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Anticipate, Innovate, Transform

The Journey to Decarbonization

CONTENT

THE JOURNEY TO DECARBONIZATION

BY MICHAEL KRUSE, LUIS DEL BARRIO CASTRO, FLORENCE CARLOT, AND OLIVER GOLLY, GUEST EDITORS

The pressing need to reduce greenhouse gas (GHG) emissions through decarbonization is well understood, but the world is realizing how difficult it will be for nations and corporations to deliver on their net zero objectives.

Eight years after the signing of the Paris Agreement, this year's *United Nations Climate Change Conference*, better known as *COP28*, will tell us exactly where we are on the journey to decarbonization and where greater focus is required. Thus far, progress has been mixed, with regions and countries showing varying levels of maturity dependent on political will, investment, and the success of climate-related infrastructure rollouts.

What's clear is that decarbonization is a multifaceted, interconnected process. It requires wide-ranging collaboration between the private and public sectors, energy companies, investors, governments, and end users (both consumers and industrial players). It must be backed by significant funding if we are to improve existing processes and accelerate the rollout of renewable power sources at scale.

Energy and utility players must lead the way in decarbonizing their operations and supporting their customers to do the same. Everyone benefits from achieving sustainability goals, and everyone has a role to play in delivering decarbonization. However, convincing corporate leaders of this and incenting them to become more sustainable can be difficult when it impacts their behaviors and routines, particularly as they grapple with an uncertain economy.

Decarbonization requires transformation and innovation. Increasing energy efficiency from end users and consumers is vital, but it's only part of the puzzle. In addition to increased collaboration and higher funding levels, decarbonization requires innovative thinking and breakthrough technologies. The world needs deep societal transformation in the way people and organizations operate, encompassing everything from transport and energy supply to industrial production.

We must embrace new ways to monitor and mitigate hard-to-abate emissions if net zero goals are to be achieved. Investing in and developing technologies such as carbon capture, utilization, and storage (CCUS) is vital to delivering net zero objectives, as is upgrading energy grids so they can operate in a complex, fast-moving world.

The journey to decarbonization will be neither smooth nor predictable — it requires commitment from all players in the ecosystem and a continual focus on long- and short-term objectives.

IN THIS ISSUE

In this issue of *Amplify*, we measure how far we've come on our decarbonization journey, look at several obstacles to progress, and present ideas for how they can be overcome.

We dive headfirst into these complex topics with our first article, which recommends focusing decarbonization efforts on urban areas. Urban infrastructures cover only about 2% of Earth's surface, but they consume roughly 75% of the world's resources and 70% of global primary energy while emitting 50%-60% of the world's GHG. Ani Melkonyan-Gottschalk and Maximilian Palmié describe the role of urban transportation systems in the decarbonization process and outline a comprehensive strategy designed to increase their overall sustainability. This includes integrating mitigation and adaptation tactics into a unified strategy, prioritizing strategies that go beyond technological improvements, optimizing the performance of multimodal logistics chains by prioritizing energy-efficient modes, and investing in the public-private cooperation necessary for decarbonization to enter a deep societal transformation process.

DECARBONIZATION REQUIRES TRANSFORMATION & INNOVATION

Next, Enrique Castro-Leon advocates for using carbon offsets (COs). He acknowledges the challenges (including several accounting issues) and reminds us that the CO market is immature, making it difficult to compare offerings. Castro-Leon says IT can be leveraged to maintain real-time inventories of carbon assets and could be used to create a system designed to meet specific GHG-mitigation goals. He describes the Scalable Carbon Offset Open Platform (SCOOP) specification currently under development at OptimiLabs, which creates a digital twin that's essentially a computer model of the physical carbon store asset. This allows CO suppliers to easily place their offsets in the carbon market of choice and demand-side entities to discharge their carbon liabilities by either paying a premium buying offsets or paying a broker to carry out a discharge on their behalf. This type of system, says Castro-Leon, establishes a formal linkage between carbon stores, carbon sources of emissions, and trading mechanisms toward global net zero goals.

Our third article examines how CCUS technologies can bridge the gap between current policies and decarbonization targets. Martin Dix and Oliver Golly say CCUS offers a range of business opportunities: capture (designing and building CO2 capture infrastructure as well as operating and maintaining these facilities), transport (via pipeline, truck, or ship), storage, usage (providing CO2 to customers instead of storing it), and CCUS as a service (managing the upstream, midstream, and downstream lifecycle). Dix and Golly detail the key players in the CCUS value chain and describe which players are well positioned to succeed at which market segment. According to Dix and Golly, "CCUS can act as a bridge to the developing hydrogen economy, reducing short-term emissions while infrastructure and capacity mature and providing a long-term solution in areas where hydrogen will not deliver effective emissions reduction."

In our fourth piece, LEAG CEO Thorsten Kramer offers a first-person account of his company's plan to transform from a coal-based electricity producer in eastern Germany to one of Europe's largest providers of green energy. Kramer is honest about the Herculean effort this plan will require, particularly in light of recent fears about his country's electricity supply. But the German government decreed that energy producers must phase out coal by the end of 2038 at the latest, and Kramer believes that: (1) green energy is the only direction worth taking and (2) if you're going to go green you must go big. He describes the ambitious project in detail, gives us a glimpse into the changes his company is already experiencing, and previews his strategy for coping with the changes still to come.

> **MULTIPLE APPROACHES CAN PROVIDE BUSINESS LEADERS WITH INSPIRATION TO ACCELERATE THEIR EFFORTS & SUCCESSFULLY DELIVER ON THEIR COMMITMENTS**

Wrapping up this issue, Senthil Sundaramoorthy, Dipti Kamath, Sachin Nimbalkar, Christopher Price, Thomas Wenning, and Joseph Cresko from Oak Ridge National Laboratory (ORNL) examine strategies for industrial decarbonization, particularly for the six most energy-intensive industries. Almost three-quarters of all industrial GHG emissions in the US come from manufacturers, and the bulk of those come from iron and steel, chemical, food and beverage, petroleum refining, pulp and paper, and cement. Sundaramoorthy et al. assert that "Energy-efficiency improvement is a feasible, low-cost approach that, in most cases, does not require any major change to industrial processes and can bring immediate emissions reductions." Along with statistics from the US Department of Energy (DOE) about potential emissions reductions, the authors describe how strategic energy management, system efficiency, material and lifecycle efficiency, smart manufacturing, and combined heat and power can bring both short- and long-term reductions in carbon emissions.

The articles in this issue of *Amplify* demonstrate the complexity of topics involved in the journey to decarbonization. They also highlight multiple approaches that can be adopted, providing business leaders with inspiration to accelerate their efforts and successfully deliver on their commitments.

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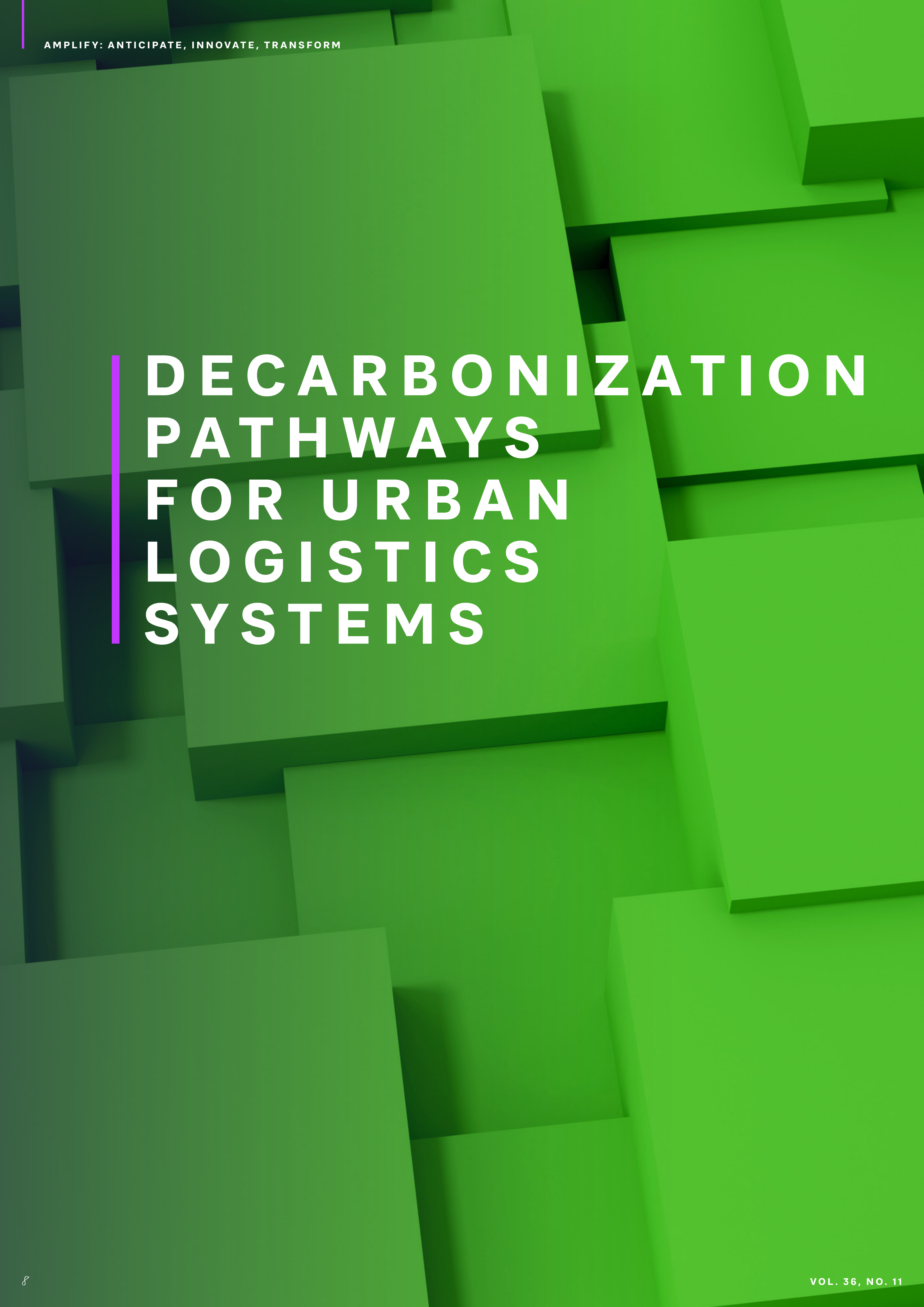

