2GS came to be, the role of markets and policy in enabling its development, and how it has employed several strategies discussed earlier in the report.

The H2GS origin story

The idea of developing green steel came from the vehicle industry. Venture capitalist Harald Mix and his investment firm Vargas, founders of Europe's first homegrown EV battery manufacturer, Northvolt, realized that the next step in vehicle decarbonization would be in the materials sector. They calculated that by slashing steel emissions, vehicle manufacturers could: 1) lower exposure to cost increases when free emission credits under the EU ETS are phased out in Europe, raising the cost of emissions-intense materials like steel; and 2) have an additional advantage over competitors by offering an even greener car to early adopter customers. This led Mix and his firm to establish H2GS.

Mitigation of upfront regulatory risk

Any new steel facility requires a source of iron ore, manufacturing equipment, transport infrastructure, and experienced personnel. A DRI steel facility using electrolysis-based hydrogen as the reductant also needs lots of low-GHG electricity. Assembling these components into a cohesive whole requires time-consuming permitting and much patient capital. H2GS started preparing the groundwork for its facility five years before its anticipated first production year by working on multiple potential barriers to deployment in parallel. The company chose the town of Boden in northern Sweden as the location for its first plant due to the access it provides to key resources. The mines of northern Sweden produce 80 percent of the EU's iron ore (LKAB 2023), and the region is home to the country's ample hydro and wind power resources. Boden is also close to transmission lines and the nearby port of Luleå, from which steel can be shipped to markets and where a railway that transports iron from the mines already passes through. Several heavy industries in the region were already electrifying before H2GS appeared on the scene. The company managed to overcome fierce competition for power capacity through successfully negotiated access from the regional grid operator in 2023, which delivers almost entirely hydro-generated electricity, as electricity applications had already been sent in before the company was announced in 2021 (VIkström 2023).[13] The company started construction on the new plant one week after initial permits were granted in 2022 and only received final permits in June 2023 (Naturvårdsverket. 2023).

Mitigation of upfront financing risk

H2GS uses project grants/loans and buyer equity participation to mitigate financial risk. It is unknown whether the company also employs below-market interest rates and financing, but support for H2GS from both the Swedish government and the European Union is substantial, and it is safe to assume that rates are favorable.

Notable early-stage investors in the project include Swedish truck and bus manufacturer, Scania; Kobe Steel, the owner of Midrex, one of two companies in the world that manufacture hydrogen direct reduced iron furnaces; and global cable and grid technology manufacturer Hitachi Energy (H2 Green Steel 2022a). The CEO of H2GS is the former CEO of Scania, while the contract with Hitachi includes not only the equity investment but also the provision that Hitachi will supply technology for H2GS' plant and buy steel from H2GS (Hitachi Energy 2023). In other words, the investors not only provided startup loans but also are part owners of the project and contribute significant equipment, personnel, and knowledge to it. H2GS' contracts with steel purchasers have also been important in terms of securing funding as they enable the company to demonstrate demand for its product when it negotiates with banks.

A key component of the H2GS finance risk mitigation strategy has been to mitigate operating risk by securing advance contracts with future customers years before commencing manufacturing. The company then uses these contracts as leverage to negotiate with banks for additional funding. The Swedish Export Credit Corporation and the German export wing of the development bank KfW, together with several private banks, are contributing €3.3 bn to the project, with additional support from the Swedish National Debt office (H2 Green Steel 2022b). By October 2022 — a year and a half after the company was announced — H2GS had secured €3.5 bn in debt financing out of its €5 bn goal (H2 Green Steel 2022b).

The European Union is also directly supporting the project through the European Investment Bank with €750 mn in senior debt (H2 Green Steel 2022b), and it recently selected H2GS as one of several projects to receive an undisclosed amount of funding through the EU Innovation Fund (European Commission 2023b). H2GS has also applied for 3.8bn SEK (350m USD) in state aid (Björkland 2023).

