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INDUSTRIAL DECARBONIZATION: PATHWAYS FOR PRODUCTIVITY AND GROWTH

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EXECUTIVE SUMMARY

This research presents findings from case studies conducted at five major cement, steel, construction and electrical products companies that are actively decarbonizing their manufacturing operations. Through interviews with senior leadership, we develop a framework to explain how these firms are able to meet their core objectives of increasing productivity and maintaining profitability while also decarbonizing. First, we find that firms are able to do so by following one or more of three distinct decarbonization pathways:

1. **Energy and material efficiency**: adopting cost-saving energy upgrades to streamline operations and save time, money, and materials
2. **Coupling decarbonization with growth through economies of scale**: capitalizing on returns from growth to finance sustainable investments
3. **New products and policy-based market restructuring**: investing in emerging technologies with large potential payoffs under climate-friendly policy regimes

Second, we find that firms evaluate decarbonization initiatives at the project level, rather than judging the return on investment (ROI) of a specific technology in its own right. Because companies sometimes accept loss-leading upgrades within a project that is profitable overall, evaluating these technologies on a standalone basis provides an incomplete picture of their prospects for adoption. In other words, we find that a purely profit maximizing view of corporate decision-making will underestimate the adoption of green technologies.

Third, it is clear that firm commitments to decarbonize are spurred by national policies and regulations. Flex and the National Cement Company of California were both responding directly to national or state policies affecting their industries, while Saint Gobain and Outokumpu took advantage of government subsidies and carbon markets created in regions where they established their most climate-friendly operations.

Fourth, our cases emphasize that senior-level firm leadership and customers' commitment to reducing emissions is a crucial precursor to advancing decarbonization strategies. It is typically difficult to disentangle executives' personal views that decarbonization is important from their strategic outlook about future outcomes concerning carbon markets, demand for green products, and other changes that would justify climate action. Regardless, without consistent and persistent prioritization by C-suite level leadership, the decarbonization agenda within firms has an uphill battle. Senior leadership also see their emissions goals as an important competitive advantage in the competition for talent.

Finally, new digital technologies are enablers of the decarbonization agenda, automating processes and increasing data collection on energy use and machinery performance that was not possible even five years ago. We also observe that productivity-improving upgrades are accelerated in regions where decarbonization is aided by supportive policies. These upgrades offset the costs of switching to cleaner energy sources or adopting the latest monitoring and dynamic adjustment technologies.

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1. Introduction

Manufacturing and industrial production more broadly are at a nexus of opportunities and challenges that promise to transform the sector as part of "the next industrial revolution."[1] Supply chain resilience, geopolitical concerns focused on advanced technological and defence capabilities, and energy security are all driving companies and countries to reassess the strengths and weaknesses of their industrial base and make investments toward greater productivity, resilience, and security. At the same time, the advent of digital technologies and computational tools promise more automated, efficient and intelligent production systems. Finally, public policies are both sources of tailwinds and headwinds for manufacturers. [2] For example, the US is investing heavily in increasing domestic semiconductor production while also creating prohibitive trade tariffs on imported manufactured goods.

Despite recent resistance to emissions reductions policies in the United States at the federal level, several decades of climate action now permeate industry leaders' values and expectations about the need to curtail and replace heavily emitting processes. Whereas in the previous decade, governments and companies emphasized impact on the climate, today, industrial decarbonization strategies can be part and parcel of companies' larger goals around growth and productivity, in which they are interested in reducing energy costs, waste and emissions while also reducing energy price risks and pursuing new market opportunities.

While achieving a return on investment (ROI) and the ability to break even on industrial decarbonization projects remains paramount, other factors such as corporate values, public policies, as well as geopolitical and economic uncertainty (e.g., natural gas price volatility in Europe due to the Russia-Ukraine war) contribute to firm decisions to pursue decarbonization. At the same time, the uncertainties involved in technology development and changing climate-related policies prevent many companies from carrying out informed, long-run strategies in the clean energy transition.[3]

This research asks the question:

Under what conditions do large manufacturing companies increase productivity and maintain returns on investment while pursuing a reduction in greenhouse gas emissions?

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[1] Mindell, *The New Lunar Society*; "MIT Initiative for New Manufacturing."

[2] TSMC, "TSMC Intends to Expand Its Investment in the United States to US$165 Billion to Power the Future of AI"; NIST, "Department of Commerce Announces CHIPS Incentives Letter of Intent with Vulcan Elements to Support Domestic Manufacturing of Critical Rare Earth Magnets"; Spar and Bernstein, "South Korea Halts $350 Billion U.S. Investment Over Immigration Raids."

[3] Mason, "Climate Policy from a Keynesian Point of View | Heinrich Böll Stiftung | Brussels Office - European Union."

The cases selected for this research focus on companies at the frontier of industrial decarbonization to illustrate how they overcame the challenges involved in decarbonization to realize substantial investments in clean production.

Through five case studies of large industrial multinational firms that have actively decarbonized part of their operations, we develop a framework that incorporates the multi-dimensional factors that inform industrial decarbonization investments and upgrades. Interviews with senior executives and plant-level leadership at five major cement, steel, construction and electrical products companies shed light on how firms are able to meet their core objectives of increasing productivity and maintaining cost-competitiveness while also decarbonizing. Considerations such as future demand for products, regulations, competitor positioning, and independent leadership priorities enrich the picture presented by much of the prevailing academic literature, which primarily assesses the merits of green upgrades based on their ability to reduce costs (see literature review below).

The paper reviews the existing literature on industrial decarbonization in section 2, presents our research methods in section 3, and discusses results drawn from the five case studies in section 4. Section 5 and 6 provide a discussion of the results and a conclusion. The case studies are included as Appendices to the main document.

2. Literature Review

Prior studies of industrial decarbonization have explored the technological pathways to achieve decarbonization goals. It can be difficult, however, to incorporate technological change, market information, and firms' own policy forecasts into these technology-focused models of the incentives that drive decarbonization initiatives.

Studies to date on the pathways to industrial decarbonization have often focused on technological performance. For example, Bauer et al.[4] identify five "archetypal transition pathways" to achieve carbon neutrality: process optimizations (i.e. energy efficiency), electrification, carbon capture and storage (CCS), circularity in material flows, and adoption of biofuels. Worrell and Boyd[5] similarly group decarbonization actions into four "pillars": energy efficiency, material efficiency, industry-specific technologies, and power grid upgrades. These classifications and many others[6] have been criticized for being "rather general and lack[ing]

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[4] Bauer et al., "Assessing the Feasibility of Archetypal Transition Pathways towards Carbon Neutrality – A Comparative Analysis of European Industries."

[5] Worrell and Boyd, "Bottom-up Estimates of Deep Decarbonization of U.S. Manufacturing in 2050."

[6] Block et al., "Decarbonization Types of Medium-Sized and Mid-Cap Firms in the Manufacturing Sector"; Buettner et al., "How Do German Manufacturers React to the Increasing Societal Pressure for Decarbonisation?"; Cresko et al., *U.S. Department of Energy's Industrial Decarbonization Roadmap*.

detail or prioritization of requirements" for firms.[7]

One popular, and more precise, approach to prioritizing decarbonization pathways is using marginal abatement cost curves (MACCs). MACCs allow businesses to quantify the cost and effectiveness of a set of emission reduction upgrades.

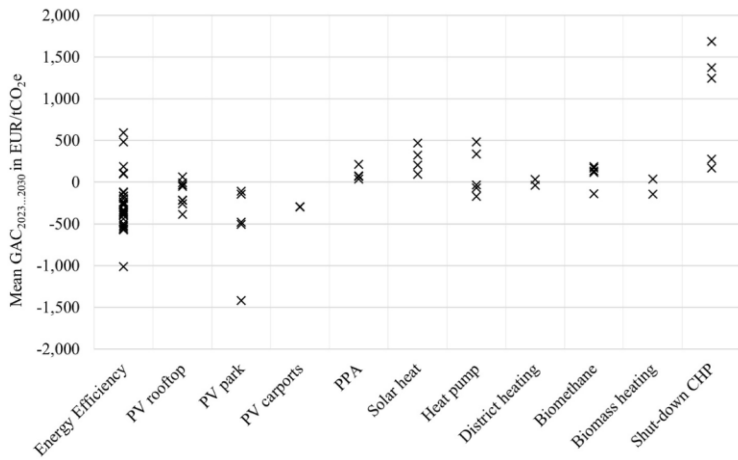

Figure 1: Typical MACC calculations for a set of carbon reduction technologies. Source: Hechelmann et al. 2023.

Researchers have identified break-even costs for technologies that reduce emissions across steel, concrete, chemicals, and electronics to determine when investments are most likely to occur.[8] One in-depth study of eight German firms, for example, compares the MACCs of various decarbonization technologies to identify low or negative cost projects that reduce emissions by small but significant amounts, as well as more expensive projects that could deliver substantial emission reductions at greater costs.[9] Modelling and scenario-planning approaches such as these tend to assume that firms lexically order economic and environmental priorities. In other words, profit maximization is the first priority and decarbonization may be pursued only if it does not negatively impact profit margins. Research on national and international policy strategies for advancing industrial decarbonization typically follow these techno-economic analyses of decarbonization projects to make policy recommendations.[10]

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[7] Johnson et al., "Toward Climate-Neutral Heavy Industry."

[8] Kermeli et al., "Energy Efficiency Improvement and GHG Abatement in the Global Production of Primary Aluminium"; Obrist et al., "Decarbonization Pathways of the Swiss Cement Industry towards Net Zero Emissions"; Johnson et al., "Toward Climate-Neutral Heavy Industry."

[9] Hechelmann et al., "Decarbonisation Strategies for Manufacturing."

[10] IEA, "Policy Toolbox for Industrial Decarbonisation – Analysis"; U.S. Climate Alliance, *Enabling Industrial Decarbonization*.

Critics have underlined how MACCs oversimplify the complexity of business decisions, for example by ignoring co-benefits of decarbonization and failing to properly consider uncertainty.[11] These strong assumptions about firms' profit-seeking behavior have contributed to decarbonization frameworks that assume that the most viable strategies are those with the lowest costs for producers, steering the literature to focus on cases of decarbonization with low unit costs of emissions.

In practice, however, businesses investing in industrial decarbonization often seem to be pursuing technologies and strategies where techno-economic analysis foresees little profitability, or fail to pursue investment opportunities that appear to be cost effective.[12] This is the case for several of the costlier investments documented in the cases below, where firms make large capital expenditures to electrify industrial processes, often even in the face of higher operational costs. These decisions are driven by a wide range of factors relating to market conditions, policies, subsidies, and executive priorities. Firms balance multiple priorities and constantly make tradeoffs between objectives. By focusing squarely on cost-saving strategies, existing frameworks are likely to overlook the potential opportunities that promise economic growth in the context of evolving technologies, markets, or regulations. Our approach enables a closer look into the ways these opportunities manifest for several of the firms taking significant steps to decarbonize.

3. Research Methods

We conducted illustrative case studies of facility-level industrial decarbonization projects and the conditions under which they occur at five multinational industrial firms in the United States, Europe, and South America. These companies were chosen because they are actively pursuing decarbonization strategies at specific facilities, they operate in multiple countries, providing a lens into cross-country comparisons, and previous working relationships with MIT provided accessibility to the companies. These cases represent firms that are in many ways at the frontier of industrial decarbonization. strategies globally.

[11] Kesicki and Ekins, "Marginal Abatement Cost Curves."
[12] Cornell, "ESG Preferences, Risk and Return"; De Haas et al., "Managerial and Financial Barriers to the Net-Zero Transition."

Firm	Location	Product	Decarbonization Strategies
International Flextronics	Sorocaba, Brazil	Contract manufacturing, primarily for electronics	Material recycling, circular production, energy efficiency
Siemens	Fort Worth and Grand Prairie, Texas	Paint line for electrical switchboards	Electrification, fuel-switching, building heating and cooling
National Cement Company	Lebec, California	Cement	Energy efficiency, low carbon cement, fuel switching, carbon capture, downstream integration
Outokumpu	Helsinki, Finland	Stainless steel	Clean energy procurement, material substitutes, material recycling, upstream integration
Saint Gobain	Montreal, Canada	Gypsum wall panels	Clean energy procurement, electrification, energy efficiency

Figure 2. List of case studies, including companies, locations, primary products, and decarbonization strategies.

To develop the case studies, our team conducted semi-structured interviews with chief executives, technology and sustainability leads, and facility-level directors at company production sites. We developed a semi-structured interview guide to capture a systematic and comprehensive understanding of the companies' decarbonization decision-making processes and outcomes.[13] Informed consent was obtained from all participants prior to beginning the interviews. Interviews were recorded whenever interviewees consented and practical considerations permitted.

Each semi-structured interview consisted of two sections. The first set of questions, which underwent iterative modifications following each interview, was designed to establish the background of our interviewee and the history and current operations of the company, as well as the company's approach to sustainability over time. These questions focused on Scope 1, 2, and 3 emissions strategies[14], as well as the data collection and accounting processes employed to determine the results on emissions reduction.

The goal of the interviews was to understand the motivations, opportunities, and barriers to specific industrial decarbonization projects pursued by each company. Each specific decarbonization initiative was discussed, with a focus on major factors that led to the decision, its impact on emissions, and the business case, both in terms of economic impact and how it was presented to senior leadership at the company. Where possible, we obtained detailed information about business thresholds that were required for any decarbonization

[13] Jamshed, "Qualitative Research Method-Interviewing and Observation."
[14] Scope 1, 2, and 3 classifications come from the Greenhouse Gas Protocol. Scope 1 emissions refer to those from onsite production, Scope 2 refers to purchased energy, and Scope 3 consists of emissions from across the supply chain.

investments, such as a minimum expected ROI. We also explored the way the policy environment shaped the decision, technologies that made the investment possible, and workforce changes related to the investment and to sustainability more broadly.

Interviews were conducted between July and November 2025. We interviewed 11 industry professionals, four of whom were C-suite executives (e.g., CEO, CTO, CFO), three plant managers or directors, and four people with a research or operations role. Interviews took place in a range of settings where observational methods were difficult to standardize, including while walking around a factory. Rather than record and code the interviews, we took contemporaneous notes and then individually created a record of each conversation immediately following the interview. Given the specificity of the projects discussed, findings were analyzed and sorted into the three categories described below.

4. Results

This research generates five key findings, the first of which outlines a three-point framework.

4.1 Three Decarbonization Pathways

First, we find that these firms typically follow one or more of three distinct decarbonization pathways, each with their own motivations and costs. First and foremost, all of the firms interviewed expect to eventually break even or achieve a minimum return on investment (ROI) from their decarbonization strategies. However, the case studies illustrate how businesses in market-based economies undertake a complex assessment of potential approaches to industrial decarbonization. Motivations to pursue decarbonization range from potential cost savings, to growing demand for green products, new business model opportunities, and opportunities to mitigate exposure to potential risks such as energy price shocks. We capture these motivations in three distinct decarbonization strategies that emerge from the case studies (Fig. 3).