DECARBONIZATION PATHWAYS FOR URBAN LOGISTICS SYSTEMS

Authors

Ani Melkonyan-Gottschalk and Maximilian Palmié

Decarbonization has become a top political agenda in many regions and countries thanks to global warming and the degradation of ecological systems. Decarbonization decreases fossil energy use by disrupting carbon sequestration with economically viable and socially acceptable alternatives.[1]

The largest part of the world's energy supply is provided by fossil fuels (coal, oil, and natural gas), with the greatest share consumed by the industrial sector (including agricultural processes, chemicals, iron/steel, mining, construction, and forestry), the transportation sector (road, rail, air, and water transport), the residential sector (household heating, cooling, lighting, consumer products), and the commercial sector (commercial heating, cooling, lighting, refrigeration, offices, stores, hospitals, and schools).

Decarbonization requires a net reduction in greenhouse gas (GHG) emissions by 80% to 100% by 2100. A decrease of GHG emissions levels by 7% on average per year, consistent with the aim of the Paris Agreement, is required to limit the global average air temperature increase to 1.5°C by 2050. The Paris Agreement asks more than 110 nations to reach net zero emissions, but most countries have not adopted the stringent laws and policies that would be necessary to achieve this.

A few countries have reached negative carbon dioxide (CO2) emissions, including Bhutan and Suriname. Bhutan emits 1.5 million tonnes of CO2 annually, but around 6 million tonnes of CO2 are consumed by the forest cover (which is 72% of the country's land mass), rendering Bhutan carbon-neutral.[2] Even with this favorable progress, the country is still on a decarbonization journey, investing in renewable energy generation and logistics infrastructure, including electric automobiles.

Sweden, the UK, Germany,[3] France, Denmark, New Zealand, and Hungary have adopted legally binding arrangements for decarbonization. Canada, South Korea, Spain, Chile, and the Fiji Islands are among the nations where legalization has been suggested.

The decarbonization process often goes further than a net reduction in GHG emissions, aligning with broader societal goals like climate adaptation, social equity/inclusion, and institutional transitions. Effective, socially acceptable decarbonization strategies must limit costs for industries and households (i.e., low abatement costs), be administratively manageable (i.e., low administrative costs), promote the development and deployment of new technologies (i.e., stimulate innovation), and contribute to broader socioeconomic goals, including the United Nations Sustainable Development Goals (UN SDGs).[4] Thus, during the decarbonization process, fossil fuel–based infrastructures undergo a systemic change, relying on radical innovation in digital technologies, institutions, and societal behaviors. In other words, a new socioeconomic paradigm is created.

FOCUSING ON URBAN AREAS

A significant concentration of economic activities (production and consumption systems), human resources, and resource overconsumption takes place in urban areas. Covering only about 2% of the earth's surface, urban infrastructures consume roughly 75% of the world's resources and about 70% of global primary energy while emitting 50%-60% of the world's GHG.[5]

Rapid urbanization significantly affects regional population distribution, creating various-sized municipalities with distinct economic development patterns.[6] The proportion of the population living in cities is projected to reach more than 68% by 2050.[7]

Diverse patterns in the global north and south drive significant changes in cities and infrastructures, with some regions facing population decline (shrinking cities), some showing peri-urbanization patterns (urban sprawl), and some taking advantage of digital transformations (smart cities).[8,9]

Given the varied urbanization patterns, decarbonization of urban systems will require flexible policy strategies focused on: (1) city cores and (2) embedding suburban and hinterland areas connected with energy and transport infrastructures into a holistic urban ecosystem.

URBAN TRANSPORTATION'S ROLE IN DECARBONIZATION PROCESS

Urban ecosystems integrate urban and rural mobility, production, consumption, and distribution systems. Both material and information flow across corridors of transportation and energy utilities, connecting urban regions into a global supply system.[10]

These flows are regulated by the complex structure of transport corridors. For example, Trans-European Transport Network (TEN-T) aims to develop coherent, energy-efficient, multimodal, high-quality transport infrastructures across the EU.[11] It comprises railways, inland waterways, short sea-shipping routes, and roads linking urban nodes, maritime and inland ports, airports, and terminals. Unfortunately, transportation and mobility systems across these types of corridors are vulnerable to disruptions caused by geopolitical instabilities, intensified global trade, new business models across logistics chains, and more frequent climate disasters.

Meanwhile, urban transportation systems lead to a substantial increase in urban energy demand, accounting for almost 30% of energy consumption globally, mostly from fossil fuels. Urban road transport accounts for 40% of all CO2 emissions and up to 70% of other pollutants (including nitrogen dioxide and particulate matter), highlighting the importance of investments in renewable energy infrastructure, improved battery technology, sustainable biofuels, and synthetic fuels.[12] The transportation sector also causes negative socio-environmental externalities, such as traffic accidents, congestion, waste, and land-use changes.

Acknowledging this, the European Commission developed the European Green Deal, which includes an ambitious policy roadmap for sustainable economic transformation, particularly in transportation systems.[13] According to this policy, logistics service providers must offer sustainable, high-quality, reasonably priced delivery services within increasingly growing and complex supply chain networks while following the EU supply chain law (EU Supply Chain Act).

Beyond the assumed ecological externalities, urban logistics and mobility have widely known issues related to operational efficiencies, including fragmented flows, high delivery frequency, unpredictable demands and returns, and additional investments by fulfillment networks to increase resilience in critical urban infrastructures.

When it comes to internalization of externalities, such as internal carbon-pricing programs or the EU supply chain law, implementation of these measures is generally associated with a high level of administrative efforts, a knowledge gap about efficient decarbonization strategies (especially for international companies acting in regions or countries with different economic structures, political levers, and laws for decarbonization), and various external disruptions like climate-related weather hazards.

THE RELATIONSHIP BETWEEN URBAN DENSITY & TRANSPORT-RELATED ENERGY CONSUMPTION

Different rates of urbanization and decarbonization in various regions and countries cause transport corridors to become a subject of global competition across transportation modes, increasing both ecological unsustainability (high energy consumption and related GHG emissions) and system vulnerability.

The ecological (un)sustainability and vulnerability of transport systems are usually analyzed either by the topological properties of the transport networks (articulation nodes, served by the corridors), which are highly dependent on urban density, or by studying the demand and supply side of the transport chains (flows) to assess the impact of the disruptions for the users, society, and governments at regional, national, and international levels.

Dependence on energy use by transportation systems is reminiscent of the Newman and Kenworthy “urban density and transport-related energy consumption” hyperbola, showing an exponential decrease in transport-related energy consumption with an increase in urban density.[14] This can be explained by the fact that high urban density allows for efficient planning of multimodal transportation systems for both passengers and goods, reducing transport-related carbon emissions.

DECARBONIZATION STRATEGIES FOR TRANSPORTATION SYSTEMS

Urban transportation decarbonization relies heavily on emissions monitoring. Most cities currently focus on Scope 1 (GHG emissions from sources within city limits) and Scope 2 (indirect GHG emissions related to the purchase of electricity, steam, and heating/cooling produced outside the city limits but consumed within the specific boundaries of a city). Communities seriously working toward efficient decarbonization must also consider Scope 3 (all other GHG emissions generated outside the city limits as a result of activities within the city limits) to transform the entire urban ecosystem.