Mitigation of operating technical risk

HSGS has mitigated technical risks largely by following the example of the preceding HYBRIT hydrogen DRI project, which showed that 100% hydrogen-based iron ore reduction is feasible, and expressed a willingness to license patented processes. HSGS also plans to operate initially as a syngas-based DRI facility, with full convertibility to electrolysis-based 100 percent hydrogen as the reducing agent. This provides a backstop in the event the company cannot access sufficiently inexpensive clean electricity to make hydrogen, the reductant used instead of coal for making iron.

Mitigation of operating market risk

H2GS mitigates operational risks in part by using premium product markets. A major anticipated target market for H2GS' near-zero emission steel is the automotive industry, and as noted earlier, Scania is a major investor in the project. Scania plans to use 100% green steel in its manufacturing by 2030 (H2 Green Steel 2023a). Investors in H2GS understand that while the hydrogen-based steelmaking process is more expensive than conventional basic oxygen steelmaking from coal, this cost uplift represents merely a fraction of the total cost of a vehicle, adding about 0.5 percent of total manufacturing costs (Rootzén and Johnsson 2016). This cost increase, the "green premium" for the clean steel, can easily be passed on to an increasingly climate-conscious customer base, presumably with an added profit margin. H2GS investors (notably Scania and Hitachi Energy) have already pledged to purchase around 60 percent of the initial 2.5 Mt per year production target for the next 5–7 years (Hitachi Energy 2023; Svensson 2022), creating a strong lead market for the product (orders worth 100bn SEK, around 9.5bn USD).

Mitigation of operating policy risk

H2GS is exposed to several ongoing policy risks. As mentioned previously, H2GS selected Boden as the home for its first plant for the town's iron ore resources, but in August 2023, H2GS made a surprise announcement that it will import iron ore from Brazil and Canada rather than acquiring it from local mines (H2 Green Steel 2023). The Swedish mining company LKAB was not willing to enter into a binding contract with H2GS to supply iron ore, citing lack of capacity and poor maintenance on the railway. The railway that transports iron ore is also Sweden's busiest, and a lack of investments in it has been identified as a bottleneck for industrial development in northern Sweden, but this may finally be permanently alleviated due to Sweden entering NATO and the railway being a critical strategic link to the Norwegian coast (IRJ 2024).

Moreover, the recent change in government in Sweden is sowing political uncertainty over whether the country will continue its effort to decarbonize the steel sector. While the new government has publicly defended the green "Industrial Leap" (Industriklivet) initiative, it has also appointed journalists and economists who have been highly critical of the Swedish state-aid program to top posts (Swedish National Debt Office 2021), sparking some concern over the new government's commitment to the program going forward. Several H2GS investors have expressed bewilderment at the current Swedish government's slow pace in approving state aid to the company, in contrast to the pace of state aid for decarbonization elsewhere in the EU. The new government's hard stance on immigration is also making it more difficult for H2GS to attract the labor force it needs — about 1,500 direct jobs, many with specialized competences — in a town with a current population of 17,000, an issue H2GS still struggles with.

In summary, H2GS very rapidly developed from an idea into a serious industrial effort that is now under construction and has great potential to disrupt and decarbonize the steel market. Consumers' increasing willingness to pay for green products as well as the push for decarbonization in Sweden and the EU more broadly have been instrumental in enabling this to occur. Nevertheless, questions remain over whether H2GS will be able to meet its tight deadlines, and H2GS' business case is still currently only meeting demand in the early adopter market segment. The story of H2GS to date shows that contrary to the last half century, when slow and ponderous industrial business models and regulation have been the norm, dramatic and positive shifts in industrial facility planning and investment can occur in highly developed countries with comprehensive development regulations, and at speeds much faster than any precedent since the early 1970s. To take steel decarbonization from a few rare projects to sector-wide diffusion — or the point at which "green steel" has become just "steel" — new and wider measures will be needed.