Decarbon-ization Pathways	**Energy and Material Efficiency**	**Coupling Decarbonization with Growth and Economies of Scale**	**New Products and Policy-Based Market Restructuring**

Business case	Costs are recovered through energy or material savings made possible by new technologies	Cost increases are covered by a profitable expansion project	Policies or external events alter markets to favor decarbonized products
Emission reductions	Flex: 7.7 tCO_2 NCC: 2400 kT CO_2 (energy efficiency only)	Saint Gobain: 44 kT CO_2 Siemens: 20.5 kT CO_2	NCC: 70,000 kT CO_2 (anticipated 35% reduction of 200,000 kT from LC3) Steel: 10,000 kt CO_2
Motivations	Motivated by regulation, customers, new technologies, and corporate leadership	Relies on market boom and customers intent on maintaining sustainability objectives	Motivated by regulation, ambitious leadership, and is disruptive for incumbent firms
Examples	Flex, Sorocaba: Adopted reverse logistics for e-waste recycling in Sorocaba, Brazil. NCC, Lebec, CA: Reduced fuel use at their cement plant with energy efficiency upgrades; reduced clinker use in cement (1L). Outokumpu, Finland: Waste to power sidestream creation at a steel production facility in Sweden.	Siemens Electrical Products in Texas: electrified a paint line and reduced natural gas usage; purchased renewable energy credits on Texas' energy grid with low power costs. Saint Gobain, QC: retrofitted a facility using subsidies and productivity upgrades to match electricity costs.	NCC, Lebec: Developed a new LC3 premium cement product; proposed a carbon capture plant with a local oil extraction company. Steel Producer, Finland: developed Biocoke "Green Circle" steel, a less carbon intensive steel production process.

Figure 3. Three pathways to industrial decarbonization.

Policy and techno-economic analyses, which assess the technical performance of a new technology to understand its economic prospects, primarily identify opportunities for industrial decarbonization within the first pathway given the challenges in modeling the potential longer term returns and tradeoffs. The case studies indicate that the second and third strategies are equally if not more important for some of the largest businesses making the most significant investments in decarbonization in market-based economies.

Strategy 1: Energy and Material Efficiency

A powerful driver of decarbonization for several of the firms we interviewed was the opportunity to reduce costs, or "save money, time, and materials", in the words of one interviewee at Flex. In contrast to the conventional perspective that industrial decarbonization is exclusively a cost for firms, which must be offset by carbon pricing or other incentives, three of the five firms interviewed were able to reduce their energy and material use, as well as digitizing logistics processes, which reduces associated costs as part of their decarbonization process. Recycling and energy efficiency processes can reduce operating expenditures at the facility level, through new technologies such as material recycling, logistics tracking, and material innovations.

"There is a misconception that going green means cost increases but sustainability can be about saving money." - Saint Gobain project leader.

In Sorocaba, Brazil, Flex has pursued a research-driven e-waste reduction strategy under tight resource constraints motivated by demand from a major customer and national level policy changes in Brazil. At first, payments from this customer for collection and recycling supported the operation and cross-subsidized development of reverse logistics operations, which were more costly. Eventually, however, as reverse logistics capabilities improved, the recycling operation became a standalone benefit for Flex, enabling a circular economy services offering that enables customers to simplify reverse logistics execution and strengthen reporting. This is one example of the small cost savings that can occasionally be achieved by becoming more efficient. Additional returns can come from quantifying emissions and earning credits in a carbon accounting program, such as that managed by CSA registries, a Canadian emissions tracking company. Flex used this company to generate credits from their recycling program that further defrayed the costs of decarbonization (Appendix 1).

The National Cement Company of California has similarly achieved cost savings through efficiency upgrades that reduce energy and material costs. Their plant in Lebec, California, received a set of energy efficiency upgrades that produced a 25-30 percent reduction in energy use and saved approximately 2400 kT of carbon dioxide emissions per year. NCC also uses less clinker in 1L cement and has explored other clinker alternatives, which both reduce emissions and enable the company to produce a greater volume of product from the same amount of the key input material (Appendix 2).

Finally, Outokumpu has managed to achieve 75 percent below global average emissions from stainless steel production through a combination of measures including using upwards of 95 percent scrap material, and recycling carbon monoxide (CO) produced in its ferrochrome operation as a source of power in its electric arc furnace. This reduces the firm's electricity consumption as well as associated Scope 2 emissions (Appendix 3). Other examples employed by the company involve finding new revenue streams, such as waste to power sidestreams for carbon monoxide produced at the steel making facility.

Box 1: Flex Sorocaba, Brazil E-waste Recycling	
Changes to product and process (What?)	Upstream policy demands led to client requests to develop e-waste recycling processes, which have since become a successful venture exported across company facilities globally, saving the company time and money.
Mechanism (How)	Cost, material, and time efficiencies
Motivation (Why?)	Firm policy guidelines set by the Brazilian government, proactive customers, and a willingness to embark on research-driven development process for e-waste recycling and reverse logistics
Results	Zero waste achieved, over 90 percent of material collected, reused, or recycled, reducing energy costs compared to a standard manufacturing process. Certifying carbon credits based on scope 3 emissions reductions for their partners due to their recycling.

These efficiency-focused strategies can have either negative or positive impact on a firm's returns, typically of a small magnitude. They are occasionally pursued to achieve decarbonization objectives despite their costs, since the impact on a firm's bottom line is minimal.

The leading firms implementing these interventions achieve moderate scope 1 and 2 emissions reductions, with more variable results for scope 3 emissions. Flex achieved a significant reduction in energy use, which saves approximately 7.7 tCO_2 per year (Appendix 1). NCC energy efficiency upgrades resulted in 25-30 percent reductions in energy use and an 8-10 percent reduction of total emissions (Appendix 2).

Strategy 2: Coupling Decarbonization with Growth and Economies of Scale

Emissions intensive processes for producing materials such as concrete and steel often involve high heat treatments, which are difficult to achieve without combustion reactions, or chemical processes that release CO_2, such as the calcination process for creating clinker in cement (Appendix 2). These are inherently difficult decarbonization challenges.

In these cases, the impact of decarbonizing is greater on the firm's balance sheet. Electrification or use of alternative fuels imposes additional operational costs that often must be offset in order to be economically viable. Without public policies that subsidize the investment, a significant amount of available cheap electricity, or a green premium on new products, investments in decarbonization are unlikely to be cost effective.

Two of the firms we interviewed primarily achieved their decarbonization objectives by expanding their operations while implementing decarbonization and productivity upgrades. This happened in both existing and greenfield facilities. This approach is driven by a combination of economies of scale achieved through growth, with customers that value sustainability.

In Grand Prairie and Fort Worth, Texas, Siemens operates facilities for assembling data center electrical switchboards. Over the past several years, the AI investment boom has generated intense demand from their major customers for expanded production. Under these conditions, economies of scale have enabled decarbonization by allowing the company to reach its internal return on investment targets more quickly, and the company has elected to take advantage of the productivity increase associated with lower unit costs to pursue sustainability, even if it comes with additional costs.

In Texas, the paint line used to coat the electrical switchboards was the facility's single largest source of carbon emissions. Both at a greenfield facility, as well as at a brownfield site approaching end of life, Siemens invested in electrifying the paint line, which has realized emission reductions of 15.5 kt CO_2 per year. This came with 40 to 50 percent higher operational costs, which were offset at the facility level by lower unit costs that followed from the higher volume of standardized products required by the data center buildout (Appendix 5).

Box 2: Siemens Fort Worth and Grand Prairie Electrical Product Electrification	
Changes to product and process (What?)	Decarbonization primarily involved electrification of the paint line heating process and HVAC upgrades. Texas was advantageous because it provided affordable electricity, quick permits, and low interconnection fees.
Mechanism (How)	By increasing production capacity and achieving economies of scale, they create room for decarbonization projects on facility level balance sheets.
Motivation (Why?)	Senior leadership made 2030 and 2050 sustainability commitments which put pressure on every existing and new facility to decarbonize. The company is experiencing significant increase in demand due to the growth of AI data centres.
Results	80% reduction in scope 1 emissions in Grand Prairie, and 100% on site emissions reduced in Fort Worth, by electrifying the paint line, installing a heat pump and electric forklifts and shifting residual emissions from the highest heat processes offsite. Scope 2: elimination of natural gas energy use (previously 48% of emissions), 4.2k Mt CO_2 reduced to 1.6 Mt CO_2, over half of which is electricity use reduced by

	purchasing RECs.

Saint Gobain similarly replaced and expanded the production line of its drywall and plasterboard manufacturing facility in Montreal while making a set of equipment modernization investments. These upgrades enabled a 40 percent increase in production capacity. The upgrade reduced energy consumption by 30 percent and saved 44,000 tons of CO_2 emissions per year. This plant is now the first net zero scope 1 and 2 emission drywall production facility of its kind in North America. Energy efficiency improvements, subsidies from the Quebec government, and large-scale power availability helped to bring clean energy costs down to an acceptable level when compared to natural gas (Appendix 4).

In both cases, the decarbonization investments allowed a facility to maintain net positive returns. In isolation, the decarbonization investments may be costly for the firm, but in the broader context of increased growth and productivity, these costs can be absorbed. Higher operational expenditures are managed by offsetting improved unit costs or premium product designations. At Siemens, for example, the electrification upgrades cost just over one third of a percent of their annual operating budget, but these costs were offset by lower unit costs of production and a greater volume of new products produced for an inelastic market (Appendix 5). This strategy is customer and market dependent. Without a growing market and steady demand, these investments are unlikely to continue.

Box 3: Saint Gobain, Montreal Gypsum Plant Electrification	
Changes to product and process (What?)	Replacing aging machinery and electrification of a heating process involved in making fiberglass. Quebec provided subsidies worth 25 percent of CapEx expenditures and the province's public utility provided plentiful clean power at reasonable prices to an existing plant in need of retrofits.
Mechanism (How)	Economies of scale bring IRR targets within reach, lower unit costs, and create space for decarbonization projects. Higher baseline OpEx for each facility is managed through a combination of carbon pricing, subsidies, and energy efficiency upgrades.
Motivation (Why?)	Senior leadership made 2050 sustainability commitments which enabled opportunities to emerge at existing plants. The company is experiencing strong growth and plants producing at capacity need to achieve productivity gains.
Results	Zero scope 1 and 2 emissions achieved at the Montreal facility. Reducing energy consumption by 30 percent and 44,000 tons of CO2 while expanding production by 40 percent. The total cost of the factory electrification project was approximately $160 million.

Strategy 3: New Products and Policy-Based Market Restructuring

For operations that are not presently commercially feasible to decarbonize, some ambitious companies are pushing the frontier of technologies at lower readiness levels, and sponsoring or conducting independent research into replacements and alternatives for substantial energy sources or material based emissions. Two prominent examples of this approach from our case studies involve investments in carbon capture and storage facilities and funding the development of new materials that have uncertain prospects but promise a competitive advantage if realized.

In the words of the plant director at the National Cement Company of California's Lebec, CA, facility, the organization's "biggest fear" is being regulated out of business just "like the oil and gas industry", with regulations that shift the emissions of cement production out of state without doing anything to curb actual CO_2 release. In order to prepare for a possible future where carbon intensive products are regulated out of existence in California, NCC is developing a new LC3 cement product, which uses an alternative process for calcinating clay rather than limestone to significantly curtail emissions involved in the chemical process. Scaling this technology is anticipated to reduce 35 percent of the company's annual 200,000 kT scope 1 and 2 CO_2 emissions. This LC3 product aims to serve clients that are willing to initially pay a green premium to avoid carbon emissions. While large public and private sector clients express interest in such a product, it will only be cost competitive at scale under a policy scenario where conventional cement products are priced in accordance with their emissions.

Box 4: National Cement Company, Lebec LC3 Cement and Carbon Capture Strategy	
Changes to product and process (What?)	A threefold strategy, focused process-level emission reductions in energy and fuel use, as well as more ambitious processes focused on reducing clinker use, and carbon capture.
Mechanism (How)	Costly energy efficiency upgrades, creative fuel substitutes available due to conveniently located fuel sources, and investment plans for future materials supported by public grants.
Motivation (Why?)	Ambitious climate objectives Desire not to be regulated out of business in California
Results	Out of the 60% of process emissions from creating clinker, 75% promised reduction using LC3 Of 33% from fuel use; 55% reduction using biofuels For the 3-5% Scope 2 emissions such as electricity use, 30% reduction in energy use from energy efficiency

A final example is Outokumpu's stainless steel production process. The Finnish stainless steel company has achieved a 90 percent reduction in emissions compared to the industry average (Appendix 3). This is due to investments in energy efficiency, biofuel adoption, and repurposing waste products. The company's "Circle Green" product currently only consists of 1 percent of their total sales but stronger carbon markets would enable expansion to a greater market of buyers.

Achieving their low-carbon product involved several methods, including vertically integrating when clients do not reduce upstream or downstream emissions and pursuing premium product markets to initially sell small volumes of more sustainable products. Sidestreams and waste product usage can contribute to initial returns from this strategy, but over the longer term, validating the scale of investment is primarily dependent on increasing demand for green products or more stringent regulations on higher emitting alternatives.

Box 5: Outokumpu, Biocoke Steel Production	
Nature of decarbonization (What?)	The firm developed a low-emissions stainless steel product line that uses biocoke instead of fossil coke and uses ~95% recycled stainless steel.
Mechanism (How?)	The firm foresees their green product line becoming cost-competitive thanks to technology improvements, future increases in the EU carbon price, and partnerships with district heating providers or sustainable aviation fuel producers that could buy their carbon monoxide sidestream.
Motivation (Why?)	The firm's business strategy is built on being a sustainability leader. They believe sustainability is a "mega-trend" that will outlive setbacks such as those in US federal policy. NGO pressure, public opinion, and attracting a young workforce were also contributing factors.
Results	Yields an additional 64% reduction in the steel's emission intensity, totaling an emission intensity 90% below industry average. Transitioning all steel production to this new process would avoid 2 MtCO2e annually, although currently only 1% of customers are willing to pay extra for the greener stainless steel.

These strategies are characterized by significant facility-level costs, which would only be validated if markets are restructured by governments to close out opportunities for high-emission competitors. The uncertainty involved in these policy decisions puts heavily emitting firms at a crossroads, since they must trade off between the likely impacts of regulations on their business prospects and the odds of the regulations being implemented in their proposed form. Their decisions are often influenced by government support for research and development investments, capital expenditures, and anticipated higher operational expenditures.

Beyond the three pathways, the case studies also identified a set of cross-cutting characteristics that shape the decarbonization pathways of firms regardless of their strategy.

4.2 Returns on Investment are Assessed at the Project Level

Across cases, we find that the profit constraint for manufacturing firms binds differently than anticipated in many of the standard accounts of industrial decarbonization. Project level returns on investment are not the only factor in decarbonization decisions. While firms are certainly constrained by the need for a return on investment on these projects, the ROI of new technologies are not typically evaluated in isolation. Rather, expected returns are assessed at the project level and loss-leading investments in new processes and technologies are not immediately ruled out if they can be bundled into a project that achieves returns commensurate with their typical standards. This was the case both for Siemens in Texas, where increasing returns to scale created headroom for greater operational costs allocated to clean energy (Appendix 5), and for Saint Gobain in Montreal, where productivity improvements were coupled with decarbonization investments to offset the costs of switching to a more expensive energy source (Appendix 4).