This is already being done by industries that are considering the impactful implementation of the EU Supply Chain Act. Scope 3 emissions should be considered while developing internal carbon-pricing mechanisms to be ahead of political regulations of CO2 pricing, which is currently €30 per ton (about US $32). Forty-four Organisation for Economic Co-operation and Development (OECD) and G20 countries, which are responsible for about 80% of the energy-related global CO2 emissions, had a carbon-pricing score of 19% at the €60 benchmark (about US $64); that is, 19% of emissions are priced at a level that equals or exceeds the benchmark of €60 per tonne CO2.[15]

In 2018, Switzerland, Luxembourg, and Norway reached a carbon-pricing score of close to 70%, acting as leading countries on the transformation pathway. They achieved this score because fuel taxes for road transport are often entirely invested in the road infrastructure; there is a significant CO2 tax for the use of fossil fuels in private households and commercial enterprise; and electricity supply is significantly decarbonized, leading to low industrial emissions.

At the urban level, Oslo, Stockholm, Tokyo, Copenhagen, Berlin, London, Seattle, Paris, San Fransico, and Amsterdam are considered the most sustainable cities in the world.[16] These cities focus intently on energy efficiency, electric mobility, decarbonization of urban logistics, greening buildings, enhancing urban-farming activities, waste management systems, and designing efficient and smart infrastructures.

Digital technologies help companies and communities improve delivery times and optimize supply chains. For example, a project to digitize China-based Huawei’s supply chain focused on mapping real-world objects like contracts and products to the digital world, automatic recording of real-time business processes and operations like cargo transportation, and managing business rules for complex scenarios using digital solutions (e.g., inventory cost accounting and order-splitting rules).[17]

One of the projects in the 2014 United Arab Emirates Smart City program involves tracking, shipping, and delivering imported and exported goods using blockchain technology. Technologies like big data, Internet of Things, augmented reality, artificial intelligence, robotics and autonomous driving, and digital twins are also being implemented to help achieve decarbonization in logistics systems and are being actively used in Dubai Harbour.

In general, technology helps cities design resilient (physical and digital) infrastructure through:

- **Implementing efficient multimodal transport chains,** which means moving cargo in a single container from door to door by combining land transport (road or rail) and maritime or river transport (vessel or barge) in one optimal transportation chain, which is cost-efficient and saves CO2. A good example of this is how UPS and DHL created services along China's Belt and Road Initiative so goods could move multimodally from Asia to Europe.[18]
- **Bundling material flows in multifunctional smart hubs,** connecting transport nodes, subway lines, click-and-collect points, pickup and drop-off points, stores, retail galleries, commercial areas, conference centers, lounge areas, restaurants, shops, office areas, coworking spaces, fitness clubs, housing, cinemas, and underground parking garages. Examples include the Arnhem Central Transfer as a gateway and transport node among the Netherlands, Germany, and Belgium; the Oculus in New York City; Rotterdam Centraal Station, the Netherlands; West Kowloon Station in Hong Kong, China; Anaheim Regional Transportation Intermodal Center (California, USA); and Transbay Transit Center in San Francisco, California.[19]
- **Designing energy-efficient warehouses by applying alternative energy sources and building information modeling.** This technology helps designers simulate and analyze buildings in a virtual environment prior to construction.
- **Implementing hydrogen energy for line-haul trucking.** For example, Toyota Motor Europe used its fuel cell technology to decarbonize the Toyota logistics network, reducing the company's overall carbon footprint and setting it on a path to full carbon-neutrality by 2040.[20] However, the economic viability of this technology is uncertain. It is estimated that fuel cell long-haul trucks can reach total cost of ownership parity (considering diesel fuel prices, road tolls, and other taxes) by 2030 in Europe if the at-the-pump green hydrogen fuel price is around 4 €/kg.[21] This can be achieved by strongly subsidizing the technology, which is not efficient. Thus, proper carbon-pricing programs should be implemented. Some of the largest shipping companies are introducing new frameworks of efficient internal carbon-pricing programs.
- **Leveraging autonomous driving systems, including drones and droid deliveries.** For example, Volocopter offers an additional layer of transportation for passenger and heavy cargo that will be highly efficient in megacities.[22]
- **Applying ultra-quiet equipment and electric vehicles to reduce delivery noise during off-hours operations.** For example, the Eco Truck, launched by Lawsons in the Greater London area, is a 26-tonne flatbed truck powered by a natural gas engine that generates 50% lower noise and 99% fewer particulates than an equivalent diesel engine.
- **Improving traffic and transportation management systems through route optimization and vehicle (re)routing.** For example, Germany-based SEVSAS provides data on priority route networks and restrictions for truck traffic;[23] Tiramizoo offers app-based services to the logistics service providers and municipalities to help them visualize and optimize their last-mile routes;[24] and the Transport for London program used Siemens's real-time optimizer to reduce traffic delay by 13%, which is expected to generate £1 billion (about US $1.2 billion) in benefits by 2036 by reducing delays for all road users.[25]
- **Applying collaborative platforms to be shared among logistics service providers.** These platforms help providers share their resources (e.g., free capacities in warehouses or tracks), which strongly supports decarbonization of urban logistics.[26] The overall goal is a transition from individually managed supply chains to open supply networks enabling structural collaboration. Companies like LOGISTEED and Collaborative Urban Logistics & Transport (CULT) offer a variety of functions to be shared, including order reception, transport, delivery, and consolidation of volume and storage.[27,28]

- **Producing selected components in local additive manufacturing (also known as 3D printing) stations.** Switching from a central factory to local 3D printing lets manufacturers produce components close to their destination. For example, Thyssenkrupp Marine Systems aims to produce components for its submarines in local fjords.[29] Manufacturers can build their own distributed network of 3D printing stations or outsource the production of some components to a third party. Compared to traditional manufacturing techniques, 3D printing can be relatively flexible, which supports contract manufacturers in bundling the production tasks of multiple partners. In addition to shorter transportation distances, local 3D printing arrangements enable component designs that outperform conventional solutions.

RECOMMENDATIONS: KEY ELEMENTS TO ACHIEVE DECARBONIZATION

Even though there are solid examples of decarbonization attempts at company, city, and country levels, a comprehensive decarbonization strategy is needed to increase the overall sustainability of urban logistics ecosystems and decrease vulnerability from external global shocks. Steps in this strategy are:

1. **Integrate mitigation and adaptation tactics into a unified strategy.** We surveyed 20 companies in North Rhine-Westphalia, Germany, about climate mitigation and adaptation in the freight sector and found that companies active in inland shipping, road-freight transport, rail-freight transport, and the courier/express/parcel industry place equal strategic importance on climate mitigation (50.3%) and adaptation (49.7%). However, notable differences were observed in the efforts being made regarding climate protection and adaptation. Nineteen of 20 companies have implemented climate-mitigation measures (although variations exist in the number of measures implemented and level of investment). The survey indicated that as specific GHG emissions increase, so does the level of investment in climate mitigation. In contrast, although climate change has had a significant impact on 50% of the surveyed freight companies, only 30% have invested in climate-adaptation measures. This may be due to a failure to integrate mitigation and adaptation tactics into a unified strategy, particularly regarding tradeoffs and synergies of practices that could improve overall performance.[30]
2. **Prioritize strategies that go beyond technological improvements to effectively address and mitigate the environmental impact of freight transportation.** For example, the growth of overall freight transport outpaces the positive impact of technological advancements in reducing transport-related GHG emissions. In Germany, although there has been an 8.5% decrease in kilometer-related CO2 emissions from trucks since 1995, the continued increase of truck traffic has offset these gains, leading to a significant 23% increase in total direct CO2 emissions from road freight.[31]
3. **Optimize the performance of multimodal logistics chains by prioritizing more energy-efficient modes.** In 2011, the EU outlined a plan on transport and mobility to shift 50% of road freight over 300 km to alternative modes like rail or waterborne transport by 2050.[32] Unfortunately, progress toward this goal has been limited so far. Between 2011 and 2021, there was minimal change in the modal shift potential of long-distance road freight (over 300 km) in containers.[33] Our findings align with this: only 30% of freight companies in our survey are considering modal shift in their climate actions.
4. **Invest in the public-private cooperation needed for decarbonization to enter a deep societal transformation process.** Satellite imagery and remote sensing are valuable for detecting and monitoring infrastructure changes rapidly and frequently (especially in remote regions); gathering data on transportation networks in a fast, affordable, precise way; and for designing more sustainable material routes. However, these technologies are too expensive to be implemented by a single company given the decentralized character of transportation facilities. Additionally, sensor data is often missing from geospatial databases. We need to develop guidelines for the compatibility of geospatial transportation data, prioritize specific transportation security requirements, and establish a transfer hub to rapidly transmit the satellite image results to users.

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LEVERAGING IT TO INTEGRATE CARBON OFFSETS WITH FINANCIAL MARKET TRADING

Author

Enrique Castro-Leon

The recent tribulations in the carbon offset (CO) markets are unlikely to affect the long-term prospects for increased demand.[1] Organizations implementing programs to reach net zero must play the long game with strategic intent.

We've seen the challenges experienced by those selling offsets ("suppliers") and those looking to offset their emissions ("emitters"). Issues vary by asset type but must certainly be addressed if growth is to resume. For example, issues facing forest-based carbon assets include double counting, permanency, additionality, inaccurate measurement and lack of transparency, inaccurate accounting, disregard for ecological and land stewardship considerations, population displacement, and a deficient rule of law for ownership.