Recommendations

This report explored a range of concrete policies that have a track record of helping heavy industrial companies reduce the upfront risks and ongoing operating costs of investing in near-zero emissions plants to levels where FIDs are feasible. Upfront support at different stages in a project's life include funding and grants for research, development, and commercialization of small-to-large pilot plants, below-market interest rates and financing, investment tax credits, and buyer equity participation. Operating or market support includes process subsidies (e.g., production and investment tax credits), public and private lead premium product markets, CfDs, and tradable zero emission performance standards.

The key takeaways of the report are as follows:

There is no one-size-fits-all policy instrument. Policymakers wishing to trigger FOAK investment might consider employing packages of these policies at various stages in a project's lifetime, depending on the commercial, political, social, and investment conditions under which that project operates as well as any existing risks that could impinge on project success.

Equitable financial support by governments across industrial sectors and products can be transformational for establishing FOAK projects and getting them off the ground at the least cost, but the relative emissions-reduction potential, technological readiness, and cost premium above existing market prices will need to be weighed. It would make sense to prioritize the most emissions-intensive parts of value chains with stable or growing demand (e.g., reduced iron, clinker, and fertilizers) in a way that is as technology agnostic as possible, driving down costs per unit. The transformative nature of a given FOAK (i.e., the extent to which it is near-zero emitting, is replicable, considers the full life cycle of emissions associated with the process, and is grounded in a broad jurisdiction-wide net-zero strategy) will need to be evidenced or else there is a risk of wasting limited financial and political resources and not transforming the sector toward near-zero emissions.

A clear and consistent long-term strategy and policy signal can provide the certainty needed to trigger broader investment in FOAK facilities. While policymakers cannot anticipate all risks, reducing perceived investment risk is key to building net-zero industrial facilities. Given the very high implicit carbon pricing needed to trigger the first full-sized near-zero emitting plants, higher than almost all existing and anticipated global carbon pricing systems, and the relatively small amount that sectoral early subsidies and follow-up tradable performance standards or sectoral carbon pricing would add to end-use costs, strong sector-based policies are likely necessary.

Long-term policy strategies to transform the most carbon-intense sectoral processes, equivalent to hundreds of dollars per tonne of CO_2, can be politically and economically maintained if: 1) those strategies are sector-specific; 2) participation by industry players is initially rewarded and then eventually mandatory; and 3) investment capital is raised privately by the sector, initially with guarantees from government, and full-cycle costs are passed through to consumers. A balance of both carrots (incentives) and sticks (mandates or taxes) is likely to be most effective in creating a demand push and pull across various value chains. It would also help if these policy strategies were coherent with those for electricity, hydrogen, and CCS supply. For instance, consideration can be given to how a FOAK plant technology fits with regional electricity and energy decarbonization supply and infrastructure plans.

Putting all the pieces in this analysis together, the authors recommend the following measures for propelling projects from TRL 5–7 to TRL 8 and beyond in both the US and other developed countries:

- **Reduce upfront and ongoing investment and operating risk associated with the first few plants.** In the US, given Congress' familiarity with ITCs and direct-pay PTCs, this could involve the provision of a first round of direct-pay PTCs for near-zero emission reduced iron (possibly for primary stainless steel as a distinct commodity), clinker, ammonia, methanol, and HVCs. For the EU and other developed jurisdictions, the establishment of CfD reverse auction mechanisms would be more effective because of their capacity to trigger investment at the least cost.
- **Create a US federal level and EU-wide tradable zero-emissions performance standard, or ideally share one across the advanced economies, which can help maintain market value for near-zero emissions commodities until sufficiently strong and economy-wide carbon constraints (e.g., carbon pricing or near-zero emissions regulations) apply, even if this could take a long time or may never occur.** Combinations of regional markets would work as well (e.g., California with Washington, Oregon, New York, and/or New Jersey), though as the case of California shows, individual state markets any smaller than California may not be large enough on their own to maintain a ZEMPS market at sufficiently low cost to consumers (Bataille, Stiebert, et al. 2023).