4.3 Climate-Friendly Regulations and Policies Steer Behavior

Policies provide the backdrop to all of the sustainability investments we observed in this research. Either by influencing the outlook of senior executives (Appendix 2; Appendix 3), supporting demand for sustainable products (Appendix 1; Appendix 3), taxing carbon emissions (Appendix 4), or subsidizing the transition to decarbonized operations (Appendix 2, Appendix 4), federal and state policies enable these investments to take place. Utilities and local governments are also important partners of these companies, primarily by making land and electricity available at reasonable prices and, for electricity, volumes needed for industrial operations.

As mentioned above, Flex and its customers in Brazil implemented their reverse logistics operation in response to national regulations calling for large producers of electronic products to develop e-waste recycling plans (Appendix 1). The National Cement Company of California also embarked on its initiatives partially out of concerns that California regulators were willing to see the cement industry relocate out of state if they were unable or unwilling to engage in efforts to decarbonize. NCC also received state and federal grants to pursue its more ambitious alternative products such as LC3 cement, while Saint Gobain in Quebec had the advantage of the Ecoperformance subsidies for clean power provided by the Government of Quebec, as well as the province's emissions cap and trade program (Appendix 2; Appendix 4). Siemens, perhaps the least dependent on direct subsidies, benefited from support from local Texas authorities in quickly siting, permitting, building, and accelerating grid connection times for their new facility (Appendix 5).

4.4 Executive and Customer Commitment to Sustainability Matters

Due to policy forecasts, a strategic outlook, or personal values, the firms making significant decarbonization investments have leaders that are committed to achieving ambitious decarbonization goals. This leadership permeates the organization and motivates other employees to seek out opportunities to implement sustainability projects aligned with their corporate objectives.

Leadership choices often have an impact through interactions with government policy. Regulations mandating certain levels of energy savings, emissions reductions, or recycled components typically engage early movers but not the entire industry immediately. In Brazil, for example, Flex responded quickly to the demand from one of its major clients to establish e-waste recycling operations following regulatory standards implemented at the national level in 2010, while its competitors were slower to respond (Appendix 1).

Geopolitics also has far-reaching implications for corporate decision-making. Siemens' Germany-based global leadership was attuned to the risks involved in exposure to volatile energy prices after natural gas prices spiked during the Ukraine war. Executives with oversight over U.S. operations spurred their employees to pursue alternative energy sources, exploring projects involving hydrogen and electricity (Appendix 5).

In some cases, leaders act due to a perceived direct threat to their business model and company viability. At the National Cement Company of California, for example, the CEO and facility director anticipate state-level regulations trending in the direction of treating the cement industry similarly to oil and gas producers – regulating them out of business and forcing them to shift operations out of state if they were unable to decarbonize their operations (Appendix 2).

4.5 Innovation and Digital Technology Enables Decarbonization

Digitization is often but not always an important precursor to decarbonization initiatives. Companies that have already digitized operations due to regulatory reporting requirements are often better positioned to respond to decarbonization-related opportunities when they emerge, because they have a more precise sense of potential cost savings. Reporting requirements related to decarbonization can be onerous but similar processes are often already in place in sectors under intense regulatory scrutiny, such as cement production in California (Appendix 2). Firms in tightly regulated markets are more likely to have technological precursors in place, such as advanced monitoring and reporting capabilities, to pivot towards greater sustainability when necessary.

Flex, for example, pioneered a reverse logistics process for collecting recycled products that started out as a digital tool for a single client, and soon became a cloud-based system tool that saves costs by coordinating an otherwise onerous recycled goods collection, disassembly, and distribution program for both businesses and individual consumers (Appendix 1). For Saint Gobain, metering technology, including sensors installed at the Montreal facility, enabled engineers to identify the initial decarbonization opportunity (Appendix 4).

We find across cases that firms focused on decarbonization allocate their digitalization, monitoring, and other productivity improving technologies preferentially to regions where decarbonization is attractive. In particular, when governments offer incentives such as subsidies or cheap available clean energy, it can lead companies to upgrade facilities sooner than they might otherwise do. In order to justify the costs of decarbonization projects, these companies prioritize investments in increasing productivity to sites that need to offset costs. In Texas, for example, Siemens executives reported that a Siemens plant in Mexico proposed a similar suite of productivity upgrades for a new factory but without also electrifying their plant. The Mexican team was referred to the team in Texas to copy their electrification model if they wanted to proceed (Appendix 5).

Thus, regions that support firm decarbonization strategies are often those that are receiving frontier technological investments and more advanced production systems. In the case of Saint Gobain, its most advanced gypsum plant operations are in Norway and Montreal because of incentives they received to make investments in state-of-the-art decarbonized manufacturing facilities.

Finally, although we do not think it rises to the level of a distinct finding, we observe that industrial decarbonization strategies have a minimal impact on the firm workforce. Industrial decarbonization does requires some employees to acquire new skills and capabilities, and is leading many companies to pursue a few new hires that are more highly educated, with a greater focus on engineering skills. Nonetheless, in our research, the effects of these investments were minimal and represented an approximately 10-20 percent change in assigned tasks . Firms adopted new reporting and monitoring processes for existing machinery, or hired one to two new FTE positions dedicated to implementing sustainability related changes (Appendix 2).

To date, the biggest observed effects of decarbonization on the workforce involve a company's recruitment prospects. Outokumpu's CTO suggests that decarbonization through innovation is a "powerful … vision … for the younger workforce" and "a big big selling point" for new talented, highly-trained, and ambitious workers worldwide (Appendix 3). Sustainability animates the career prospects of many workers entering manufacturing and participating in ambitious decarbonization projects is a major draw for those choosing their first jobs in the sector.

5. Discussion

Our case studies demonstrate that firms can maintain productivity and cost-competitiveness while also decarbonizing according to one or more of three distinct decarbonization pathways. Energy and material efficiency, taking advantage of growth and economies of scale, or investing in emerging technologies with large potential payoffs under climate-friendly policy regimes can all enable genuine emission reductions. Across cases, firms pursuing decarbonization are enabled by executive leadership, supportive policies, and advances in digital technology, with limited impacts on companies' workforce. Together, these findings suggest the following insights about industrial decarbonization by large manufacturing firms.

5.1 Techno-economic analysis presents an incomplete picture of the prospects for decarbonization at large industrial manufacturing firms

Our research finds that the traditional techno-economic models based on isolated analyses of carbon-neutral technologies do not fully capture the range of strategies behind the decarbonization investments examined in this paper. The literature accurately captures the first of the three models identified through our interviews. Pursuing energy and material efficiency can be profitable, especially in competitive markets with low margins. Saving "time, money, and material" (Appendix 1) is the simplest account of how a company is motivated to pursue decarbonization: by immediate returns associated with reducing emissions, through a reduction of either materials or energy use.

The other two models we identified – sustainability through growth and economies of scale, and the pursuit of new products and markets – are not as well captured by the existing literature. Firms making investments on these grounds are finding ways to navigate around short term costs and counting on future demand for sustainable production and products. This is partially a challenge of modelling longer term changes in technology, market behavior, and regulations. Potential cost savings of existing technologies are often evaluated within a few years, and forecasting the improvements of existing technologies is fraught with uncertainty.

Perhaps more importantly, the two other strategies emerge from interactions between decarbonization investments and business cycles or policy changes respectively. First, growth and economies of scale become an opportunity for decarbonization when a firm can capitalize on a market boom generating strong demand for its products. Offsetting the costs of investment through lower unit costs of production only works under certain market conditions, which are not knowable by examining a green technology in isolation. Second, policy-based market restructuring is also independent of technological capabilities. Whether a government chooses to impose a price on carbon, changes existing regulations, or supports emerging technologies changes their prospects independently of current-day price comparisons with competing products.

Essentially, comparing the costs of alternative technologies only provides part of the information taken into account by businesses facing investment decisions. It is not that techno-economic models are inaccurate, rather, they give a partial view of the relevant decision at the firm level. Investments are made due to a combination of factors and our case studies suggest that the relative costs of competing technologies is a major but not exclusive factor for businesses.

5.2 Profit maximization is pursued alongside competing priorities

The finding that companies accept trade-offs between ROI and other competing objectives such as climate targets aligns with research on corporate decision-making in other academic disciplines, including legal and economic history. Several theorists of corporate decision-making emphasize the discretion available to corporate leaders to pursue objectives distinct from profit-maximization, particularly in the absence of perfect competition. Modelling approaches that assume perfect competition can overlook the fact that decisions *within* organizations do not necessarily conform to standard economic frameworks that model action *between* firms.[15] This creates space for leaders to make decisions based on their expectations of uncertain future outcomes, as well as personal values. These leaders do not necessarily face pressures to maximize returns in each individual investment decision they make, so long as investment targets are met where they are most attentively scrutinized, which is typically at the facility and project level.

The behavioural economics literature on satisficing presents a congruent framework, which stresses that the limited information and computational power available to any economic actor means that they set and pursue an acceptable level of returns rather than optimizing for a maximum value.[16] This closely reflects the observations of companies that pursue decarbonization in cases when they are able to achieve their baseline metrics of profitability.

Essentially, corporations have multiple inputs to their decision making but are constrained by the requirement to achieve minimum returns on investment set centrally by company

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[15] Ciepley, "Beyond Public and Private"; Singer, *The Form of the Firm*; Anderson, "Private Government | Princeton University Press."
[16] Simon, "Theories of Bounded Rationality."

leadership. So long as that threshold is achieved, companies do pursue other objectives, and will choose between different available profitable opportunities based on values and long term expectations, which are difficult to model precisely.

5.3 Decarbonization is not at odds with economic growth

Companies have shown that, either through cost savings, opportunities for expansion, or changing market and policy conditions, opportunities exist for profitable industrial decarbonization. Decarbonization is often understood to involve a trade off between growth and emissions reductions. This is not an accurate model of the strategies surveyed above. Instead, companies have grown while decarbonizing, given appropriate policy and market circumstances. Growing markets offer opportunities to use economies of scale to decarbonize profitably, given supportive conditions and motivated leadership. Supportive policies can also encourage firms to take on new opportunities, such as expanding fledgling products and industries, by setting expectations about where markets will go in the future.

6. Conclusion

The five case studies discussed in this paper provide a level of granularity that is not as common in the prevailing policy and technoeconomic literature on industrial decarbonization. We develop a framework for understanding under what conditions large, international industrial companies are willing to make such investments and how they can pursue decarbonization strategies in the context of increasing productivity and growth. These strategies, energy and material efficiency, sustainability through growth, and new products and market restructuring, each provide a potential pathway forward for industrial companies that not only meet business thresholds but also can have ancillary benefits in the form of workforce retention and attraction and technologies that improve monitoring capabilities and yield downstream efficiency benefits.

Several key factors play a role in companies choosing to pursue these strategies. First and foremost, these initiatives had to meet basic ROI thresholds, although companies would often extend some flexibility to projects that promised especially large CO_2 reductions. Often, creative project proponents would find productivity improvements, such as overdue equipment upgrades, that could be coupled with decarbonization upgrades to provide an overall net positive return on investment despite the additional costs of going green. These costs could often be absorbed by the expected growth achieved by the investment in increasing economies of scale which drives productivity. Expectations around demand for greener products by customers and consumers is also a precondition for many of these investments. Commitment by senior leadership, driven either by policy changes or their values, underpin the success of these initiatives.

Overall, the companies in this study are leading the way in decarbonizing because of opportunities to increase efficiency, harness new technologies, increase growth and productivity, and implement a vision that forecasts opportunities for greener production processes. Industrial decarbonization is not always cost saving in the near term. However, a longer-term perspective and commitment by firm leadership combined with increasing demand by consumers and policies that have historically encouraged firms to decarbonize, are creating significant opportunities for firms to achieve a win-win-win - increase productivity, achieve acceptable ROI and reduce emissions.

APPENDIX 1: FLEX SOROCABA CASE STUDY

1. Introduction

Flex Ltd. is a global manufacturing company that offers a broad range of integrated circularity services that encompasses analytics, returns and screening, repair, refurbishment, asset recovery, product and parts resale, and recycling. Flex operates a manufacturing hub for electronics in Sorocaba, a city 100km from São Paulo, in Brazil. Flex's site in Sorocaba manufactures electronics including printers, computers, mainframes, and servers primarily for customers serving the Brazilian market. Their research and development operations innovate in recycling technologies and systems for electronic products. The site combines design innovation, advanced manufacturing, and aftermarket services such as repair, refurbishment, and recycling to extend material life cycles.

Within the manufacturing hub, Flex's site in Sorocaba has developed a first of its kind "integrated ecosystem" in Brazil that pioneers circular manufacturing technology to reduce e-waste. In 2000, Flex began its e-waste separation initiative and has since achieved zero waste from 2018.The Flex site in Sorocaba saw a 94% reduction of material waste and a 38% reduction of plastic material costs.

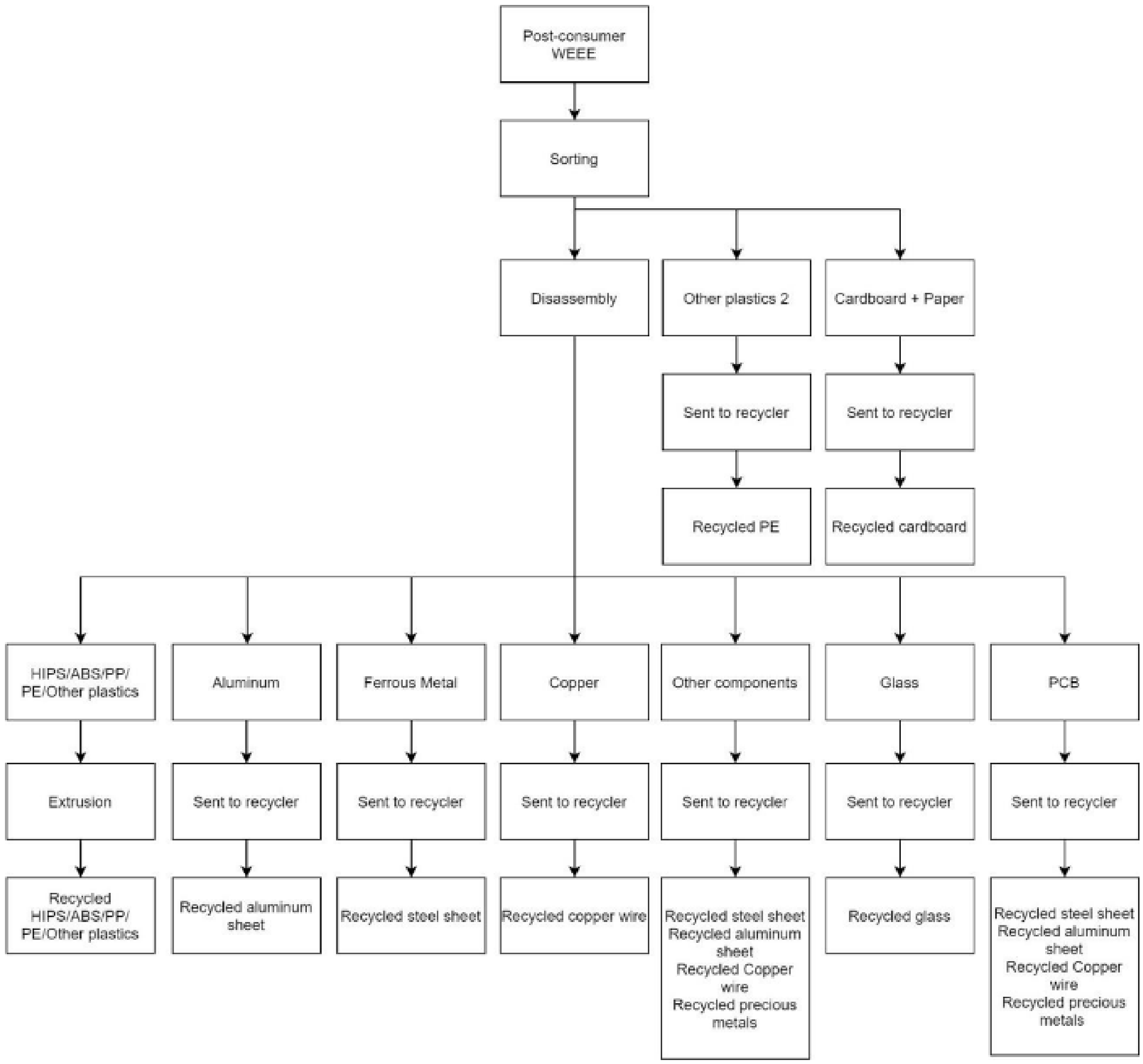

Figure 1: Flex in Sorocaba Process Flow. Source: CSA Registries

Flex's site in Sorocaba's circular economy ecosystem includes a cloud-based reverse logistics system, automated materials separation, and IoT-enabled collection bins to transform electronic waste and reintroduce materials into the supply chain by repairing, harvesting and recycling parts and materials. This process has reduced scope 1 and 2 greenhouse gas emissions by 41 percent, saving energy used in normal plastics production and eliminating 44 kilotonnes of CO_2 in scope 3 emissions. It produces both finished products and reused raw materials that customers can redevelop into new electronics on their own.