Most of these markets are no more than a couple decades old, unlike those based on fossil fuels, which started trading well over a century ago. Thus, any effective strategy must be long term but flexible enough to accommodate changes in the technical and business environment, enabled by informed decision-making.

BloombergNEF distinguishes between behavioral demand and fundamental demand for COs.[2] Behavioral demand comes from marketing campaigns or first-time corporate initiatives; fundamental demand comes from departments or entire organizations treating offset purchases as a cost of business. It was behavioral demand that led to some large corporations claiming they had achieved net zero, without technical basis, resulting in reputational damage and exposure of offset-offerings deficiencies, potentially tainting the entire offsets market.

KYOTO, CARB & COP

The concept of COs was established under the Kyoto Protocol in the United Nations Framework Convention on Climate Change (UNFCCC) to enable countries to meet their emissions targets using the UN Clean Development Mechanism (CDM).

The Kyoto Protocol gave rise to the compliance carbon market, including the EU Emission Trading System (EU ETS), the California Air Resources Board's (CARB) Cap-and-Trade Program, the Regional Greenhouse Gas Initiative (RGGI), and China's National Emissions Trading Scheme (ETS). Compliance markets are managed by government agencies, with compulsory participation by certain entities such as electric utilities.

The 2015 *United Nations Climate Change Conference (COP21)* in Paris enabled the use of market mechanisms and created a voluntary offset market. The compliance market now stands at around US $1 trillion; the voluntary market is around $1 billion.

The 2021 *United Nations Climate Change Conference (COP26)* in Glasgow introduced rules to reduce double counting or overestimation of offsets and improve the quality of credits offered in the market, and a net zero expert group was commissioned to issue recommendations to increase integrity in net zero commitments, with guidelines on how COs should be applied.[3]

COMPLEXITY, RISK & CONTROVERSY

CO application is fraught with complexity, risk, and controversy, which some think is undeserved.[4] Sarah Leugers, Gold Standard's chief growth officer, was quoted saying, "It's frustrating that such energy is being used to criticize people doing something, when the people doing nothing are often let off the hook."[5] COs are seen as an attractive option because they are inexpensive and consistent with the appeals for immediate action at *COP26*, albeit as an imperfect, emerging mechanism.[6]

Emitters compensate emissions with emissions avoided ("credits") or removed elsewhere ("removals"). The assumption is that emissions are global, so it doesn't matter where they happen. However, the cost of compensating an emissions event can vary enormously depending on location. This lets traders take advantage of a cost differential or arbitrage to come up with the most economical compensating transactions, and because there has been no pressure toward quality or transparent offerings, it has become a race to the bottom.

> **MOST CARBON CREDITS ARE TRADED IN THE COMPLIANCE MARKET & MOST COs ARE TRADED IN VOLUNTARY MARKETS**

For the purposes of this article, a CO unit represents the effect of removing one ton of greenhouse gases (GHGs) from the atmosphere, usually measured in CO2 equivalents (CO2e). This sequestration can take place as carbon stored in the biomass of a growing forest or through CO2 direct air capture. A carbon credit represents the avoidance of the emission of one ton of GHG through an industrial process (e.g., substitution of coal with natural gas or wind or solar energy for electricity generation), installing high-efficiency stoves, or through forest-preservation programs.

Currently, most carbon credits are traded in the compliance market, and most COs are traded in voluntary markets, although there is some cross-feed. A compliance market participant short on allowances can purchase them as offsets from voluntary carbon markets, and a voluntary market participant can generate credits from emissions-avoidance programs. Most of the criticism of compliance markets is leveled at voluntary markets, which are largely unregulated, self-regulated, or regulated by nongovernmental entities.[7]

CONSIDERATIONS FOR APPLYING CARBON OFFSETS

The controversy around COs and credits arises from issues of permanency, additionality, and accounting for both sequestered carbon in offsets and avoided emissions in credits.

Table 1 shows a decision matrix for incorporating COs into a GHG and climate-mitigation strategy. Each column shows a course of action for the entity: do nothing, select CO instruments based on emissions avoidance, use short (impermanent) carbon, or use carbon in long-term storage. Note that each consideration may involve outcomes that impact external parties.

"Divergence & uncertainty" in Table 1 refers to the spread between negative and positive outcomes among market participants due to the inherent externalities of emissions. The emitting entity may end up reaping enormous benefits if the externality cost is borne mostly by society, but this has the potential (albeit small) to result in backlash, penalties, stifling regulation, or a long-term

COURSE OF ACTION FOR CARBON OFFSETS	DO NOTHING	EMISSIONS AVOIDANCE OFFSETS	SHORT CARBON OFFSETS	LONG CARBON OFFSETS
Potential for loss & damage to society	High	Medium	Medium	Lowest
Externality cost	High	Medium	Low	Lowest
Moral hazard for emitters	Low	Low	Medium	Highest
Divergence & uncertainty	Highest	Medium	Medium	Lowest
Implementation cost	None	Low	Medium	Highest
Availability	Now	Now	Now	Future

Table 1. Carbon offset decision matrix

negative business environment. "Moral hazard for emitters" comes from the de-risking (i.e., license-to-pollute) effect of COs.

The "externality cost" refers to the cost borne by society due to the emitter's operations. COs are a mechanism to internalize externalities: at least part of the cost of emissions is accrued to the entity, either via market mechanisms through the purchase of offset instruments or by regulatory entities through carbon taxes or credits.

Outcomes for externality costs are essentially the reciprocal of moral-hazard outcomes. Externality cost is lowest and moral hazard is highest when pricing signals make emissions immediately expensive.

It's important to remember the CO market's low maturity level. Before Henry Ford established the assembly line method for manufacturing, there were dozens of manufacturers, each with a hand-crafted offering, made with individually manufactured parts. Vehicle owners had to be expert mechanics (or hire one) to maintain and repair their vehicle. Similarly, current CO offerings are one of a kind, making it difficult to compare offerings.

Purchasers are left to assess offerings and develop risk strategies. For most offset buyers, this work is a distraction from their main mission, and entities that manage this due diligence usually find that doing so delivers no respite from allegations of offset shortfalls or greenwashing (because the goalposts keep moving).

There is a complex supply chain behind every CO offering with an opaque value-added chain — and any system is vulnerable to exploitation when participants don't know where profits are made.[8] In addition, the carbon mass in a tree changes over time. Trees grow, get harvested, and can be affected by fire and other natural disasters, yet offset transactions are treated as a one-time, permanent construct.

The impermanency of the underlying asset cannot compensate for the permanency of emissions that can persist for hundreds of thousands of years. That means emissions liabilities must be registered in a permanent record. If the balancing offset is disturbed by some event, additional assets should be assigned for rebalancing, in a transaction not unlike a margin call.

CARB's compliance market sets aside a buffer pool of forests held in reserve that cannot be negotiated to make up for potential future shortfalls. This program has been criticized as insufficient.[9] The main issue is that this allocation is static and can't factor in change. More precise, dynamic allocations might be possible with better data.

THE NEED FOR IT IN CARBON MANAGEMENT

A recent International Energy Agency (IEA) report states that existing technologies could deliver 80% of the emissions reductions necessary by 2030.[10] The report is referring to technologies like renewables, efficiency improvements, and methane-emissions reductions, but there is a foundational technology hiding in plain sight: information technology (IT).

IT can be used to maintain a real-time inventory of carbon assets, perhaps through a digital twin model as described in the following section. Any carbon-inventory shortfall would be immediately noted and corrected using predefined policies. If the underlying assets are trees, they grow, and this growth could be accounted for in the offsetting ledger.[11]

Researchers are advancing the notion that forestry assets can make a quantifiable contribution to GHG mitigation, even when they are less than permanent.[12] The current practice of equating forestry assets to claim net zero is insufficient because the emissions are permanent, but the offsetting asset is not. Permanency can be achieved (at least from a statutory perspective) through the assignment of backup assets or policies to bring in replacement assets to make sure the liability is covered during the statutory period.

For the CARB compliance market, this period has been set for 100 years. This dynamic suggests that emissions liabilities never truly go away, especially when offsetting is done with impermanent assets. The need for permanent, reliable records that live beyond the organizations that created them demonstrates the need for an advanced IT infrastructure.