Finally, as a closing note, an attitude of experimentation can be a major boon to FOAK policy; though failures will surely occur, they may profitably be seen as the necessary cost of learning. The broader the pool of actors (i.e., firms and governments) this cost can be spread across, the less consumers, individual firms, and all levels of government will need to pay.

Appendix: Calculation of FOAK Premia by Product

Product Tax Credit (PTC) incentive amounts for near-zero emissions production of different industrial materials were developed based on cash flow models developed by the authors, or in the case of High Value Chemicals (HVCs) on cost premium values identified in a literature review (Table 7). The focus of the assessment was on non-energy-related industrial products or materials that account for the largest contributions to global industrial emissions and will see growing demand as the world transitions to a low-GHG economy. From this global perspective, it is estimated that the production of steel, cement, ammonia, methanol, and HVCs represents over 7.5 Gt of CO_2e annually, or 20.4 percent of all emissions. HVCs are defined as olefins (e.g., acetylene, ethylene, propylene, butadiene) produced from steam cracking of natural gas and naphtha mainly for plastic polymer production. Aluminum, while commonly discussed as a highly traded GHG-intense material and subject to the EU Carbon Border Adjustment Mechanism (CBAM), was not included in this analysis because most of its associated emissions are scope 2 electricity emissions. The remaining roughly 2 tonnes per tonne of aluminium produced from cathode decay can be eliminated by requiring the use of inert anodes as they are developed. All the policy instruments in this analysis could also be applied to aluminum.

In order to develop cash flow models, financial data including project CAPEX and OPEX costs were gathered from the literature and private conversations with industry stakeholders to represent archetype low-carbon production facilities in North America. For the steel, cement, methanol, and ammonia sectors, cash flow models had already been developed previously by the authors (Stiebert and Bataille 2022; Bataille, Stiebert and Li 2023; Forman 2023), the results of which were drawn on for this report. Table 7 lists the main sources of financial data from the literature and industry stakeholders used for the cash flow models and to determine FOAK premia by sector.

The financial models consider large-scale FOAK plants as those that will be constructed and beginning operations by the end of 2028. The scale of the plants was determined based on proposed facilities globally as well as available resources of suitable site locations indicated in the literature.

Table 7: Sources of financial data to determine FOAK premia by sector

Sector	Reference
Cement	Lehigh Hanson Heidelberg Cement Group. Personal Communication.
	Obrist, Michel D., Ramachandran Kannan, Thomas J. Schmidt, and Tom Kober. 2021. "Decarbonization Pathways of the Swiss Cement Industry Towards Net Zero Emissions."" *Journal of Cleaner Production* 288 (March 15, 2021): 125413. https://doi.org/10.1016/j.jclepro.2020.125413.
	Cormos, Calin-Christian. 2022. "Decarbonization Options for Cement Production Process: A Techno-Economic and Environmental Evaluation." *Fuel 320* (July 15, 2022): 123907. https://doi.org/10.1016/j.fuel.2022.123907.
	Gardarsdottir, Stefania Osk, Edoardo De Lena, Matteo Romano, Simon Roussanaly, Mari Voldsund, José-Francisco Pérez-Calvo, David Berstad, Chao Fu, Rahul Anantharaman, Daniel Sutter, Matteo Gazzani, et al. 2019. "Comparison of Technologies for CO_2 Capture from Cement Production — Part 2: Cost Analysis." *Energies* 12, no. 3: 542. https://doi.org/10.3390/en12030542.
Steel	Fischedick, Manfred, Joachim Marzinkowski=, Petra Winzer, and Max Weigel. 2014. "Techno-Economic Evaluation of Innovative Steel Production Technologies." *Journal of Cleaner Production* 84 (December 1, 2014): 563–580. https://doi.org/10.1016/j.jclepro.2014.05.063.
	IEA. 2020. "Iron and Steel Technology Roadmap: Towards More Sustainable Steelmaking." IEA 50 (October 2020). https://www.iea.org/reports/iron-and-steel-technology-roadmap.
	Mayer, Jakob, Gabriel Bachner, and Karl Steininger. 2019. "Macroeconomic Implications of Switching to Process-Emission-Free Iron and Steel Production in Europe." *Journal of Cleaner Production* 210, no. 2 (February 2019) 1517–1533. https://doi.org/10.1016/j.jclepro.2018.11.118.
	Medarac, Hrvoje, Jose A. Moya, and Julian Somers. 2020. "Production Costs from Iron and Steel Industry in the EU and Third Countries." Publications Office of the European Union. doi:10.2760/705636, JRC121276. https://data.europa.eu/doi/10.2760/705636.
	Vogl, Valentin, Max Åhman, and Lars J. Nilsson. 2018. "Assessment of Hydrogen Direct Reduction for Fossil-Free Steelmaking." *Journal of Cleaner Production*, 203 (December 1, 2018): 736–745. https://doi.org/10.1016/j.jclepro.2018.08.279,
Methanol	International Renewable Energy Agency. 2013. Production of Bio-Methanol. Technology Policy Brief 108." January 2013. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2013/IRENA-ETSAP-Tech-Brief-I08-Production_of_Bio-methanol.pdf?rev=5ea20e7c84c4472f8eeed8111ff8daf9.