This methodology has been exported to other Flex locations, and the company has a global commitment to reach zero waste in 50 percent of its manufacturing and logistics sites by 2025.

Helping achieve these objectives, Flex's site in Sorocaba has established at least 450 recycling collection points operating across Brazil. We interviewed the Senior Director for Innovation and New Ventures at Flex in Sorocaba and General Manager at FIT, which is a consulting and research organization that develops technological solutions in a wide range of business cases for Flex, who led the project for several years beginning in 2012.

2. Background

2.1 Electronic waste recycling

Electronic waste is a rapidly growing contributor to global emissions. Reducing e-waste involves establishing circular product cycles for electrical products, through improved collection of waste products, making devices easier to disassemble and sort, and changing product design to better incorporate recycled materials.

In Brazil, e-waste recycling is not heavily incentivized and only 2-3% of electronic products are recycled at end-of-life, which is relatively low compared to recycling rates in North America and Europe, but higher than Africa and some parts of Asia, which also produce less e-waste to begin with. Globally, up to 22 percent of e-waste is recycled, a large share of which consists of larger products with less complex electrical systems.[17] Improving the rate of recycled products involves adopting reverse logistics operations, which coordinate the retrieval of waste products for recycling among customers, distributors, suppliers, and manufacturers.

Reducing e-waste in the manufacturing process by designing products to use recycled materials is challenging because customers that design and sell electronic products have precise specifications and typically will not tolerate deviations based on environmental factors. Disassembly is also not considered in traditional manufacturing, especially for electronics, and plastics are not as easy to disaggregate compared to other materials such as copper and nickel that can more easily be sorted visually or by density.[18]

2.2 Flex's product and process innovation

[17] UNITAR, "Global E-Waste Monitor 2024."
[18] Balkenende and Bakker, "Developments and Challenges in Design for Sustainability of Electronics."

To succeed in circular manufacturing, Flex concentrates several capabilities into its facility in Sorocaba:

- reverse supply chains: organizing recyclers, repair centers and logistics partners to collect products at their end-of-life for recycling and reuse.
- reverse logistics: organizing the deconstruction and distribution process for recycled goods, such as by finding buyers for each recycled component
- recycling facilities: establishing dedicated facilities for advancing circular production
- research and development: through its research and development center, Flex develops new disassembly, recycling, and sorting methods to improve circularity

The company's investment in innovation is driven by the belief that the circular economy produced through these methods will ultimately be more efficient than the old linear model. Primary challenges addressed in developing these new processes and products involve:

2.2.1 Identification of material

Flex's site in Sorocaba has developed novel techniques to differentiate between recyclable materials, since density and colour are often indistinguishable in the plastics that make up electronic products. Sorting different plastic types, such as ABS, from non-recyclable products presents a greater challenge than similar processes for metal and other industrial products. Other products have different magnetic, density, and visual properties, while different kinds of plastic are often hard to separate without further analysis. While manual processes continue to be necessary for the highest fidelity plastic sorting operations, automation is proving useful for many components of the process.

2.2.2 Quality control

The site's recycling operations are treated as research and manufacturing operations comparable to the production of new products, which enables customers to rely on the quality of products from circular supply streams as part of ongoing production and service programs. Warehousing and safety standards at the recycling plant match those of their assembly factories. Supply chains for their copper and aluminum recycling program, for example, were established over several years, with the same network of upstream partners required for their regular supply chains. Each step in the process requires arranging agreements with suppliers of recyclable products and finding customers to receive the final materials once they are produced.

2.2.3 Innovation in material compositions

Flex is now experimenting with different processes such as changing the colors and laser engraving techniques of their products, as well as inventing entirely new materials, that make it easier to recycle products when they reach their end of life. This is in the hopes of promoting them to customers to further improve the recycling potential of their products.

2.3 Market context

The recycling initiatives at Flex's site in Sorocaba are compensated for recycling materials or reducing waste, which enables lower material costs for customers. Digitizing and upgrading their logistics operations, for example, has in some cases led to substantial reduction in logistics costs. The company has now been operating its reverse logistics and recycling facilities for over 12 years, and is exporting its process to other locations.

The primary constraint on improved product design are the precise specifications and tight margins in contract manufacturing for electronic products. Ohde says that design constraints emerge from the industry-wide monetization challenge. Circular products must meet the same specifications as those made from virgin materials. Manufacturers cannot rely on a "green premium" for electronic products and organizations are determining whether marketing goods as sustainable is a viable business strategy.

In a context where manufacturers are not held financially responsible for the disposal of end-of-life (EOL) electronics, there is typically no business case for the recovery of equipment as reverse logistics and processing costs will outweigh the waste materials revenue. While take-back programs for expiring equipment, focused on materials recovery, very often represent a cost for the brand, other circular strategies often make financial sense. This is Flex's experience with several of their circular design and recycling operations, such as extending product lifespans, harvesting high value parts, and other emerging initiatives in circular design.

In similar markets such as plastic bottle recycling, where there are several large companies that have to hit recycling targets, there is more of a premium for recyclable products and a willingness to pay for recycling collection services. But in electronics, suppliers who are seeking out sustainable alternatives must compete directly with the linear economy. As a result, successful electronic products manufacturers such as Flex have seen certain cost savings from efficiency to help decarbonization objectives.

3. Results and Analysis

3.1 Explicit and implicit motivations for decarbonization

Initially, the push to increase recycling was motivated by 2010 regulations on e-waste in Brazil requiring companies to have a strategy for reverse logistics and a recovery threshold set as a percentage of material sent to market, without setting explicit percentage of recycled content requirements in individual products.

The initiative began with regulatory intervention in Brazil, combined with an executive culture at Flex focused on reducing waste of "material, time, and money" which motivated one of their major customers to seek out Flex as a partner in recollecting the products it produces when they reach their end of life. It took 1 year to scale operations and quickly grew into a major initiative.

In the absence of market premiums available for recycled materials, the economic rationale for recycling strategies in electronics manufacturing often relies on cost reductions from operational efficiencies and compensation for recycling certain products. While some programs receive compensation for collecting recyclable materials, manufacturers frequently incur costs to acquire or process waste, particularly when material quality is low or significant manual labor is required to restore recyclability. Additionally, reverse logistics represents a substantial cost driver, with expenses for product recovery often exceeding those of the recycling process itself, sometimes by a factor of two. The costs of logistics involved in recovering products are typically twice those of the actual recycling operations across Brazil.

3.2 Public policies and carbon accounting rules

A primary driver of this innovation is the 2010 Brazilian National Solid Waste Policy, which sets out a framework for shared responsibility over recycling in several industrial sectors, including electric and electronic products. The law requires producers and distributors to manufacture products such that they can be easily recycled and sets out a chain of responsibilities enabling reverse logistics, with each actor doing their part whether that consists of obligating consumers to return products to distributors, obligating distributors to return products to manufacturers, and manufacturers taking responsibility for proper disposal and deconstruction of products.

This policy applied pressure to Flex's largest customers without mandating explicit recycling quotas. One prominent customer proactively requested that Flex collect and recycle its electronic products on its behalf, kicking off the innovation process. Flex was able to develop its recycling process through up front investments, supported by a major client, that later paid off in terms of efficiency and circular economy services that are now a standalone benefit for Flex. Eventually, as reverse logistics capabilities improved, it enabled a circular economy services offering that enables customers to simplify reverse logistics execution and strengthen reporting.

3.3 Role of technology and digitization

Flex's e-waste recycling process has been advanced by significant investments in digitization and measurement research through their dedicated on-site laboratory. The reverse logistics process began as a customer-specific web portal designed to manage the flow of goods returning from collection points, disassembled, and distributed to end users of recycled components. This digital tracking system has now developed into a cloud-based system for reverse logistics that has digitized an otherwise onerous process for Flex's customers.

This has enabled Flex to expand its operations to serve final consumers of recycled goods directly, while initially only business-to-business operations were feasible. For example, recycled printers are deposited at collection points such as malls and client collection sites fitted with sensors that measure waste levels and notify Flex collection staff once they are 80 percent full.

Other relevant monitoring technologies include a recent partnership with CSA Registries, a Canadian third party company specializing in Scope 3 emission measurement.

4. Conclusion

Proximate causes of this innovation involve Flex's site in Sorocaba pursuing a research-driven decarbonization strategy under tight resource constraints motivated by demand from a major customer. Ultimately, national regulations on electronic waste recycling were a large initial accelerator of decarbonization efforts, which are now a part of Flex's strategy across their operations worldwide.

Upstream policy demands led to customer requests to develop e-waste recycling processes, which have since become a successful venture exported across company facilities globally, increasing time efficiency and saving money. This may ultimately have originated from firm policy guidelines set by the Brazilian government, but proactive customers and most of all, a willingness to embark on a research-driven development process for e-waste recycling and a drive to achieve cost, material, and time efficiencies was key to this investment.

APPENDIX 2: NATIONAL CEMENT CALIFORNIA CASE STUDY

1. Introduction

Vicat is a French multinational cement conglomerate, with 10,000 employees and $4 billion in annual revenue. An 8th generation family-owned company started by the son of Louis Vicat, inventor of artificial cement, Vicat includes 16 cement, 273 concrete, and 71 aggregate plants and has remained focused on these products as competitors have pursued expansion into chemicals, software, asphalt, and other materials. The US division, National Cement Company (NCC), operates in California, Alabama, Georgia, Tennessee, and South Carolina. In the 1990s and early 2000s, NCC made significant upgrades to their California cement plant, implementing cutting edge technology in energy efficiency. Since then, the plant has pursued related innovations in alternative fuels and low carbon cement options to further drive down their emissions.

NCC sells their cement to concrete clients, including their own downstream concrete-making subsidiaries. The company aims to pursue sustainability without compromising on profit targets. Company executives in California believe that "working towards environmental performance doesn't come at the expense of your bottom line. You can actually have both." They see their own decarbonization decision as a combination of regulatory pressures and company values. While European and California state regulation creates a situation where business owners feel that they "must do [decarbonization investments], because it's the law", any investment also "needs to align with company vision."

We spoke to the Plant Director, Environmental Manager, Chief Financial Officer, and NCC California President at the Lebec, CA, facility.

2. Background

2.1 Cement production

Cement is the binder and key ingredient in concrete, which is the most common man-made substance on earth by weight.[19] Cement production, which is upstream from concrete production, begins near a natural limestone deposit. Limestone (calcium carbonate $CaO.CO_2$) is carefully blended with small quantities of corrective raw materials, ground, and heated at high temperatures to produce clinker. Heating releases the CO_2 naturally contained in the limestone. Clinker is ground up and blended with additives (gypsum, raw limestone, calcined clay), which produces various cement types – such as Ordinary Portland Cement, Portland Limestone Cement, Limestone Calcined Clay Cement.

Emissions from this process are divided into four categories: 60 percent consist of process emissions, coming primarily from the chemical reaction of heating calcium carbonate that releases CO_2; 33 percent stem from fuel use, gradually evolving from fossil fuels to larger proportion of low-carbon renewable resources, used to heat the clinker furnaces; Scope 2 emissions such as electricity use account for only 3-5 percent of total emissions, while Scope 3 emissions such as trucking the cement to concrete plants are also responsible for about 5 percent of total emissions. Scope 2 and 3 emissions are incorporated into Environmental Product Declarations, but not when reporting to California Air Resources Board (CARB) for the purposes of Cap and Trade.

Demand for cement production tracks economic activity and construction starts. California's cement production has yet to recover from a 2005 high of 15 million tons per year, which fell to 6 million tons in 2010 and has since recovered to 10 million tons in 2025. New investments typically happen in anticipation of a growth period, rather than during periods of peak demand.

2.2 National Cement Company Product and Process Innovations

NCC pursued three primary innovations in sustainability: energy efficiency, reduced fossil fuel use and switching to low-carbon renewable fuels, and developing low-carbon blended cement. NCC is also exploring the potential of carbon capture technologies to reduce emissions.

[19] "Energy Efficiency Improvement and Cost Saving Opportunities for Cement Making | Energy Technologies Area."

2.2.1 Energy efficiency

A primary focus of the Lebec plant overhaul pursued in the early 2000s was a set of energy efficiency upgrades that produced a 25-30 percent reduction in energy use. Similar upgrades at a facility in Birmingham cost about $300 million dollars to put in place. The primary vectors for energy efficiency upgrades in the cement industry consist of improved process controls and automated monitoring of grinding, crushing and mixing operations, as well as higher efficiency operating equipment such as variable speed drives for fans, and more efficient kiln heating and rotating systems.[20] Plant directors note that getting permits for this kind of reconstruction and upgrading project in today's business environment would be challenging.

2.2.2 Fuel switching

Cement is typically produced using high temperature reactions fueled by petroleum coke, derived as a byproduct of oil and gas production and refining. Other firms use coal and natural gas. One alternative to these heavily polluting fuels is shifting to biomass, which encompasses fuels rich in biogenic carbon such as agricultural waste. As one example, in California's Central Valley, local farmers must dispose of millions of tons of pistachio shells. This material is a cost-effective fuel for cement production.