IT-BASED CARBON-TRADING SYSTEM

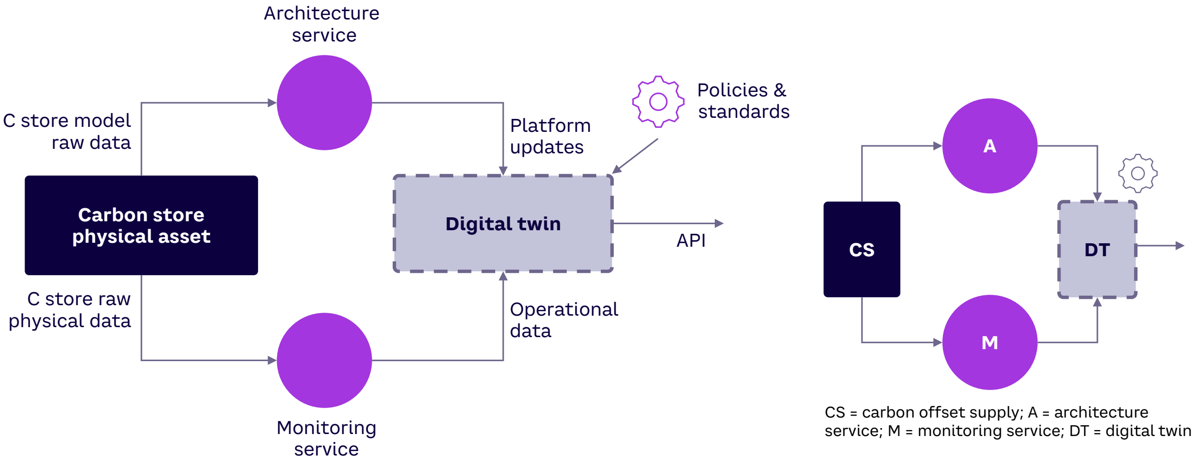
Let's look at how IT could be used to create a system designed to meet specific GHG mitigation goals. Here are some relevant considerations:

- No technological breakthroughs are assumed that would impede immediate deployment. All functional blocks and services are available in-house or can be outsourced as part of normal corporate IT practices.
- Assembly or integration may be needed for certain capabilities, but the components are readily available.
- The cloud service ecosystem can be architected to present a unified, consistent view to users accessing heterogeneous resources.
- IT enables complex strategies, such as building targeted portfolios like asset swaps under Oxford University's recommended offsetting policies or meeting permanency requirements by serially substituting impermanent assets.[13]

In the remainder of this article, we use the Scalable Carbon Offset Open Platform (SCOOP) specification under development at my company, OptimiLabs, for illustration. SCOOP instances are composites of preexisting cloud services joined through application programming interfaces (APIs).

The foundational component of a SCOOP-based carbon-trading system is a *carbon store* or a *carbon supply* subsystem (see Figure 1). In most cases, the physical entity is not directly observable. Data from these sensors needs to be cleaned, correlated, and derated to specific policies to factor in permanency and additionality. Also, storage must be provided to keep a historical record, and a mathematical model must be integrated to produce forecasts if needed. These capabilities, including introspection, are encapsulated within a *digital twin*, essentially a computer model of the physical system.

Digital twins are developed by expert teams familiar with relevant carbon-storing processes in the target physical system and the associated metrology. They can be deployed in-house or by a third-party provider. In either case, the model must comply with applicable policies and standards and is subject to monitoring and audits by regulatory agencies for accuracy and transparency.



CS = carbon offset supply; A = architecture service; M = monitoring service; DT = digital twin

Figure 1. Carbon store subsystem (detailed and abbreviated diagrams)

Digital twins are revised and updated regularly under a preestablished protocol or after certain events. For example, if the underlying carbon store asset is a forest tract, its digital twin keeps track of the biomass in that tract, along with GPS coordinates, as a mechanism to detect and prevent double counting.

The model uses logic to estimate carbon stored in biomass and the soil based on multimodal measurements from drones or aircraft and in-person physical measurements. Growth models for the mix of vegetation in the tract are integrated to enable growth forecasts.

Operational and event data collection are handled by a monitoring service provider, ideally a non-interested third party. In-house data collection may be admissible following policies and with appropriate safeguards.

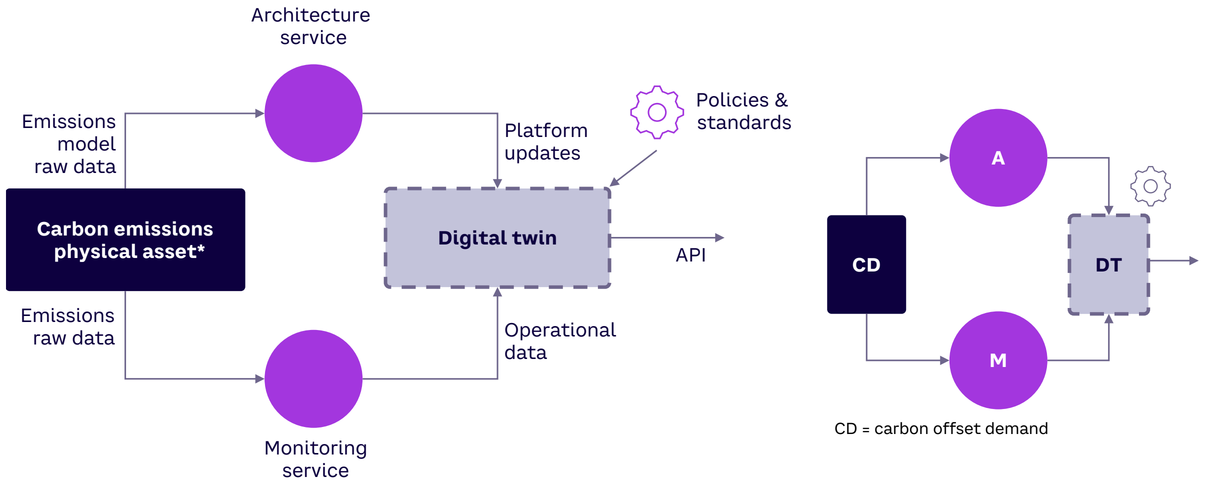
The carbon inventory can be queried through an API. The data provided by a digital twin must meet legal requirements to serve as a foundation for financial securities.

In the SCOOP model, carbon store and carbon emissions (carbon demand) subsystems are represented with the same physical asset/digital twin structure, except that the emissions subsystem now represents emissions physical assets (e.g., data centers) instead of a carbon store (e.g., a forest) — see Figure 2. (Going forward, we use the abbreviated version of the diagrams to make the larger-scale subsystems easier to read.)

The dashed border on the digital twin blocks represents nonphysical, cyberspace, or cloud entities defined by IT. The circles represent business functions or capabilities. Historically, these functions were implemented in-house, but with the cloud becoming ubiquitous, they are increasingly outsourced to third-party providers. These providers bring deep, specialized knowledge and expertise in their fields that operating entities would have trouble fulfilling. They also bring a professional reputation that builds trust into the system, enhanced by the participation of independent standards and financial-oversight agencies (private and state agencies with statutory mandates).

SCOOP is scalable in the sense that multiple carbon stores can be integrated in any number and combination into a carbon market through a CO management system, shown in Figure 3 along with examples of possible industry verticals. Carbon stores within a given market segment may have a common architecture to maximize reuse value.

In general, CO suppliers seek revenue from placing their offsets in their carbon market of choice while demand-side entities seek to discharge their carbon liabilities by: (1) paying a premium buying offsets to discharge or retire their carbon liabilities or (2) paying a broker to carry out the discharge on their behalf. More complex strategies are possible as markets evolve, including futures strategies or fixed-price contracts.



*Representing demand

Figure 2. Carbon emissions subsystem

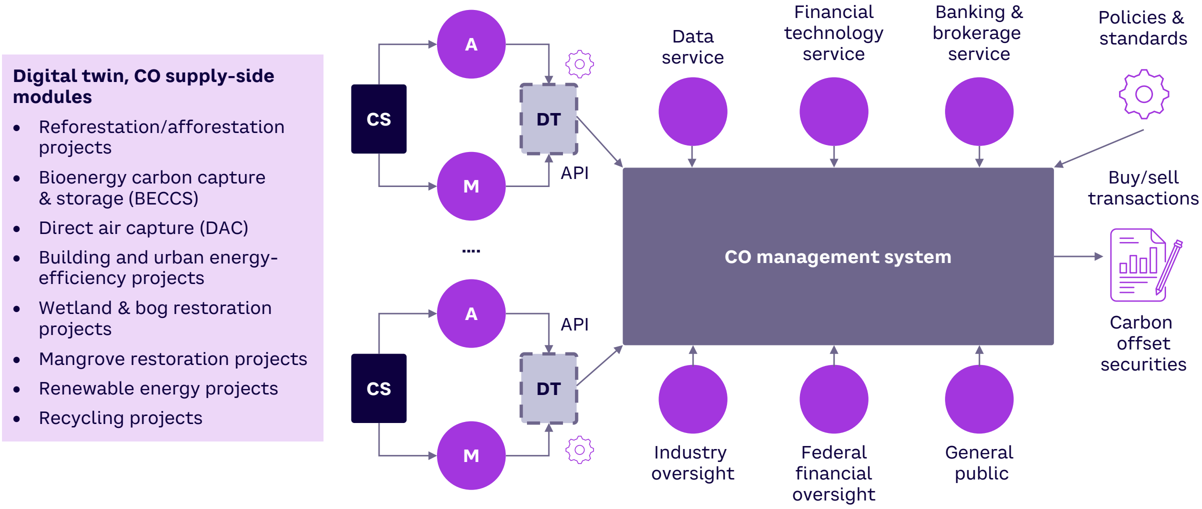


Figure 3. CO market

This type of carbon market becomes an ecosystem that allows one-of-a-kind suppliers to plug in their platform and access a much larger market. It also enables horizontal participation in which emitters seeking to compensate their emissions aren't distracted from their main mission by the need to assess offerings and develop risk strategies. The market also facilitates pooling offerings from several smaller suppliers to satisfy large purchases.