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Sector	Reference
Methanol (cont'd)	Enerkem. 2023. "Projects and Facilities." https://enerkem.com/company/facilities-projects/.
	IRENA and Methanol Institute. 2021. "Innovation Outlook: Renewable Methanol." https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf?rev=ca7ec52e824041e8b20407ab2e6c7341.
Ammonia	Ghavam, Seyedehoma, Maria Vahdati, I. A. Grant Wilson, and Peter Styring. 2021. "Sustainable Ammonia Production Processes." *Frontiers in Energy Research* 9 (March 28, 2021): 580808. doi: 10.3389/fenrg.2021.580808.
	World Energy GH2 Inc. 2022. "Project Nujio'qonik GH2: Environmental Assessment Registration." https://www.gov.nl.ca/ecc/files/2202-Registration-Document.pdf.
HVCs	Frosi, Martina, Antonio Tripodi, Francesco Conte, Gianguido Ramis, Nader Mahinpey, and Ilenia Rossetti. 2021. "Ethylene from Renewable Ethanol: Process Optimization and Economic Feasibility Assessment." *Journal of Industrial and Engineering Chemistry* 104 (2021): 272–285. https://doi.org/10.1016/j.jiec.2021.08.026. https://www.sciencedirect.com/science/article/pii/S1226086X21004743.
	McKechnie, Jon, Mohammad Pourbafrani, Bradley A. Saville, and Heather L. MacLean. 2015. "Environmental and Financial Implications of Ethanol as a Bioethylene Feedstock versus as a Transportation Fuel." *Environmental Research Letters* 10, no. 12 (December): 124018. https://iopscience.iop.org/article/10.1088/1748-9326/10/12/124018.

To estimate the profitability of a FOAK project, the net present value (NPV) and simple internal rate of return (IRR) were modeled based on typical ranges in OPEX, CAPEX, and revenues. Physical unit production costs were calculated in the model for comparison with market prices and to understand the potential profitability gap on a production unit basis, reflecting how PTCs are typically designed. Minimum, central, and maximum values or ranges were entered for important cost variables that materially shifted the result. A sensitivity analysis of the major variables was conducted to understand how each variable affects project economics. Monte Carlo analysis was employed to understand the probability of different outcomes based on a range of minimum, central, and maximum values for key parameters directly related to the technology and investment decision. By running many simulations within the range of values, the analysis can determine a histogram or distribution of the outcomes for the NPV or IRR of the project.

Modeled project CAPEX and OPEX costs (Table 8) are additional to baseline production. All costs are in 2022 USD. Component costs were varied across a range in the analysis to consider uncertainty.