Other fuels are widely available, such as used tires (Tire Derived Fuel) which provides environmental value by diverting tires from landfills, utilizing the 30% biogenic content of tires and are combusted under favorable conditions in the cement kiln (high temperatures, long residence time, with no ultimate waste). Although not currently used at Lebec, Municipal Solid Waste (MSW) is another fuel type that enables recycling of material that typically goes to the landfill and is rich in biomass.. MSW requires Carbon 14 testing to determine biogenic carbon levels (typically 50 - 75%) since unlike pure biomass products, not all MSW is biogenic (e.g. paper waste vs plastic waste). NCC started employing TDF in the 2000s to reduce nitrogen oxide (NOx) emissions but have since pursued the strategy also to minimize CO_2 emissions. Presently, they have replaced 55 percent of their fuel with alternative fuels, compared to a US average of 14 percent and 6 percent in California. Fuel is responsible for one third of the plant emissions. NCC's current emissions reduction goal is to replace 70 percent of the 200,000kT of tCO_2 emissions produced through fuel combustion in 2019, by 2029.

Biomass is considered to produce no emissions from a carbon accounting perspective, since it is biogenic carbon that originally trapped carbon from the atmosphere using photosynthesis.

[20] Coito et al., *Case Study of the California Cement Industry*.

NCC only uses waste products to ensure that people are "not growing for biomass" or producing biogenic products that would not otherwise be used simply for the sake of burning it.

For existing plants, the opportunity to switch fuel sources is variable. The availability of biogenic fuels is "very facility specific". Although biofuels are often cheaper than non-renewable options, the primary issues in transitioning to sustainable options are the costs of transportation, sourcing, permitting, capital expenditures involved in adapting machinery and operational costs to transition production. Such a retrofit either takes a full plant shut-down for several weeks, or a gradual, 5 percent incremental transition that is implemented during regular yearly plant downtime.

Plant executives suggested that as a result upgrades are unlikely to happen during boom markets, nor when demand turns down, unless there is anticipation of future growing returns. These factors introduce risks that prevent adoption even if profits are available, since they involve a reduction in output during a learning curve phase. The financing required for such a transition means it must be a priority for the organization at a global level, often pushed by regulatory mandates, as well as fitting into the global company's outlook on decarbonization investments. The NCC executives see a combination of regulation, such as California NOx regulations in 2005, California AB32 Global Warming Solutions Act of 2006 and subsequent Cap-and-Trade emissions trading scheme, and California SB596 in 2021 mandating net-zero cement by 2045, crucial factors for facilitating these investments.

2.2.3 Low Carbon Cement

Clinker production is responsible for 95 percent of process emissions, and two-thirds of overall emissions. Ordinary Portland Cement (OPC) is traditionally 95 percent clinker and 5 percent gypsum, but blended cement products have been in development for nearly 50 years. These products mix limestone that has not gone through the process in the furnace that releases CO_2 with pozzolanic byproducts such as fly ash. The American Cement Association, an industry group, has supported Type 1L Cement, which is a reduced clinker alternative, allowing substitution of up to 15 percent clinker with raw limestone. Adoption varies across the country but NCC executives point out that it is inexplicably low among California producers other than NCC, despite clients who have expressed willingness to pay a green premium. Since clinker is the most emission intensive product in cement making, and often also the limiting factor in production, reducing clinker usage seems like an easy win for cement producers.

The NCC executives state: “We need the industry to move faster and we will continue to promote the qualities of Type 1L."

In addition to engaging traditional customers of cement and concrete, NCC is increasingly engaging with project owners on their choice of materials. Owners such as the California Department of Transportation are interested in these products for infrastructure projects that have a specific mandate to adopt low carbon options. Owner interest in blended cement exists in every customer category.

LC3 (Limestone Calcined Clay Cement) cement is the next generation of blended cement NCC is developing. LC3 has similar characteristics to regular cement, but with much lower emissions. The calcined clay produces about 25 percent of the emissions of clinker (200 vs 800 kg of CO_2 per tonne of production) and its properties allow for a cement with calcined clay/raw limestone mix to contain as little as 50 percent clinker. This yields a 30-40 percent reduction in carbon intensity of the finished cement due to the reduction in clinker.

LC3 performance is not identical in all respects to OPC, such as the time it takes to set, but this aspect is accommodated via customer specifications since customers typically do not need the fast setting characteristics of OPC. Promising routes include partnering with owners of data centers who have emission targets to try out large scale projects. Since NCC is globally resourced, they believe that this alternative could quickly expand worldwide.

LC3 is not necessarily cheaper to produce than traditional cement unless there is a clay deposit right near the plant. NCC does have initial startup costs to adapt production and additional supply chain costs that need to be absorbed as market uptake scales. Like most cement production, this process would have to primarily serve a local market; however, data center customers and other larger customers are willing to pay a premium to secure access to this type of blended cement.

Widespread adoption of blended cement in the U.S. might also contribute to domestic manufacturing and production in the U.S. Presently, 20 percent of all cement consumed in the U.S. is imported from other countries. This is largely due to limited clinker production capabilities in the U.S. Blended cements allow for larger quantities of cement to be produced locally, at a given clinker volume. Therefore, as the U.S. cement industry continues to produce more blended cement, it could replace the need for imported cement with less well regulated emissions reporting.

2.2.4 Carbon Capture

All of the emission reduction strategies detailed above, if perfectly successful, promise a maximum 35-40 percent emission reduction compared to NCC's 2019 baseline. Addressing the remaining 60 percent of emissions from cement production (the process emissions from limestone calcining) depends on capturing carbon dioxide, paired with solutions to utilize or sequester carbon dioxide.

To address this outstanding challenge, NCC is working with a carbon management entity involved in the permitting and operations of Class VI injection wells for carbon dioxide. As envisioned, NCC would capture the carbon dioxide at the cement plant and transport it by pipeline to a permitted, safe, and monitored well located in a depleted oil field. It would require using a very large CO_2 compressor with significant energy needs, as well as natural gas for the capture of the CO_2. Such a project would cost upwards of $1 billion and present a significantly new cost structure, with new capital and operating costs. Carbon capture risks increasing the price of cement without offsets available, such as the 45Q federal tax credit for captured CO_2 and the carbon abatement value under the California Cap and Invest program. This makes it a high-stakes venture, even with the anticipated rise in CO_2 prices into the future.

This work is partly inspired by a Canadian plant in Saskatchewan that is selling CO_2 for enhanced oil recovery with Saskpower, currently in a piloting phase. This project started in 2014 thanks to incentives from the Canadian government, and is currently capturing 1 $MtCO_2$ per year following 10 years to stabilize operations. Public sector support would be required to support such large capital expenditures, as well as for subsidizing operational expenditures until the cost of CO_2 becomes high enough or regulation makes carbon neutral cement the only permissible option for use in California. The high costs cannot be priced selectively for certain clients the way premium cement products are currently marketed, since the carbon capture must operate at 100% capacity to justify initial investments.

2.3 Market Context

The key point delivered by NCC's executive team regarding their market was that cement production is energy intensive and trade exposed. The US imports about 20 percent of all cement consumed, with California having the same share of imports. The increase in imports is partially driven by plant closures, with 2 of California's 9 plants shutting down since 2010, but also by lower production costs that translates in some cases to lower prices. Imports to California mostly come from Vietnam, which has had low sale prices since 2019 due to overcapacity following the Chinese real estate downturn. While recent years have seen stronger demand, the increase in imports is a long-term economic risk to the California industry.

California cement producers are also required to comply with climate policies such as SB596, which seeks to have all cement be carbon neutral by 2045. NCC executives believe that ultimately these competitive issues, combined with unregulated imports, will have to be addressed through a border control of some kind, similar to the European Union's Carbon Border Adjustment Mechanism.

3. Results and Analysis

3.1 Explicit and Implicit Motivations for Investment

The drive to invest in decarbonization at NCC stems from a belief that emission reductions are "possible, while preserving and maybe improving your bottom line", coupled with a fear of being regulated out of business if their industry appears intransigent in the face of climate change. NCC is the only company selling 1L at scale in California, even though the product is available elsewhere in the US. In the words of the plant director, the organization's "biggest fear" is being regulated out of business, just "like the oil and gas industry", with regulations that shift the emissions of cement production out of state without doing anything to curb actual CO_2 release.

["As long as we're at the table, we're proactive, we have a seat at the table … we don't want to lose a seat at the table."]

3.2 Public Policies and Carbon Accounting Rules

In 2012, as directed by the passage of AB32 passed in 2006, California implemented a market-based emissions compliance system called Cap-and-Trade. The emissions scheme – which is administered by the California Air Resources Board (CARB) – has a steady decline in the overall cap (2% for cement, 4% across the board for other industries), which is slower for cement because of leakage (imports) and the energy intensive production process. Most recently, in 2025, California extended the effective period of this system from 2030 to 2045, and renamed it to Cap-and-Invest, highlighting the program's goal of redirecting revenue to a variety of programs designed to reduce emissions. This policy aligns with Vicat internal sustainability targets, which are aiming for 2050 carbon neutrality across the value chain.

There are also technical issues with CARB's Cap-and-Invest system, which applies product benchmarks that currently do not recognize emission reductions resulting from production of LC3 cement because it uses a standard benchmark for cement regardless of how it is produced. NCC believes this will eventually change, but this is an example of how the regulations can inadvertently disincentivize the desired outcomes. At the same time, the upward trend in electricity rates in California create challenges for certain categories of capital expenditures. Finally, prescriptive building codes also produce overly specific demands from clients for existing materials, and NCC is aiming for acknowledgement of the benefits of blended cement, or performance codes that allow all materials that meet a certain threshold to be automatically permitted for construction.

NCC is advocating for a Carbon Border Adjustment Mechanism-equivalent policy for California, rationalizing investments needed to produce net-zero cement and leveling the playing field with less regulated cement produced out of state. That would only be feasible if protected from imports, both from other countries and neighboring states, which depends on setting up reliable third party standardization, verification, and inspection mechanisms to assess carbon emissions by imported materials. Enforcement between states poses potential legal challenges but NCC argues it is already being done for other products in the state (e.g. in electricity, renewable fuel standards for trucking in CA, regulations on parts like water-saving faucets, banning of certain paint chemicals, etc.).

3.3 Role of technology and digitization

AB32 Cap-and-Trade emissions reporting, which originates with the 2006 Act focused on NOx emissions alongside CO2, is currently done through extensive at site audits with authorized third party verifiers.[21] As required under CARB's Mandatory Greenhouse Gas reporting regulations, NCC has set up continuous emissions monitoring systems (CEMS) to measure air emissions, and are sent monthly to an outside lab for physical measurement. This involves hiring a new independent auditor every 3 years, who "turns every stone" to certify that data provided by NCC are consistent and accurate.

Other technological upgrades to their facility, such as cement trucks powered by renewable natural gas also give NCC a better concrete EPD, verified by Climate Earth, a software tracking third party system. While there were costs in terms of time and learning to establish these monitoring systems, they find that now that they have set it up, it is easy to implement.

3.4 Changing workforce

The changes involved in pursuing decarbonization have had some impact on staffing at NCC, with more specialists and government communications people brought on to market green investments, as well as additional hires involved in climate research, policy and compliance, and research at Vicat headquarters, including a new innovation department and digitalization team.

[21] "AB 32 Global Warming Solutions Act of 2006 | California Air Resources Board."

CEMS and auditing has added 1-2 full-time jobs, with other responsibilities delegated to regular employees to implement new processes and operating procedures. While these changes are "not something you can take lightly … it's something anybody can do". Obligations under Title V (U.S. Clean Air Act) mean that most firms are set up to complete the measurements requested by the decarbonization compliance audits, such that new processes required for CO_2 monitoring will not pose a burden. Similar audits would be a much bigger lift for their international competitors, and likely also out of state competitors.

4. Conclusion

NCC has pursued multiple strategies to decarbonize their operations over the past several decades. This began with energy efficiency upgrades to their Lebec, CA, cement plant, and is now focused on using alternative fuel sources, new clinker substitutes, and carbon capture technology. While California state regulations have motivated this focus on sustainability, the company is pursuing industrial decarbonization as a long-term business strategy.

Cement is emission intensive, such that small improvements to NCC's yearly CO_2 production can have outsized effects. If LC3 cement fully replaced their conventional products, it could decrease the carbon intensity of their products by close to 50 percent. Energy efficiency upgrades have saved approximately 1 percent of CO_2 each year that they have been implemented.

NCC sees its low-carbon products as a premium product, which could be adopted by sustainability leaders and scaled through public procurement programs. The company has built on decades of investment in sustainability with its most recent plans for decarbonization. Their investments in energy efficiency have brought down process emissions and they are currently capable of producing Type 1L cement, despite low demand for this product in California. Whether LC3 cement and carbon capture, their more ambitious and expensive projects, will succeed depends on governments willing to support the new products rather than displacing the industry to another jurisdiction that is less intent on reducing its emissions.

APPENDIX 3: OUTOKUMPU CASE STUDY

1. Introduction

We interviewed the Chief Technology Officer (CTO) and their team at Outokumpu, a major European stainless steel producer with production facilities in North America and Europe. The company holds a quarter of the region's market share and produces over 2 million tons of stainless steel annually.

Stainless steel production is an emissions-intensive industry where 2 to 7 tons of CO_2e are emitted for every ton of stainless steel.[22] The CTO hopes to prove that decarbonization can be profitable, but, so far, decarbonized stainless steel products have only gained traction among the 1 percent of customers willing to pay a green premium. This case explains the challenge of decarbonizing stainless steel and the technology, policy, and business changes that would enable its uptake.

[22] See Case Study 4 Appendix 1

2. Background

2.1 Decarbonization of the Stainless Steel Industry

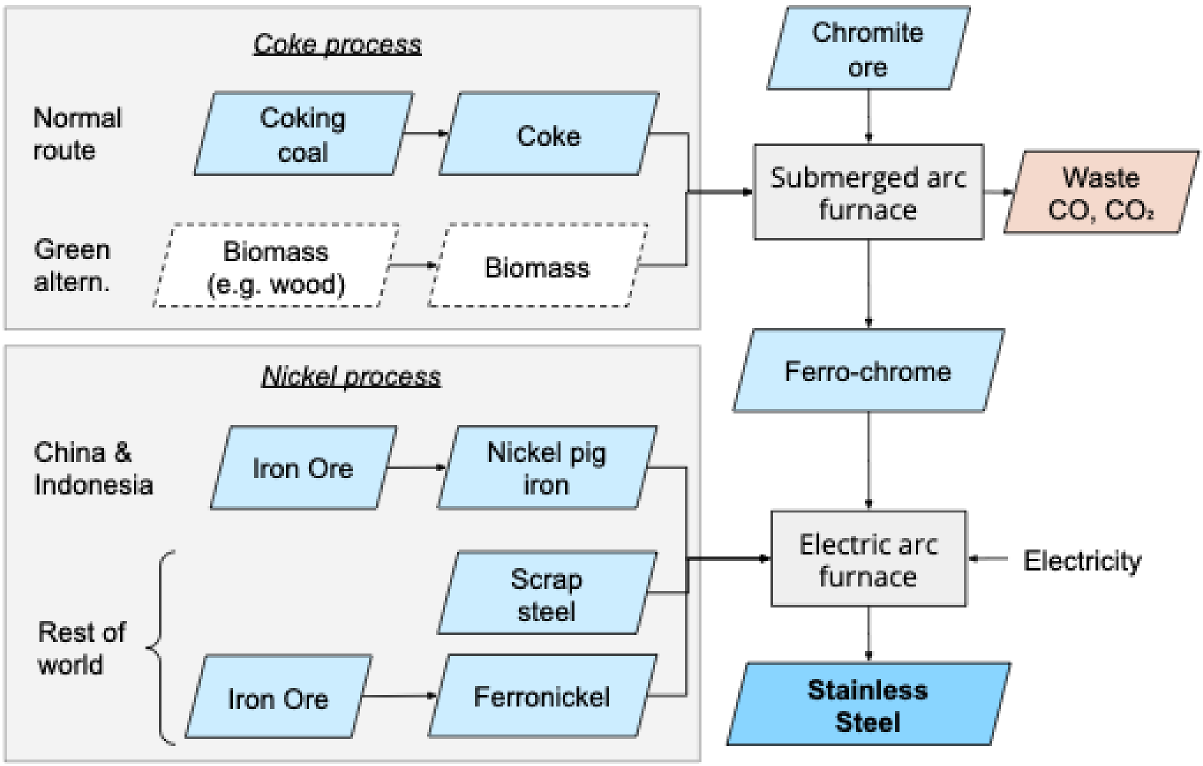

Figure 1: Stainless steel production process

About 60 million tons of stainless steel are produced annually, over 60 percent of which are produced in China.[23] Limited literature exists on the decarbonization of stainless steel because the topic has been eclipsed by the much larger industry of non-stainless steel which accounts for 7 to 10 percent of global emissions.[24] While similarities exist across both production processes, the topics are not to be confused.