This type of system is agile, modular, and resilient: small changes don't trigger extensive rearchitecting, and the separation of policy from implementation makes it easier to track shifting requirements. As a particular industry gets closer to net zero, certain classes of assets or transactions may be disallowed and new policies introduced (e.g., a requirement that offsets can be applied only to Scope 3 emissions),[14] to prevent the moral hazard of using cheap offsets to continue business as usual.

A similar arrangement exists for the demand side (see Figure 4). Of course, the details for the emission subsystems will be particular to the industries involved. Instead of CO securities, this market can issue paper to trade carbon emissions liabilities or purchase carbon-liability policies akin to those in the insurance industry.

The last component in the trading ecosystem is a CO trading platform accessing multiple instances of markets shown in Figures 3 and 4, enabling emitters and suppliers to participate in a global carbon market (see Figure 5).

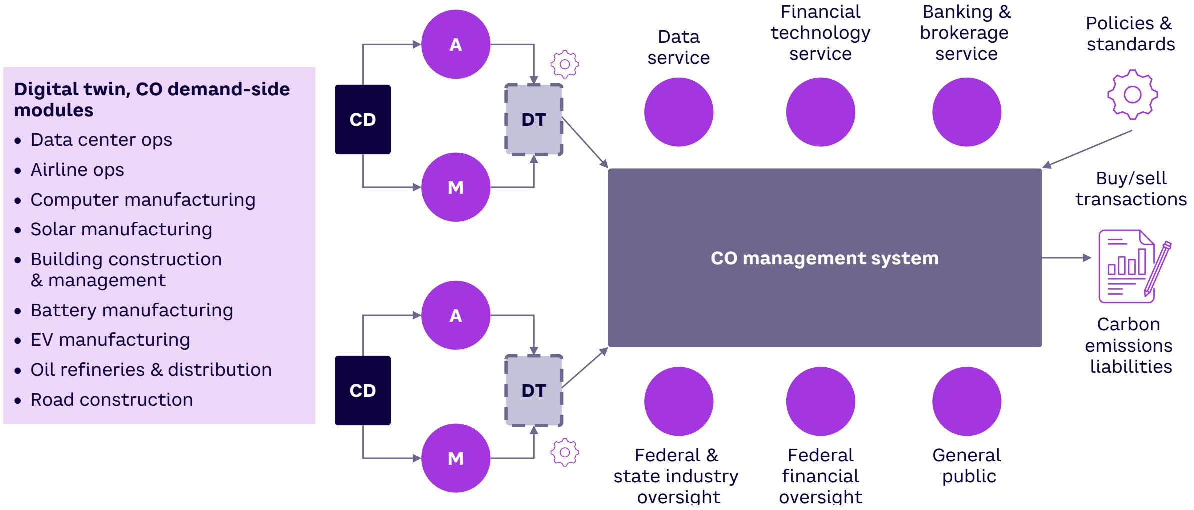


Figure 4. Carbon emissions market

GLOBAL INTEGRATION

How does a SCOOP-based trading ecosystem fit into the UNFCCC Clean Development Mechanism and Paris Agreement Article 6 strategies? It establishes a formal linkage between carbon stores, carbon sources of emissions, and trading mechanisms toward global net zero goals. This can be seen by representing the concepts in Figures 1-5 as a voluntary market stovepipe (see Figure 6). The system can keep track of stores and emissions even if they have been retired, facilitating accounting toward net zero. Transaction records persist even if the original trading partners become defunct.

The stovepipe on the left of Figure 6 applies mainly to voluntary CO markets. Policies are needed to discourage abusive practices seen to date in CO markets. The policies are specific to a region/country and may disallow certain transactions, such as offsetting a large percentage of Scope 1 emissions to prevent offsets being used as a license to pollute or an oil company claiming to be carbon neutral because the emissions from burning the oil produced are assumed to be Scope 3 emissions borne by the buyers.

NEXT STEPS

Critics of CO markets (especially voluntary markets) say they are unlikely to be a long-term mechanism for mitigating GHG emissions, but it's important to remember that COs are just one mechanism toward net zero.

The concept of COs being applied to mitigate global warming has been around since the *Rio Conference* in 1992, but the concept of net zero only gained traction after a relatively successful *COP21* and following a disappointing 2009 *COP15*. "Net zero" as a concept is still interpreted differently across different regions and will continue to evolve. The same is true for COs.

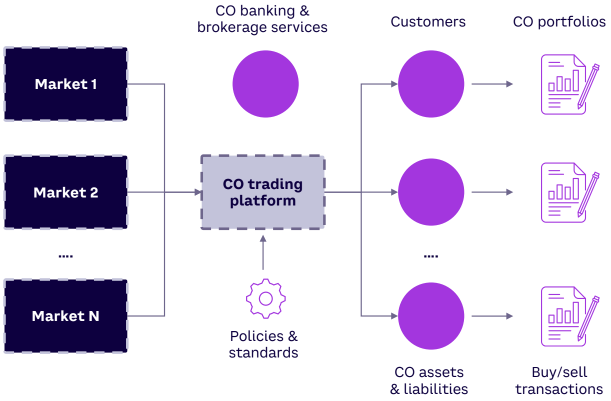


Figure 5. CO trading platform in an integrated CO market ecosystem

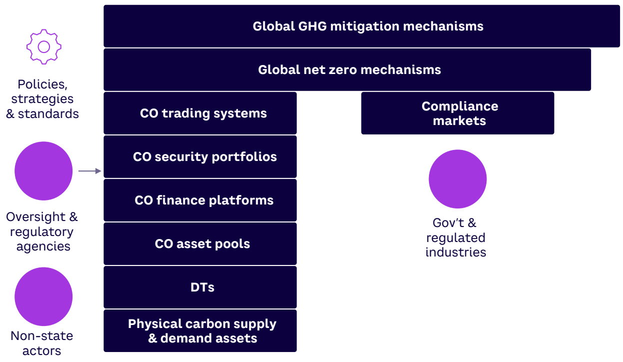


Figure 6. Integration of voluntary market CO-trading stovepipes with global GHG mitigation mechanisms

Corporations must approach this as they would any strategic-planning exercise in the presence of unknowns and risk. Table 2 shows a template for such a plan, inspired by milestones described in "Untangling Our Climate Goals: What's the Difference Between Carbon Neutral and Net Zero?"[15] by the Energy & Climate Intelligent Unit (ECIU). Implicit in this table are decisions such as disallowing the use of credits for Scope 3 mitigation. These items can be changed easily to accommodate local regulations. All actions are integrated with line-of-business activities to make sure the quality of the offsets matches the needs of the application.

MILESTONES SOUGHT	GOAL	ACTION	DESIRED OUTCOMES
Emission reductions	Mitigate Scope 1 CO2 emissions & certain Scope 2 & 3 emissions	Apply science-based best practices under generally accepted standards	Reduction of own emissions relative to baseline with independent verification; actions front-loaded with plan, regular updates, or audits
Carbon neutrality	Mitigate Scope 1 & 2 CO2 emissions with carbon credit & removal offsets	Credit & removal offset mix must meet statutory guidelines; use of credit offsets phased out on a schedule	Carbon-neutral operations with independent verification & regular audits; covers Scope 1 & 2, some Scope 3 emissions
Net zero CO2	Residual Scope 1, 2 & 3 CO2 emissions balanced out with removal offsets	Credit offsets not allowed; removal offset portfolios continuously upgraded in permanency & quality by statute or public guidelines	Initiative extended to cover all of Scope 1, 2 & 3 emissions
Net-zero GHGs	Net-zero initiative now comprehends CO2 & other GHGs	Incorporate technology advances to improve processes & update offset portfolios	Initiative extended to cover all GHGs
Carbon negativity	Develop removal capability that exceeds emissions; start addressing historical emissions	Continuous improvement practices in effect	Steady-state optimized, integrated processes for GHG management

Table 2. Framework for strategic GHG management

Also implicit in Table 2 is the notion of progression toward more stringent milestones in the bottom rows. As the world progresses toward net zero, it can be assumed that most emission-reduction credits will have been taken and that entities that have emissions reductions in their portfolio that were initially acceptable may be obligated to replace them with higher-quality removal assets as recommended by the Oxford Principles. A SCOOP-based IT system can be used to provide a scoreboard to inform and track these corrective transactions.

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[14] In a nutshell, Scope 1 emissions from an entity are direct emissions from operations, such as in-company combustion of fossil fuels. Scope 2 emissions are indirect emissions from purchased energy, including electricity, heat, or steam. Scope 3 emissions are other indirect emissions in supply chains and outsourced activities. For more information, see: "Greenhouse Gas Protocol." World Resources Institute, accessed November 2023.