Ultimately, the ranges used (minimum, central, and maximum values) were intended to represent reasonable expected costs for the FOAK archetype project design, location, and investment period. CAPEX costs for archetype projects were subdivided into different component costs where possible.

The model assumes a range of market prices for production based on historical price ranges in North America. In calculating the initial PTC value for FOAKs, no premium pricing for low-carbon production was assumed in the market price or other types of investment or tax incentives that may be available to low carbon production but not baseline production — any premia would be subtracted from the PTC or equivalent. A variable discount rate was used to calculate the present value of future cash flows. The rate depended on the expected rate of return or the hurdle rate that investors can expect to earn relative to the risk of the investment. These rates represent the average weighted costs of capital identified in the literature — i.e., 5 to 9 percent (KPMG 2023).

To capture the effects of uncertainty, the Monte Carlo analysis samples a triangular distribution of minimum, central, and maximum values for each variable, establishing a normal distribution for financial modeling outputs such as the internal rate of return for the project overall. A triangular distribution is essentially a continuous probability distribution shaped like a triangle between minimum, central, and maximum values. This report uses 5,000 Monte Carlo simulations to develop histograms of results and to determine 10th, 50th, and 90th percentile outcomes. The values for HVCs are not based on cash flow modeling, but rather on literature reported values of incremental production costs.

Incremental CAPEX and OPEX unit production costs for each of the five products are summarized in Table 8 below. The costs include the modeled ranges for Monte Carlo analysis.

Table 8: Modeled incremental costs per tonne of product for low-carbon production

Sector	Incremental CAPEX Cost Per Tonne Central (Modeled Range)	Incremental OPEX Cost Per Tonne Central (Modeled Range)
Steel	$106 (+12%/-11%)	$226 (+12%/-11%)
Cement	$53 (+/-30%)	$30 (+/-20%)
Ammonia	$136 (+/-29%)	$198 (+32%/- 24%)
HVCs	$491 (+40%/-24%) Costs from the literature are not divided between CAPEX and OPEX	
Methanol	$159 (+36%/-21%)	$89 (+34%/-13%)

Other important model parameters varied in the cash-flow model are included in Table 9 with minimum, central, and maximum values.

Table 9: Monte Carlo ranges of sensitivity for important model variables

Model Variables	Sector	Min	Central	Max
Weighted average cost of capital	Steel	8%	10%	12%
	Cement, methanol, ammonia	5%	7%	9%
	HVCs	Unknown, included in range of cost values modeled		
Expected simple IRR (internal rate of return)	Cement, methanol, ammonia	13%	15%	20%
	HVCs	15%	15%	15%
	Steel	Steel modeling of PTCs was based on changes in production costs to achieve near-zero, not rates of financial return assuming a sales price		
Market commodity prices around long-term historical average	Steel	-9%	—	+16%
	Cement	-24%	—	+24%
	Ammonia	-19%	—	+49%
	Methanol	-24%	—	+19%
	HVCs	-21%	—	18%
Capital investment depreciation life	Steel, ammonia	15 yrs	17 yrs	20 yrs
	Cement, methanol	15 yrs	20 yrs	25 yrs
	HVC	15 yrs	15 yrs	15 yrs

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Notes

1. This report focuses on iron and steel because they are considered hard to abate, and it excludes other metals such as aluminum that are considered relatively easy to abate (except for graphite electrode emissions), though a similar exercise could be done for the latter group, too.

2. At one time, most fertilizer was made from hydrogen produced through hydropower-based electrolysis, but these facilities have been long replaced by methane and coal-fed facilities (IEA 2017).

3. There are some large pilot near-zero emissions iron and steel plants (e.g. Hybrit in Sweden) as well as cement and concrete plants (e.g., CLEANKER in Italy and a 60% capture plant in Brevik, Norway), and two ammonia plants may come online in Asia in the next few years, but as of the publication of this report, no full-commercial-scale near-zero emissions plants are past final investment decision and under construction.