Stainless steel is steel (iron with small amounts of carbon) strengthened with chromium (10 to 20%) and nickel (up to 15%). It is produced in electric arc furnaces (EAFs) where stainless steel scrap (recycled stainless steel) is combined with ferronickel (FeNi) and ferrochrome (FeCr) to produce the desired stainless steel blend. In China and Indonesia, where the scrap supply is

[23] World Stainless, "Stainless Steel Melt Shop Production Increases by 7% in 2024."
[24] Zhang et al., "Iron and Steel Industry Emissions."

outpaced by stainless steel demand, nickel pig iron (NPI) derived from iron ores is produced and used instead of scrap and ferronickel.[25]

The emission intensity of stainless steel production is highly dependent on the proportion of stainless steel scrap used, also known as the scrap ratio. The industry association World Stainless estimates that stainless steel composed of 30 percent scrap steel is 3.5 times more emission intensive than stainless steel composed of 85 percent scrap steel.[26] Although World Stainless provides few methodological details, their estimates align with the notion that most emissions occur in the production of virgin metals, especially NPI, and thus, any increase in the usage of scrap directly reduces the emission intensity of stainless steel. The availability and usage of scrap is expected to increase as metal products reach their end-of-life in China and the country's growth rate slows.[27] In Europe, the scrap ratio is already at 90 percent.[28]

At high scrap ratios, stainless steel remains an emission intensive product due its reduced but persistent need for virgin ferrochrome and ferronickel, producing about 30% of the emissions of primary steel.[29]

Ferrochrome Production

Ferrochrome is produced from chromite ores that are mined principally in Russia, Kazakhstan, South Africa, and Finland. Chromite (oxygen-rich) is converted to ferrochrome (oxygen-free) in a submerged arc furnace (SAF) wherein coke, a coal derivative, triggers a chemical reduction reaction.[30] Carbon dioxide (CO_2) and carbon monoxide (CO) are by-products of this reaction and a significant source of greenhouse gas emissions (especially since the toxic carbon monoxide is typically burnt and converted into CO_2 before venting).

There exists three potential technologies to reduce these ferrochrome process (by-product) emissions.

1. *Biocoke*. Biocoke is a coke substitute produced from biomass (e.g. wood) instead of fossil fuels and, as such, emissions from biocoke are arguably offset by the carbon

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25 Basuhi et al., "Clean Energy Demand Must Secure Sustainable Nickel Supply"; Rao et al., "Carbothermic Reduction of Nickeliferous Laterite Ores for Nickel Pig Iron Production in China."

26 World Stainless, *CO2 Emissions Report*.

27 See 2015 and 2019 data from "The Global Life Cycle of Stainless Steels".

28 Stainless Stocks and flow Sankey Diagram - EUROFER

29 Allwood et al., *Steel Arising*.

30 This reaction is commonly denoted as: $FeCr_2O_4 + 4C \rightarrow FeCr_2 + 4CO$

captured during the biomass's growth. Biocoke, especially biocoke produced from wood pellets, is a promising substitute for coke in submerged arc furnaces.[31]

2. *Carbon capture, utilization and storage (CCUS)*. In the non-stainless steel industry, CCUS is already being explored as an emission reduction solution, often in conjunction with oil producers to use the captured CO_2 for enhanced oil recovery (EOR).[32] In China, steelmaker Baoshan Iron & Steel Co is working with oil producers Sinopec and Shell to jointly develop CCUS.[33] As of December 2025, no stainless steel manufacturer has announced plans to develop CCUS.

3. *Alternative reduction processes.* Non-stainless steel producers are developing "direct reduction iron" processes wherein iron (an input to steel) can be produced using green hydrogen instead of coke. Similar research, although preliminary, is underway for establishing a reduction process for ferrochrome production that does not utilize fossil reductants.[34] One promising route is via sulfide chemistry.[35]

2.2 Product and Process Innovations

Outokumpu operates electric arc furnaces (EAFs) at its stainless steel production facilities in North America and the European Union, as well as a submerged arc furnace (SAF) at its ferrochrome production facility. It also operates its own chromite mine. Most (65%) of its direct emissions (Scope 1) are process emissions from its ferrochrome production facility. The figure below provides a breakdown of the company's direct and indirect emissions.

Interestingly, Scope 3 emissions make up most (77%) of the company's total emissions despite the emission intensity of ferrochrome and stainless steel production. The company notes that reducing Scope 3 emissions is challenging and competitors that use lower scrap ratios tend to have even higher Scope 3 emissions.

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31 Bazaluk et al., "Metallurgical Coke Production with Biomass Additives."
32 Pathways to decarbonisation episode seven: the electric smelting furnace
33 Lv and Aizhu, "Baosteel Inks CCUS Research Agreement with Sinopec, Shell and BASF."
34 Paktunc et al., "Mechanism of the Direct Reduction of Chromite Process as a Clean Ferrochrome Technology."
35 Stinn and Allanore, "Sulfide Route to Chromium–Nickel–Molybdenum Ferroalloys for Stainless Steel Production."

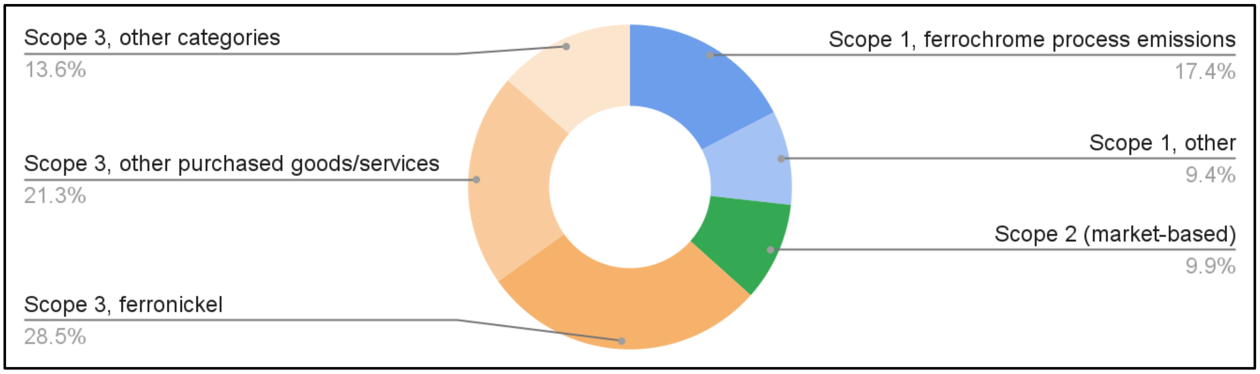

Figure 2: Stainless steel company emissions breakdown

The company's product carbon footprint sits at 1.4 tons of CO_2e per ton of stainless steel which is 45% below the European average (~2.5 tCO_2e/t) and 75% below the global average. The company achieves this superior performance for several reasons:

1. *High use of recycled steel*. The firm's scrap ratio is ~95%, reducing the firm's dependency on virgin materials, especially ferronickel and ferrochrome which are major emission sources.
2. *Low-emissions electricity grid*. The company's European facilities, which account for 84% of its electricity usage, are located in countries where over most (85%) of the electricity is generated from low-carbon sources, mainly nuclear as well as hydro and wind power. (The company's U.S. facility however does not operate in a low-emission region.)
3. *Renewable energy credits (RECs)*. For its European facilities, the company purchases Guarantees of Origin (also known as renewable energy certificates) to ensure that 95% of its electricity supply comes from renewable or low-carbon sources. (The company does not purchase RECs for its facilities in the Americas.) This allows the company to claim a 32% reduction in Scope 2 emissions, reducing its total emissions (Scope 1, 2, 3) by 5.4%.
4. *Carbon monoxide recycling*. The firm's vertical integration allows for the carbon monoxide (CO) produced in its ferrochrome operation to be used as a source of heat in its pre-heating furnaces. Other ferrochrome suppliers, in South Africa for example, simply flare the carbon monoxide. Although using the carbon monoxide waste for power does not reduce the firm's direct emissions, it does reduce the firm's electricity consumption and associated Scope 2 emissions.

Already well-below industry average, the company plans to further reduce its emission intensity. In 2021, the company set emission reductions targets validated by the science-based targets initiative (SBTi) of reducing its Scope 1, 2, and 3 emission intensity by 42% by 2030 compared to the average of 2014-2016 levels.[36] At the time, no other company had set a 1.5°C-aligned SBTi target. So far, the company has accomplished three quarters of this emission reduction goal. To complete the remaining quarter, the company hopes to grow its "Circle Green" product line which currently makes up only 1% of its sales volume.

In mid-2022, the company launched this line of Circle Green stainless steel products which use ferrochrome produced using biocoke (derived from pyrolized wood) instead of fossil coke. In doing so, the company is able to offer a stainless steel product with a carbon footprint of 0.5 tons of CO_2e per ton of stainless steel (instead of 1.4 tCO_2e / t), nearly 90% below the industry average.

2.3 Market Context

Biocoke is currently four times as expensive as regular coke which forces the company to charge a green premium on its Circle Green stainless steel product line. Out of its nearly 400,000 tons of annual ferrochrome production, only 1% are Circle Green products because the portion of customers willing to pay the green premium is small. In its first few years of operations, Outokumpu disclosed that it delivered Circle Green products to 24 customers including:

- Fiskars group, a cookware manufacturer that sought out sustainable stainless steel to increase its products' appeal among its US market, where high-end consumers are increasingly eco-conscious. Fiskars was the first Circle Green customer.
- Alstom, a train and metro manufacturer that is using the Circle Green stainless steel for the body of its Metropolis Metro cars as part of its eco-design process.
- A knife manufacturer, producing a special series of long-lasting knives with a low carbon footprint.

3. Results and Discussion

3.1 Implicit and Explicit Motivations for Investment

This company became a sustainability leader for several reasons. For one, the company believes there is a "mega-trend" where in the long-term, despite recent setbacks in US policy, climate change and reducing emissions will be of pressing concern to shareholders, customers, and the broader public. Moreover, the company's sustainability strategy is also about supply

[36] See the Science Based Targets initiative data. Download the Excel; filter for *Corporate* organizations in the *Mining - Iron, Aluminum, Other Metals* industry that are aligned with *1.5°C* (near-term); sort by *date_updated*

chain security: the more visibility they have into their supply chain and associated emissions, the easier it is to avoid sourcing conflict minerals, a priority given NGO pressure and public opinion in Nordic countries.

Despite this, the company notes that its most sustainable stainless steel product, called Circle Green, with at least 50 percent lower carbon footprint than the company's other sustainable stainless steel products, is currently not profitable beyond the niche markets they have found. Anybody who says otherwise has either found a niche or is mistaken in their cost evaluations, says the CTO. He provides the following hypothetical example illustrate the conditions required for Circle Green products to be cost competitive with regular stainless steel, given that coke is an ingredient to Circle Green stainless steel:

> *Assume that fossil coke sells at 350 € / ton while biocoke sells at 1400 € / ton, a 4x increase in price. To switch all 400,000 tons / yr of ferrochrome production to biocoke would cost a company 280 million euros (assuming 2:3 coke-to-ferrochrome ratio). Such an investment with no expectations of return is not justifiable to shareholders. However, suppose that, thanks to process and technology improvements, the cost of biocoke was reduced to 1000 € / ton. Moreover, switching to biocoke would result in ~2.5 tCO_2e avoided / ton of ferrochrome which amounts to 1 million tCO2e avoided or 100 million euros saved in avoided emission trading system (ETS) fees, Europe's cap and trade system (assuming 100 € / tCO_2e) . Finally, biocoke produces more carbon monoxide (CO) as a byproduct than fossil coke. The additional CO can be burnt to produce power and heat that can be resold to the grid and district heating systems, respectively, effectively lowering the cost of biocoke by an additional 400 € / ton. If these factors were to align, these combined savings would reduce the effective cost of biocoke to 350 € / ton, on-par with fossil coke.*

In this example, the CTO stressed the importance of factors such as co-location. District heating and grid capacity are essential if a company is to resell the heat and power generated from its carbon combustion process. It was noted that part of the reason coke and fossil fuel products more generally are so cheap is that the oil and gas industry has been optimizing their use of sidestreams and by-products for over a century.

3.2 Impact of Policies and Carbon Accounting Regulations

As highlighted in the earlier example, the European Union's Emission Trading System (ETS) is expected to play a major role in making decarbonized stainless steel products cost-competitive. The EU considers steel production to be an industry at risk of carbon leakage, which involves companies shifting production to areas with less stringent emission standards.[37]

[37] Official Journal of the European Unit Volume 62

As such, stainless steel producers receive free allocations in proportion to their production volumes and according to a benchmark set according to the 10% least-emitting manufacturers. Thanks to these free allocations that roughly match the company's Scope 1 emissions, the EU ETS is not currently a significant cost to the company. However, as the free allocations are phased out between 2028 and 2033, the company expects to pay 100€ / ton of CO_2 (higher than the current price of ~65€ / ton but lower than the 200€ / ton the company says some consultants predict). At 100€ / ton, the company would see an added yearly cost of 100 million euros. The company explained that nobody wants to accept this cost. "Our options are to decarbonize or shut down."

The role of carbon accounting systems also plays an important role in the company's ability to decarbonize. This company emphasized that a precondition to charging a green premium is obtaining a product carbon footprint(PCF) certified by an external party such as industry experts. They publish these PCFs, which contain details on life cycle assessment methodology. Moreover, every batch of stainless steel comes with a carbon footprint certificate. For its Circle Green products, the carbon footprint is calculated for every batch to account for the batch's mixture and electricity consumption (other product lines use yearly averages).

The CTO explained that a few years ago, there was a strong push for greater transfers of this emission data throughout the supply chain. While worse market conditions have reduced companies' enthusiasm for tracking Scope 3 emissions, doing so is still the direction where sustainability is headed.