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About the author

Enrique Castro-Leon is CTO and founding member of OptimiLabs, a start-up dedicated to systems integration and technology innovation. He currently leads a project that formally models carbon offset supply chains across multiple verticals for seamless integration into financial systems, employing service engineering principles. Dr. Castro-Leon also advises a leading US university and research institution on formulating a strategic roadmap for Alzheimer's research. Previously, he worked for Intel Corporation, overseeing the transformation of lab-as-a-service, or lab-in-the-cloud, for both corporate and ecosystem partner engineering labs and supported platform development for server and client processors. Dr. Castro-Leon also led initiatives to integrate platform power monitoring and control capabilities into data center–wide solutions. Additionally, he served as an enterprise architecture consultant advising executive audiences on technology integration and development strategies.

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CARBON CAPTURE, UTILIZATION & STORAGE

BRIDGING THE GAP

Authors

Martin Dix and Oliver Golly

Accelerated plans to drive decarbonization hide an uncomfortable truth: greenhouse gas emissions are increasing in many countries and sectors. Since 2020, global energy-related carbon dioxide (CO2) emissions have grown by 7.2%.[1] Consequently, many nations will miss their 2030 CO2-reduction targets, including such large emitters as the US, China, the UK, and Germany.[2]

Despite major growth in renewables and revitalization of nuclear energy, the expansion of the hydrogen economy, and energy-efficiency gains, there is a widening gap between policies and targets. This situation is particularly acute in areas such as baseload power generation using coal/natural gas, decentralized combined heat and power generation, and industries with energy-intensive processes like chemicals, cement, iron, and steel and food processing. These emissions are proving stubbornly hard to abate, and although clean hydrogen and other sustainable fuels may offer a partial solution, it is unlikely to be widely available until well into the 2030s.

Traditional levers are not enough. To bridge the gap, we must accelerate adoption of carbon capture, utilization, and storage (CCUS) technologies to either reuse CO2 that has been produced or store it securely. This is especially true in Europe, which has some of the world's most ambitious climate targets.

CCUS is widely accepted as a viable technology approach for decarbonization. Its potential has been recognized and endorsed by the United Nations (UN) Intergovernmental Panel on Climate Change (IPCC) as an essential part of the transition to net zero.[3] Importantly, it also creates a range of transformative opportunities for businesses across the value chain.

CLOSING THE EMISSIONS GAP WITH CCUS

CCUS enables both short-term and long-term emissions reductions. It can act as an interim solution for industries like chemicals, iron production, and steel production now, while clean hydrogen supply and infrastructure scales up to meet requirements in the 2030s. It also provides a more permanent solution for industries like cement that cannot fully adopt hydrogen due to unavoidable emissions arising from production processes.

> **TO BRIDGE THE GAP, WE MUST ACCELERATE ADOPTION OF CCUS TECHNOLOGIES TO EITHER REUSE CO2 THAT HAS BEEN PRODUCED OR STORE IT SECURELY**

CURRENT EUROPEAN PICTURE

The combination of its industrial base, far-reaching climate targets, and tightening regulations means Europe has an urgent need to decarbonize. But to date, Europe's progress has lagged other regions, including the US, Australia, and Japan.

This is starting to change. Twenty European countries have either built or plan to build carbon-capture facilities that will be operational by 2030, dramatically increasing capacity from today's annual 1.8 megatons of CO2 captured to up to 102 megatons by that date, as shown in Figure 1. Europe would shift from representing under 5% of global carbon-capture capacity to 28%.[4]

These figures may be on the conservative side, as they are based on announced projects already at the advanced development stages. Further capacity increases are likely due to potential policies from the EU and national governments, driven by pressure to meet climate targets. For example, Germany is expected to introduce a comprehensive carbon management strategy in the coming months that could lead to a growth in local projects.[5] Some experts see an even stronger uptake of carbon-capture capacity: GlobalData forecasts almost 140 megatons of CO2 per annum,[6] and Rystad Energy predicts more than 200 megatons.[7]

Eighty percent of this capacity will be concentrated in five Northern European countries, led by the UK (51 megatons of CO2), the Netherlands (13 megatons), Norway (10 megatons), France (6 megatons), and Germany (4 megatons).[8] These countries plan to use carbon capture in the production of blue hydrogen and/or ammonia, especially the UK and Norway. Further applications vary significantly between countries, based on expected needs:

- **UK** — power and heat generation, especially for gas and biomass power plants
- **Norway** — waste to energy plants and cement production
- **The Netherlands** — coal power generation
- **France** — iron and steel production
- **Germany** — cement production

IMPACT ON EUROPEAN EMISSIONS

The increase in carbon-capture capacity will have an enormous impact on European emissions. Even basing calculations on the conservative 102 megatons prediction, it will correspond to ~10% of CO2 emissions covered by the EU Emissions Trading System (from power generation, heavy industry, and civil aviation) in 2022.[9]

This impact will not be distributed equally across Europe, with countries around the North Sea benefiting most, notably Norway (where it will make up 32% of 2022 emissions), the UK (16%), and Sweden (10%).[10] By contrast, carbon-capture facilities are predicted to represent just 2% of French emissions, 1% of those in Germany, and a negligible amount in Italy, as shown in Figure 2.

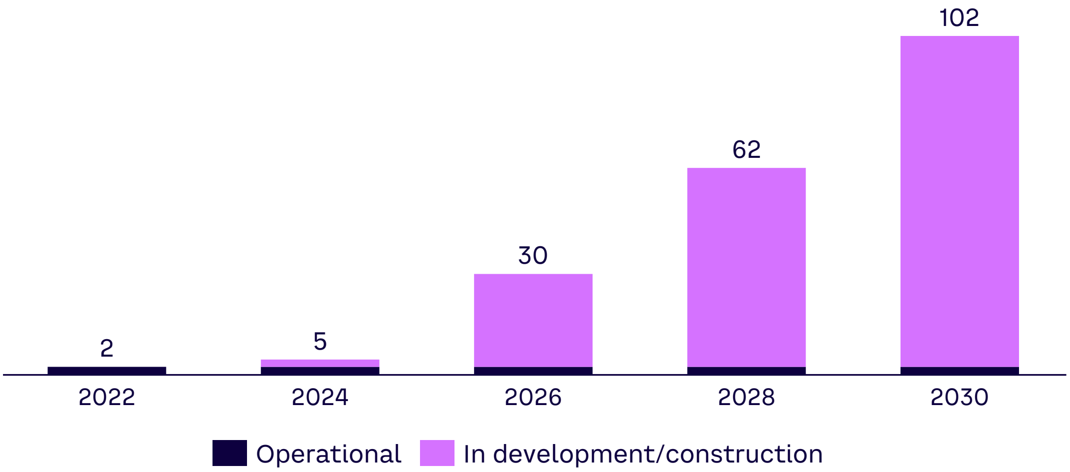

Figure 1. CCS capacity in Europe operational by 2030 by project status (source: Arthur D. Little, International Energy Agency [IEA])

CCUS OFFERS A RANGE OF BUSINESS OPPORTUNITIES TO PLAYERS ACROSS VALUE CHAIN

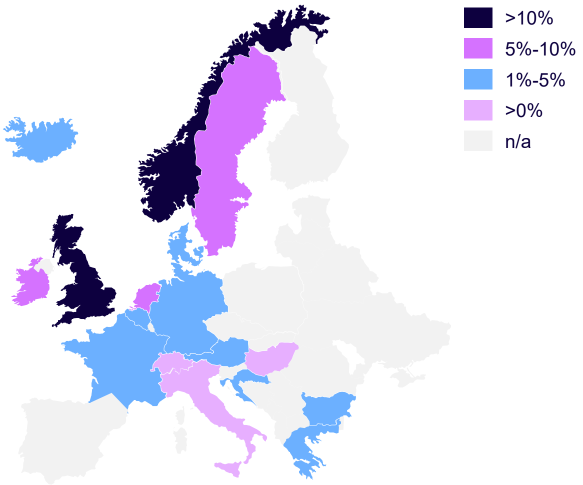

Figure 2. Share carbon-capture capacity (2030) vs. country emissions (2022) (source: IEA, European Environment Agency)

CCUS AS BUSINESS OPPORTUNITY

In addition to emissions reduction across Europe, CCUS offers a range of business opportunities to players across the value chain:

- **Capture.** Responsible for 50%-66% of total carbon-capture and sequestration costs, the capture market requires significant capital investment but offers the highest revenue potential. Opportunities include designing and building CO2-capture infrastructure, operating and maintaining these facilities, and providing trading services for CO2 commodities and allowances under the European Union Allowance (EUA).
- **Transport.** Distributing CO2 via pipeline, truck, or ship (or offering an end-to-end transport/distribution service) provides the smallest relative economic potential, but investment costs are low.
- **Storage.** The design, building, and operation of CO2 storage facilities requires significant investment, particularly if storage is offshore.
- **Usage.** Providing CO2 to customers as an alternative to storing it opens new revenue opportunities.
- **CCUS as a service.** Rather than focusing on individual parts of the value chain, players can manage the entire upstream, midstream, and downstream lifecycle, a significant opportunity.