4. For example, Sublime Inc. is trying to pioneer an electrochemical way to separate calcium oxide, the GHG-intense precursor for making the clinker needed to produce cement, from calcium silicates or limestone in order to replace the standard calcination process, which uses 850°C heat.

5. Where it has been considered at all, there is debate about what level of mitigation is necessary for Paris Agreement compliance. In this debate, 90% implies 10% residual emissions that must be offset with CO_2 removal technologies, 95% means 5%, etc. There is a dynamic tension between the ultimate commercial feasibility of CCS by sector, the capacity to eliminate the use of fossil fuels altogether, and the eventual technical feasibility and cost of large-scale CDR. Based on the best available knowledge, 90–95% capture and 5–10% residual emissions are rules of thumb, though they are subject to developments (Bataille 2023a; Bataille, Al Khourdajie, et al. 2023). The authors are exploring this research area further in other projects.

6. Policies to incentivize green heavy industry have a complex trade dimension in that they typically have a regional or national focus and are not always aligned with the industrial policies of trade partners. This has the potential to create trade friction and distort existing markets by moving investment from one global region to another. One example is the EU's Carbon Border Adjustment Mechanism (CBAM) (European Commission 2021), which entered into force in 2023 and will impose a levy on high-carbon imports beginning in January 2026 to level the playing field for green domestic production. In return, India has threatened to levy a cumulative emissions tax on European imports to India. Regardless of the eventual outcome in

this case, it is clear that the realignment of international trade policy around green production is a dynamic and unfolding process (Kaufman, Saha, et al. 2023; Kaufman, Bataille, et al. 2023a 2023b; S. Saha et al. 2023). As well as the tensions it can cause, there are political opportunities. For example, ongoing negotiations around green subsidies and reciprocal recognition of emissions reduction policies have been framed as a means of building up supply chain resilience among allies (Executive Office of the President of the United States 2021).

7. The authors would like to thank one of the anonymous reviewers for suggesting that the discussion of the roles of different types of FOAK facilities be expanded.

8. A production tax credit amount of $0.026 per kWh or full investment tax credit of 30% is available to projects over 1 megawatt that satisfy apprenticeship and prevailing wage requirements, and 20% of this if the latter requirements are not met (US DOE 2023c). Additionally, projects can receive a stackable 10% of the PTC or 10 percentage point (ITC) bonus credits for either or both of the following: meeting domestic content thresholds and locating facilities in fossil-fuel-dependent "energy communities."

9. $0.6–3.0 per kilogram is offered on a stepwise GHG intensity scale for 10 years for facilities that begin production before 2032.

10. HVCs are defined as olefins (acetylene, ethylene, propylene, butadiene) produced from steam cracking of natural gas and naphtha, mainly for plastic polymer production.

11. Cement was not included in AB 262. Partially in response to this, and given that 48% of concrete is poured for infrastructure (Bataille and OECD 2019), in 2023, as part of California Senate Bill 596, CARB was required to develop a comprehensive strategy by July 1 2023 for the cement sector in California to achieve a greenhouse gas emissions intensity of 40% below baseline levels by 2035 and net-zero GHG emissions by 2045. Similar low embodied carbon cement and concrete bills have been enacted in New York (2021-A2591A) (New York State Senate 2023) and New Jersey (S287) (NJ Legislature 2023).

12. H2GS has offtake agreements of various kinds with: Adient, BE Group, Bilstein Group, BMW, Electrolux, Ingka/IKEA, Kingspan, Kirchhoff, Klockner & Co, Lindab, Marcegaglia, Mercedes-Benz, Miele, Mubea, Porsche, Purmo Group, Roba Metals, Scania, Schaeffler, Volvo, Zekelman Industries, and ZF Group (TFX News, 2024).

13. In late March 2024, some of H2GS' power was reallocated to LKAB's own hydrogen DRI project on the grounds that the latter is further along. At the time of writing, the matter is before the Swedish courts.

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