To assess its company-level emissions, Outokumpu has collected Scope 3 emission data on 95% of its suppliers using a mix of supply chain-specific information and industry averages from databases. To do so, they used their financial data to create an inventory of their suppliers. They found that 45% of their Scope 3 emissions stem from their purchase of nickel. Interestingly, a 10x variation in the carbon footprint of nickel was found depending on the supplier. For example, Canadian suppliers have a 10x lower carbon footprint than Indonesian suppliers, largely due to differences in the nickel type (sulphide vs laterite) and processing methods.

3.3 Changes in Workforce

The changing business conditions have led Outokumpu to seek out new employees capable of assessing the prospects of emerging technologies including carbon capture and storage, and biocarbon production. This has involved a growing proportion of chemical engineers compared to the typical focus on metallurgical and mechanical experts. Recent hires have also involved experts in AI, automation, and monitoring systems. However, most employees involved in decarbonization are shifting 10 or 20 percent of their time to new tasks, which generally require slightly higher-educated or engineering-focused skills, rather than leading to dramatic changes in hiring practices.

However, the most significant impact of decarbonization on the company's workforce comes from the talent that can be recruited through the company's reputation as a sustainability leader. The CTO says: "You cannot imagine how powerful this vision as a sustainability leader in the steel industry can be for employees who work at our company. Especially the direction of our vision "towards a world that lasts forever" and its execution is a big selling point for working at our company for the younger workforce."

Offering new hires the opportunity to become part of the solution to a significant global problem has become a selling argument for attracting well-trained and ambitious new workers. Whether in the United States, Germany, Sweden, or Finland, the executive reports that younger people have a core interest in sustainability, which is harnessed by the pursuit of a paradigm shift in legacy industries such as steel production that could previously make only marginal changes to energy efficiency but are now redesigning processes, either in supply chain or in the production process altogether.

4. Conclusion

The stainless steel manufacturer in this case study explains why decarbonized stainless steel makes up only 1% of their sales to date. Making decarbonized ferrochrome, a key input to stainless steel, requires biocoke, an alternative to fossil coke that is four times as expensive. For biocoke to become cost-competitive with fossil coke, a confluence of changes are needed including a) process and technology improvements (already under way), b) a cost on carbon of 100 € / ton via the EU emission trading system with safeguards against carbon leakage, and c) opportunities for the company to use or resell its carbon monoxide by-production to either a district heating network or for sustainable aviation fuels.

Appendix 1.1 Stainless steel emission intensity

There exists surprisingly few reliable estimates of the industry-average emission intensity of stainless steel production. One systematic review of the steel literature referenced only one study that considered stainless steel alongside regular steel.[38] The referenced study estimated that stainless steel production in China in 2015 emitted 1.4 to 1.8 tons of CO_2e per ton of steel.[39] However, the study (gate-to-gate only) did not include certain upstream emission sources which might explain why these values are significantly lower than other estimates. For example, a peer-reviewed Australian study estimated the emission intensity of stainless steel to be 6.8 tons CO_2e / ton in 2005 although no details exist as to their calculations or assumed scrap ratio.[40] The industry-led association World Stainless estimates the emission intensity to be 2.1 to 6.9 tons CO_2e / ton depending on the scrap ratio.[41] Interviewees in this case study mentioned that the average emission intensity of stainless steel in Europe is 2.5 tCO_2e/t and 7 to 8 tCO_2e/t in Asia. All in all, it appears that typically between 2 and 7 tons of CO_2e are emitted per ton of stainless steel produced.

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[38] Rihner et al., "Life Cycle Assessment in Energy-Intensive Industries."
[39] Jing et al., "Assessments of Greenhouse Gas (GHG) Emissions from Stainless Steel Production in China Using Two Evaluation Approaches."
[40] Norgate et al., "Assessing the Environmental Impact of Metal Production Processes."
[41] International Stainless Steel Forum, *Stainless Steels and CO2; Industry Emissions and Related Data*.

APPENDIX 4: SAINT GOBAIN CASE STUDY

1. Introduction

Saint Gobain is a 360-year-old construction materials company that produces gypsum drywall, fiberglass, glass, and roofing shingles, among many other products. The company employs 161,000 people in operations in over 80 countries. It is committed to decarbonizing its global operations dramatically over the next several years. It has exceeded its 2030 targets of 33 percent global scope 1 and 2 reductions and is now pursuing 2035 targets and aims for net zero global production by 2050. Gypsum production is responsible for a large share of Saint Gobain's emissions, primarily due to the natural gas burned to power industrial processes.

Saint Gobain has operated a drywall and plasterboard manufacturing facility In Montreal since 1973. The plant currently employs 120 people, Saint Gobain recently replaced and expanded the production line while making a set of equipment modernization investments that enabled a 40% increase in production capacity, reduced energy consumption by 30 percent, and saved 44,000 tons of CO_2 emissions per year.[42] This plant is now the first net zero scope 1 and 2 emission drywall production facility of its kind in North America. It follows a similar retrofit of a plasterboard plant in Frederikstad, Norway, in 2023.

We spoke with several executives responsible for developing and implementing this project over the past several years.

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42 Saint Gobain Montreal, "Press Release: 2025 Inauguration."

2. Background

2.1 Gypsum Drywall Production

Gypsum drywall is a common building material made of a core of gypsum plaster inserted between two sheets of paper used to create fire-resistant interior walls and ceilings. Drywall production is a multi-step process, which involves using a fluidized bed reactor to calcinate gypsum typically powered by natural gas. In the Montreal plant, Saint Gobain installed an indirect heating technology that could be electrified, eliminating the emissions associated with combustion.

2.2 Saint Gobain's Product and Process Innovations

The potential to electrify these industrial processes began with discussions between an energy engineer at Saint Gobain and suppliers at the company's Quebec facility. The facility was one of the most advanced in terms of metering systems for power use and controls set up to establish an energy management system. Initially highly speculative discussions on the prospects for a zero carbon plant converged on the idea that Quebec was particularly well-suited for decarbonization programs because of a set of government support initiatives and advanced capabilities for monitoring power usage relative to other similar plants. Gradually, they accumulated a list of programs that would bring down potential capital expenditures, while exploring opportunities to reduce operational expenditures, which dominate the project returns over time.

A project in Norway that pursued similar decarbonization upgrades at a smaller scale provided early insights in supplier selection and technologies, including developing new operating procedures such as powering up machinery in a sequence that was more energy-efficient. A central decision-maker reported that upcoming prospective projects across North America would also be much more streamlined as a result of further learnings from the Montreal investment experience.

2.3 Market Context

There is debate over how to best price the products produced through these decarbonized processes across manufacturing industries. A company that manages to reduce costs can either gain market share through a greener product that is made through processes that generate higher productivity or increase margins by pricing green products at a premium.

It is not clear, however, whether customers are willing to pay a green premium. Given that a company is meeting their ROI targets on a project, they do not necessarily need to increase prices. However, it is typical to associate decarbonization and sustainability with increased costs, even if this can be offset through productivity gains achieved through upgrading machinery or similar investments."There is a misconception that going green means cost increases but sustainability can be about saving money." suggests one architect of the project.

In situations such as this, the most successful business strategy may instead be offering a greener product at the same price to attract more customers and expand market share by "respecting people's way of life and giving them a better alternative" to existing products, rather than pushing more expensive green products while curtailing alternatives.

3. Results and Analysis

3.1 Explicit and Implicit Motivations for Investment

From the global CEO downwards, Saint Gobain's strategic outlook is focused on "light and sustainable construction"; achieving better performance with less material and energy. This is understood as a "differentiator" from competitors that is "also the right thing to do". This decision was ultimately motivated by emphasis on carbon reduction by senior executives which "empowered [the team] to come up with projects." This culture encouraged an energy engineer in the North America office to explore the possibility of a new decarbonized process in the Montreal facility.

The project depended on public subsidies and productivity improvements to reduce capital and operational expenditures. Grants made available by the Government of Quebec were crucial for reducing capital expenditures (CapEx). These grants vary significantly as a fraction of overall project expenditures, up to 75 percent of the total upfront project costs. These are not needed for every such project, such as those with smaller up front investments such as implementing Variable Frequency Drives, a machinery upgrade that can be implemented to reduce electricity use. Larger projects also have longer payback times and demand more internal resources.

Typically, projects such as the one in Montreal which aimed to reduce natural gas usage require upfront support given their larger relative costs. This project received 40 million dollars in subsidies to support total capital expenditures of approximately 160 million dollars – a rate of 25 percent public to private expenditures.

However, operational expenditures are by far the bigger hurdle compared to CapEx. One of the key architects of the project emphasized that "grants help with CapEx and get projects off the ground but getting the project done requires [addressing] OpEx." Power costs needed to come down to a range where they would be near to competitive with natural gas. In the best case scenario, hydropower was available at three times the cost of natural gas, while the worst case forecasts had electricity costing about 15 times more. Three factors were responsible for closing this gap.

First, a carbon tax implemented in Quebec slightly improves relative costs by making gas more expensive. Second, energy efficiency measures have reduced 30 percent of the energy costs compared to the pre-upgrade baseline. The Montreal facility was long due for improvements that promised to greatly enhance productivity, both by expanding capacity to process a higher volume of orders and upgrading aging equipment. The decarbonization investments were implemented alongside upgrades that generated a 40 percent increase in production. This significant increase in output would be more than met by market demand for the product, which provides a strong incentive for the project as a whole.

There is a 25 percent difference in efficiency between Saint Gobain's most and least productive facilities producing similar goods, due to aging machinery that requires replacement every 20-25 years. This gap was exploited to meet business targets while also decarbonizing, by offsetting the costs of switching from natural gas to electricity with productivity improvements. The project lead suggested that it is "easier to do [decarbonization projects] in old plants versus new ones" because of the way businesses set ROI targets.

Finally, incentives helped to close the remaining gap. The Quebec utility offers tiered pricing for large volume electricity purchasers, with the aim of incentivizing surplus power consumption and attracting industrial clients to use available clean power.

These preferential rates are only available due to surplus power, however, and are liable to be reduced in regions where other uses such as cryptocurrency and AI data centers take up excess demand for power. All told, carbon taxes, incentives, and efficiency upgrades brought the cost of electricity close to that of natural gas.

While Saint Gobain has ROI targets for each project, these vary by business unit, region, and type of project. Projects that offer to reduce CO_2 emissions are also occasionally granted extended timelines for repayment schedules within the company, so long as they do not lead to far higher costs. Most important is correctly estimating electricity related operational expenditures, by correctly estimating future carbon prices and gas prices. A key project architect explained that "timelines are key", while the costs of the full set of inputs to the project are not known in advance, one "need[s] to know costs of electricity" to move a project forward.

Most importantly, carbon reduction technology upgrades sit on a single project-wide profit and loss statement. As a result, they are most attractive if their costs can be offset by productivity improvements. If those improvements are made separately, they can no longer be claimed as part of a carbon reduction project. In the case of a heat recovery upgrade at a plant elsewhere in Canada, for example, mechanical improvements were made ahead of a potential energy efficiency upgrade, which subsequently could no longer be justified under the same profit and loss statement. Similarly, a project very similar to the Montreal plant upgrade took place concurrently in the United States. This plant achieved a 25 percent efficiency upgrade, without electrifying at the same time. Once the efficiency gain was realized, it can be harder to justify further near term decarbonization upgrades at the same facility.

One consequence of this observation is that assessing the returns on investment of a decarbonization technology in isolation will not provide a full picture of its prospects for adoption. Understanding the trajectory of decarbonization involves assessing market conditions that either provide or eliminate opportunities for firms to pursue larger expansion projects that create fiscal room for decarbonization investments.

3.2 Public Policies and Carbon Accounting Rules

The Government of Quebec's ministry of environment and climate change has several grants in place that enabled this project to succeed. Most important was the Ecoperformance program, which subsidizes capital expenditures involved in the transition to clean energy sources. Similar programs, such as the Emissions Reductions Program in Alberta, are technology neutral and reward efficient and cost effective upgrades. The project proponents at Saint Gobain felt that programs such as these conducted "thorough reviews" such that those who did not receive a grant felt that it was given to those who were more qualified, compared to other policies that reward only those with "new, flashy technologies".

Our interview subject also credited returns under the cap and trade program as a helpful proposal and supported work to implement a carbon contracts for differences plan that would set a fixed future carbon price to overcome uncertainty.

Power availability is also crucial. It is not evident that utilities can always provide enough power at a cost that works for the companies. In Quebec, a long term contract with upfront payments enabled the project to proceed. In other cases, studies just to determine whether it will be possible to deliver power can take up to 24 months.

The project architect also recognized the political implications of these projects. With a utility or provincial government, success requires everyone to be "aligned and wanting it". This "takes a ton of work" and can be cyclical, changing with political dynamics as they evolve.

3.3 Role of technology and digitization

In North America, Saint Gobain is pursuing digitalization of its production lines, achieving advanced smart manufacturing on regular lines without having to do significant overhauls of existing factories. This is enabling continuous data capture that allows the company to fine tune processes. Seventy sensors across a production line can provide continuous data for 6 months, which is plugged into a model that generates energy savings. Given the recent attention focused on artificial intelligence, these features are now being promoted more, but they have been an important part of enabling decarbonization upgrades for several years.

3.4 Changing workforce

While electrification is not leading to a demand for new skill sets among operating staff, the digitalization process is more likely to require newly skilled employees in the coming years. Saint Gobain leaders believe additional employees will be needed to support and manage digital upgrades, while the company only has a few people centrally so far equipped to assist with digitalized operations.

In heavy industry manufacturing, they anticipate that AI is not going to replace people but rather is going to help with better planning, and more efficient equipment use, such as through predictive and more dynamic maintenance based on tracking performance and machine learning analysis. The workforce will need to be upskilled to understand and implement these new opportunities.

4. Conclusion

Saint Gobain has committed to reach net zero emissions by 2050, advancing eligible projects from the ground up in places where operational expenditures, driven by the relative costs of clean and conventional energy sources, are not prohibitive to new investments. The Montreal facility represented an opportunity to increase production while reducing emissions.
This is difficult to achieve elsewhere, particularly if decarbonization is pursued without simultaneous productivity improvements, such as regular equipment upgrades, which offset the costs of decarbonization.

Ensuring parity with conventional OpEx was far more important than CapEx when advancing the project. Energy efficiency improvements, subsidies from the Quebec government, and large-scale power availability helped to bring clean energy costs down to an acceptable level when compared to natural gas. Because of these incentives, Quebec now has a state-of- the-art leading facility, as does Norway. Similar investments have not been made elsewhere, where energy efficiency upgrades were made without achieving zero carbon targets, underscoring the opportunity for investing in advanced manufacturing technologies and green production under the right conditions.

APPENDIX 5: SIEMENS FORT WORTH AND GRAND PRAIRIE CASE STUDY

1. Introduction

Siemens is a multinational conglomerate based in Germany focused on industrial, transportation, energy, and building technologies. In Fort Worth and Grand Prairie, Texas, Siemens facilities belong to the Electrical Products division and are focused on producing power distribution switchboards and other electrical products involved in safely supplying and monitoring power for commercial and industrial buildings. Siemens has committed to achieving net zero carbon emissions across its value chain by 2050, with absolute scope 1 and 2 GHG emissions reduced by 90 percent by 2030, relative to a 2019 benchmark. This goal is to drive a number of downstream initiatives across their global operations, including by shaping the development of a new net-zero facility opened this year in Fort Worth, Texas.

In Grand Prairie, a brownfield site for industrial electric switchboards and switchgear has been pushed to its production frontier by the recent rapid expansion in data center construction driven by investments in artificial intelligence (AI). It happens to be the case that the facility required significant upgrades just as the market for their main product exploded, enabling sustainability to be part of their growth strategy in responding to this demand. While the facility has historically been adapted for custom, low-volume orders for a variety of products including low-voltage switch gear and electrical breakers, the recent AI boom has customers demanding higher throughput of the facility with lower lead times and costs.

The Fort Worth plant is a greenfield site being developed to respond to these rapidly changing conditions which was announced in 2023 and opened in March 2025. It is organized for larger volumes of standard engineered-to-order electric switchboards for data centers. The facility has also been set up to take on work that has returned to the US from Mexico as a result of US tariffs. In exchange for delivering faster production volumes with lower costs, they require clients that can commit to locking in orders for several months and large minimum order sizes of switchboard sections parts. The facility was built to serve large data center customers who demand faster production volumes with lower costs, setting up the close partnerships and capabilities to act as a Tier 1 supplier that can evolve its products as requirements of server racks change.

This rapid surge in demand for Siemens electrical products created an opportunity for Siemens to build on its reputation as a leading sustainable manufacturing company, responding to both internal executive pressure and company goals as well as client expectations to make upgrades that reduced emissions while expanding production to meet surging demand.

2. Background

2.1 Powder Coating for Electric Switchboards

The lion's share of Scope 1 and 2 emissions involved in manufacturing electric switchboards involve powder coat painting the metal components that house the electrical products. Powder coating involves a six-step process: individual metal pieces are suspended from metal hooks by hand, are pre-treated to remove protective coatings and oil, dried off in 250-degree Fahrenheit ovens, cooled at precise humidity settings, powder sprayed with industrial paint, and then cured for 25-30 minutes at 400 degrees Fahrenheit.

This process traditionally required natural gas-powered furnaces that made up 80 percent of the facility's natural gas consumption. Other demands for natural gas involve building HVAC systems and forklifts that operate inside the facility. In 2021, Scope 2 emissions were 4,263 MtCO2e, or 1,662 MtCO2e considering the Renewable Energy Credits (RECs) purchased to offset emissions.

Embodied carbon in the steel and copper materials in the switchboard panels are considered under the company's 2050 goals. Siemens procures lower emissions steel and copper wherever possible, and sends scrap materials, such as waste cut outs from copper and steel sheets, back to suppliers for reuse and receive scrap proceeds.

2.2 Siemens' Product and Process Innovations

The Siemens facilities implemented four major upgrades, focusing initially on a small number of high-impact initiatives and moving gradually to several smaller incremental changes. While the Fort Worth facility has been able to start from a clean slate, ensuring it has zero onsite emissions, the Grand Prairie facility has had to adopt upgrades without disrupting production or outsourcing components of the production process that are more difficult to decarbonize.

In both cases, electrifying the paint line was the investment with the greatest carbon impact (15.5kt CO_2/yr saved), and was followed by installing electric HVAC systems (5kt CO_2/yr saved), including a 400-ton heat pump and 1200 ton water cooler. Onsite energy generation such as a solar voltaic system was not installed in Texas because the business case was relatively weak where grid electricity costs are 60% lower than in jurisdictions with higher electricity costs, such as California (11¢/kWh including clean energy credits vs 28¢/kWh). In Pomona, California, Siemens did install solar energy to power a similar facility.

Subsequently, both facilities in Texas have implemented smaller impact initiatives such as purchasing electric forklifts, installing EV chargers, and setting up third party contracts with suppliers to handle emissions intensive processes that could not be decarbonized, such as cleaning the painting hooks. The hooks hold up individual metal pieces during the painting process and get coated with thick layers of paint that must be melted off with a high temperature furnace or blasted off with abrasive media.

Siemens executives argued that shifting these most difficult to decarbonize operations off-site (from Scope 1 to Scope 3) to achieve net zero status is sensible given that upstream suppliers "are the experts in their own product [paint hooks] and know best how to innovate to reduce the emissions." The Strategy and Process Technology team is conducting research into how to reduce this small fraction of company emissions (see below) and is willing to pay for an onsite carbon-free cleaning process if one were established.

2.3 Siemens' market context

Siemens is seen industry wide as a leader in sustainability and the electrical products division in particular is 2-3 years ahead of their internal corporate emission reduction goals. This has contributed to their contracts with major U.S. based data center clients, a business relationship that is driven primarily by Siemens' reliability and ability to provide wraparound maintenance and support services for its systems.

While their clients are not willing to pay an explicit green premium to subsidize Siemens' sustainability investments, Siemens attracts clients that want sustainable manufactured products and cutting-edge technology deployed in their manufacturing processes. Rather than a specific price point or new degree of market access that can be quantified against their decarbonized process, Siemens aims to uphold its reputation as a high-quality, sustainable producer relative to its competition. The greater demand for their products has made clients somewhat less price sensitive, particularly given that they can offer improved per-unit costs at the greater scale demanded for data centers relative to other clients.

Within a facility, paint line electrification adds a third of a percent to annual operational expenditures. While global leadership drives the decarbonization agenda, actions are taken by plant directors. Facility-level leadership is expected to drive innovation at the plant level while meeting plant level profit and loss objectives. As a result, they push their teams to find productivity improvements that make up for the added costs.

In context, higher paint process costs are a small fraction of the overall operational expenditures. Sixty to seventy percent of this cost is for material inputs such as copper and steel, and of the remaining thirty percent, labor is the most significant. Power costs, including those incurred from decarbonization, lie in the top ten line items but likely represent no more than two to three percent of the overall operational costs.

3. Results and Analysis

3.1 Explicit and Implicit Motivations for Investment

According to Siemens executives, three levers allowed the projects to proceed. First, the demand boom for electrical products driven by the AI data center buildout from 2022 onwards led major clients to apply pressure to Siemens leadership, stressing the importance of expanding production. This effort was successful at convincing Siemens US executive management to build a brand new facility in 2024 and modernize via the Grand Prairie upgrade project. Phase 1 of the new Fort Worth facility was rapidly constructed to begin operations in under a year. Second, these customers are interested in sustainability, where Siemens has a competitive edge. They often request to visit and see the carbon-neutral facility, and it helps them with their internal decarbonization goals as they rapidly expand production. Finally, the Grand Prairie facility paint line was reaching its end of life and required significant maintenance and HVAC energy costs to continue operating without replacement, motivating a switch to a more efficient and carbon neutral system.

Nonetheless, all Siemens projects need to achieve an internal hurdle rate of financial viability within three years. According to a Siemens executive, sustainability investments are no exception to the rule. Siemens global operations have funds available to allocate to sustainability projects, however the upgrades pursued at these facilities relied exclusively on returns to be financed through site revenues. Some leeway was provided by allowing the team a significant extension on achieving the return on investment. Investment decisions at Siemens are made according to a well-defined hierarchy based on size, with progressively senior executive sign off needed through different levels of authority.. Capital expenditure allocations are granted based on a business plan that looks at historical performance and estimated benefits with the project implementation.

It is not the case that this was a simple cost-effective investment with few alternatives. Despite very cheap electricity in Texas, it remains more expensive than natural gas – leading to approximately 40-50% higher energy operational expenditures. The higher OpEx costs were built into the Profit and Loss statement for this facility alongside productivity gains from expanding operations and increasing the production rate (e.g.: line throughput increases due to line speed increases and a 23,000 sq. ft expansion in Grand Prairie). The implication of this strategy is that decarbonization upgrades like this one are most feasible for a company with Siemens' accounting structure during a production surge, where demand for their products is leading customers to accept premiums as part of the package of achieving their desired results. The company's accounting processes are conventional among other large producers, suggesting that this trend is likely to be replicated across the industry.

When asked why their leadership did not opt to pursue the expansion minus the electrification to achieve larger margins, the executives we interviewed suggested that continuous improvements will enable lower operational expenditures over time; aspirationally, this would enable the decarbonization investment to "pay for itself" given the productivity improvements involved with expanding the facility. Unpacking this claim in subsequent interviews revealed the crux of the sustainability challenge for this organization.

When the global leadership issued its initial decarbonization directives, it did so with a top-down approach that then delegated implementation investment and strategy to its respective operating businesses.. After sharing a detailed accounting of the costs of HVAC, paint line, forklift upgrades, etc. it provoked a serious reflection on the cost of sustainability actions, as the sites in Texas are among the first to fully tackle Scope 1 reduction measures. Siemens has since been openly sharing its learning across its sites, with customers and industry events.

The company's own sustainability goals have led Siemens to not expand or update its plants using natural gas-based technology. Even with the substantial investment and operational costs, executives suggested that global leadership "would never sanction" a similar expansion plan using natural gas. A plant in Mexico asked for funding for a natural gas-based expansion at the same time as this project was proposed and was directed to instead meet with the Texas team to study their process method. The productivity improvements involved in the facility expansion and the greater standardization of products demanded by data centers enabled greater volume and less customization, and hence lower unit costs. This created accounting headroom relative to Siemens' standard ROI considerations and made increased operational expenditures acceptable both to senior leadership and to plant directors. The project's success has led leadership to encourage other Siemens facilities to study and adopt similar trajectories. The project has also been presented to other companies interested in electrifying their paint lines thanks to a consortium-style working group established among like-minded producers.

3.2 Public Policies and Carbon Accounting Rules

This project developed with minimal direct influence from local policies or subsidies. The main interaction with public authorities involved conversations with Texas utility companies to accelerate grid connection times, as the power capacity available for the facility was a significant barrier during the upgrade process. To see greater decarbonization projects, they advocate for policy makers to "incentivize utility providers to improve, grow, and scale their energy infrastructure" and "otherwise leave it to them". The municipal government in Fort Worth was also involved alongside the Siemens Real Estate team in helping Siemens to quickly construct their new facility. This has not been the case in all geographical locations; power availability has delayed or hindered electrification projects in other sites.

Indirectly, energy costs are shaping their decision-making. As the Ukraine war cut off Russian natural gas supply, Siemens' German leadership became more motivated to shift away from natural gas, even in high temperature processes where electrification is more expensive. Given that Germany has advanced the use of hydrogen-powered projects, the Texas team explored hydrogen as an initial option but the lack of supply in Texas made that less viable. Hydrogen would have had to be transported by pipeline from Austin or transported and bulk stored, either option has exorbitant costs. A research team lead suggested that Inflation Reduction Act incentives would have made hydrogen cheaper than electricity, if they had remained in place, however availability of this resource was also a significant challenge. Regarding energy cost risks due to a spike in electricity or unexpectedly cheap natural gas, Siemens' leadership is expecting local executives to sort out emerging issues now that they have committed to this transition, but note that the shift to electricity provides more load control and flexibility, with less volatility in energy cost. More precise controls, energy use monitoring, optimizing start-up peak demands and other options are being explored, and can be supported by Siemens' own technology. In the meantime, they are lowering heating costs by saving energy through greater insulation upgrades.

3.3 The Role of Technology and Digitization

Digitization and automation have played an important role in these investments. This includes metering tracking on the floor at the breaker level, enhanced by AI and soon to be automated to track energy use and production levels. Robots are currently employed to move stuff around the facility and are in a research stage for observing processes using computer vision. Siemens Texas has constructed a digital twin of the entire production process, which is one year from implementation. A major use case for AI is expected to be tracking worker productivity and optimizing both between workers and across production systems.

Overall, research and development in the Strategy and Process Technology team involves commissioning studies with OEMs and academic departments, capacity analysis to serve incoming demand, process technology research, process control systems (e.g., lean manufacturing and safety, and troubleshooting). These areas are generally required steadily throughout market cycles and as a result the team's funding does not fluctuate significantly with investment booms and busts, although opportunities for new projects come with firm-level new projects and demands.

Ongoing research projects are across a wide range of manufacturing process arenas. In the powder coating process arena, one focus involves hydrogen fueling for the paint lines, which seems to be driven by executives' view that hydrogen has potential to play a significant role in decarbonized industrial policies in certain markets, although it is currently not cost competitive in the United States. Hydrogen promises a clean fuel for curing paint, but questions remain about the interactions between paint media and hydrogen. Another area includes the cleaning of paint hooks. They have explored CO_2 and sand/bead blasting, as well as converting the heating of fluidized sand beds from natural gas to hydrogen fuel. At this time, the process has been outsourced, while procurement colleagues continue to search for decarbonized processes at vendors. This includes a willingness by Siemens to potentially pay a green premium for outsourcing services to a supplier with zero emission performance. The team is also investigating internal process alternatives for decarbonized solutions for paint hook cleaning. Outside the powder coating area, process studies range from laser welding to Autonomous Mobile Robots and Autonomous Guided Vehicles (AMR/AGV) implementation. Finally, AI is being adopted in manufacturing coupled with a series of data analytics projects. Their most promising leads involve anticipating order volumes, demand mix, and using advanced analytics and AI to help anticipate load and material demands.

3.4 Changing Workforce

Siemens has targeted a workforce training strategy managed by engineers in the Smart Infrastructure division, who educate leadership and technical experts on sustainability opportunities within their portfolios, and conduct facility walk-throughs to ask design questions and explore what upgrades might be possible. This training focused on highlighting the areas of highest emissions within the factory so that technical experts can work with their suppliers and seek out options. One leader strongly emphasized the value of this training. He says that "you have to educate and upskill the people who are in charge" of the technical components, and have knowledge of facility specific opportunities, in order to see changes happen. "Now my technical counterparts [at other factories] have someone they can trust [for technical advice on sustainability issues.]"

New employees at the Fort Worth facility undergo extensive in-house training for over 4 weeks, not specific to sustainability, before they are able to work on the line. In-house training was implemented to support the hiring boom associated with the surge in production due to AI data centers. The plant-level leadership sees a broad trajectory of manufacturing coming back to the US, in a minor sense because of tariffs, but largely due to broader pressures to develop more resilient industries and lead in areas such as AI. They now see the challenge as upskilling people to be ready for upcoming opportunities.

4. Conclusion

Siemens global leadership made 2030 and 2050 decarbonization commitments which put pressure on every existing and new facility and supply chain to decarbonize. In Texas, the Siemens electrical products division has found themselves in demand as the boom for AI data centres takes off. Clients have pushed the company to rapidly scale new operations, and importantly, these clients also value sustainability. By increasing the scale of operations and achieving economies of scale from the volume of standardized products required by these clients, Siemens has realized opportunities for decarbonization while continuing to meet their profit targets.

Economies of scale have enabled decarbonization by allowing the company to reach its internal profit targets more easily, and the company has selected to take advantage of the productivity increase associated with lower unit costs to pursue sustainability, even if it comes with additional costs. For this strategy to succeed, it was important that the capital expenditures required to electrify the paint line were aligned with acceptable profit and loss statements across individual plants.

Texas was a fortuitous place to pursue these opportunities. Public authorities enabled growth through quick access to the land, building permits, and electricity required to rapidly expand. The learnings from this initiative are now spreading to other Siemens plants and similar companies finding themselves able to expand operations in a sustainable manner.

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