EUROPEAN REGULATORY DRIVERS

The “carrot and stick” of regulatory costs and subsidies will drive both the volume and the value of the CCUS market. For industrial and power-generation companies in the European Economic Area (EEA), applying carbon capture removes the need to pay for EU carbon allowance certificates under the EU Emissions Trading System (ETS). It also opens new revenue streams if the captured carbon is sold as a commodity or if it generates tradeable carbon-removal certificates (e.g., when processes generate negative emissions such as through captured and stored biogenic carbon).[11]

This means current and future carbon pricing is critical to the economics of CCUS. In the case of the EU ETS, carbon prices have significantly increased since 2020, from a range of €5-€25 tCO2 to €80-€100 tCO2 in 2023. Prices are expected to rise above €110 (around US $116) tCO2 by 2030.[12]

Comparing carbon prices with the levelized cost of carbon capture and storage (CCS) shows it can be a cost-effective option for selected industries if the current levelized cost is below €100 (about US $106) tCO2.[13] This means CCS is particularly relevant for industries with high concentrations of CO2 in flue gas, including producers of ammonia or ethylene oxide, and for newer plants that incorporate CCS from the outset and have large annual carbon-capture volumes.

As technology matures, the levelized cost will fall further while carbon prices rise. This means lower-cost CCS facilities (e.g., new builds and large-scale plants) could be economically attractive in most industries (see Figure 3). However, CCS will still not be cost-competitive without subsidies in certain industries, including iron and steel production and power generation from natural gas.

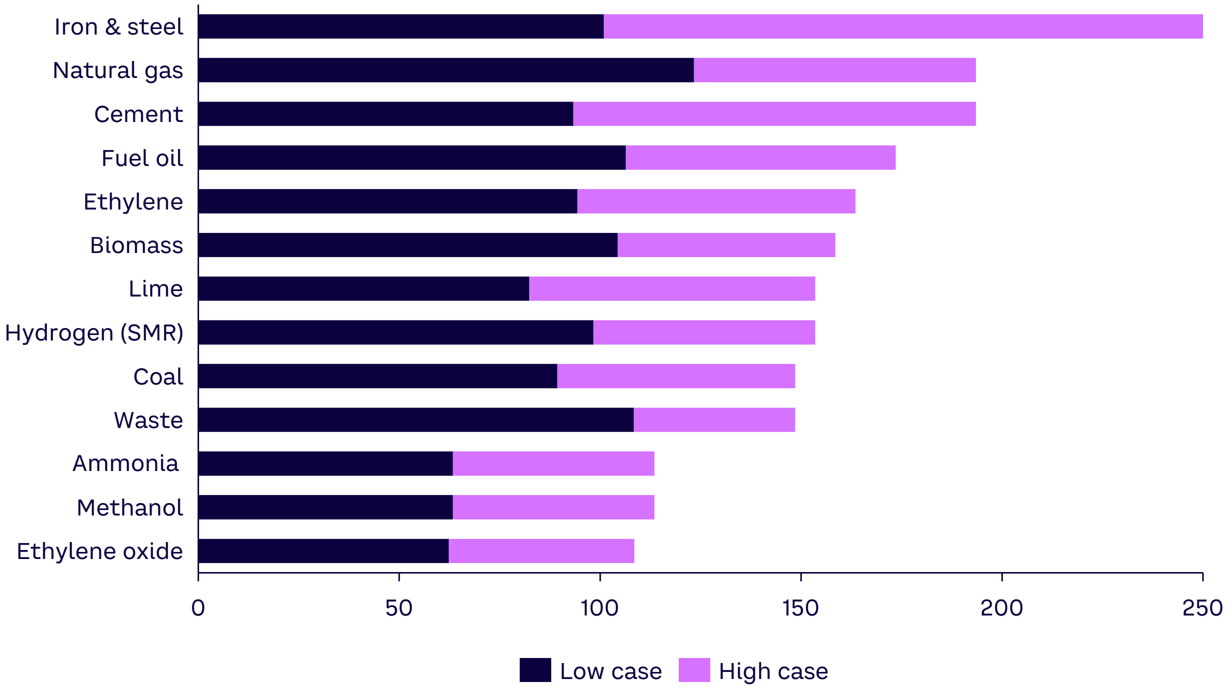

Figure 3. Levelized cost of CCS for selected industries, €/tCO2 (source: Arthur D. Little, IEA, Global CCS Institute)

Industries not yet commercially attractive for CCUS require subsidies. Countries that are focusing on CCUS (including the UK and the Netherlands) have established subsidy programs. For example, the Netherlands applies the same subsidy program (Sustainable Energy Transition Subsidy Scheme [SDE++]) for both renewable energy projects and CO2-reduction efforts such as CCUS.

The Porthos Project, which aims to store CO2 in the North Sea, was awarded half of the 2021 SDE++ budget as subsidies.[14] If other European countries introduced similar subsidy programs to the UK and the Netherlands, it would likely accelerate their local carbon-capture industries.

THE CCUS VALUE CHAIN

Given its accelerating growth, the total European market for CCUS is expected to be between €10-€12 billion (US $10.5-$12.6 billion) by 2030 (according to Arthur D. Little analysis based on conservative predictions of 102 megatons of capacity). The CCUS value chain brings together a wide variety of players across its different stages, and unlocking individual opportunities and accelerating the ecosystem requires every player to understand the specific challenges they face.

Key players in the CCUS value chain include:

- **Capture.** Companies in this space are either energy-intensive industries/power plant operators looking to apply carbon capture to decarbonize their assets or energy utilities serving as an enabler/service provider to customers. Successful players are likely to have strong B2B/industrial customer relationships, allowing them to offer capture as part of an integrated energy strategy.
- **Transport.** These players are usually infrastructure operators (e.g., gas distribution/transmission system operators) aiming to handle the transport and logistics of CO2 onshore and offshore, either via pipelines or truck/ship. This space is best suited to companies that have infrastructure in place and already operate in adjacent areas.
- **Storage/usage.** Storage opportunities abound, especially for oil and gas companies with a combination of project management capabilities and access to storage sites like depleted gas fields. Suppliers must build relationships with companies looking to incorporate captured carbon in novel products, such as e-fuels or green building materials.

- **Enablers.** These include companies that can provide technologies and services (e.g., plant engineering or maritime logistics) that act cross-functionally on all levels of the CCUS value chain, along with suppliers of products and services and policymakers that can shape the role and market uptake of CCUS. Success as an enabler requires building effective partnerships with players across the value chain and strong project management capabilities.

BUILDING A STRATEGIC ROADMAP

To unleash the potential of CCUS, each competitive segment must take specific success factors into account.

CAPTURE

- **Energy-intensive industries and power plant operators.** These players must be able to compare the short-term/long-term role, potential, and cost of CCUS in decarbonizing their assets and operations with alternative pathways such as hydrogen. Given that the market is still in development, effective scenario planning is essential for strategic decisions. These what-if scenarios, which also cover potential alternatives to CCUS, must be combined with signposts, such as changes in the regulatory landscape, EUA price developments, and technological breakthroughs. The results of these exercises can be used to generate no-regret decisions now and decarbonization roadmaps and investment decisions down the road.
- **Energy utilities.** Energy utilities are ideally positioned to support their business clients in effectively applying CCUS. To achieve this, they must understand the value the CCUS market provides and determine the most attractive business opportunities. To understand market dynamics, energy utilities must build a picture of potential future CCUS demand, broken down by country/region and industry and mapped against a range of scenarios. From that, they can highlight and investigate attractive customer segments with unmet needs, based on factors such as the industry sector and access to CO2 infrastructure. This provides the basis to define a comprehensive business offering that includes a clear view on the best position to take within the CCUS ecosystem (e.g., becoming an orchestrator of partners across the value chain or focusing as an expert in specific areas), outlines attractive opportunities, and highlights required capabilities and partnerships.

TRANSPORT

- **Infrastructure operators.** Infrastructure companies need to identify relevant upstream (capture) and downstream (storage/usage) partnerships. Achieving this requires defining key partnering criteria and using these to carry out an effective target search across the ecosystem. For upstream partnerships, such as energy utilities, these criteria could include access to relevant customers and the availability of critical capabilities to further expand their footprint in the CCUS market. For downstream partnerships, such as with oil and gas companies, key criteria will be the availability of (or access to) storage capacities. As growing demand leads to less available storage later in the 2020s, securing early strategic partnerships with storage providers could be critical to success.

STORAGE

- **Oil and gas companies.** In Europe, almost all planned CCUS storage capacities are being developed in the North Sea, primarily by oil and gas companies, who are the gatekeepers of offshore storage facilities. To ensure there is sufficient carbon storage to meet accelerating demand, these companies need to quickly and effectively develop suitable storage sites. To do this, they must focus on capabilities like effective project-site scouting (locating sites with high potential, such as depleted gas fields), local stakeholder engagement (creating strong relationships, especially with policymakers and regulators in the permitting process), and developing relevant in-house capabilities (especially project development).

ENABLERS

- **Suppliers.** A robust supplier landscape is critical for providing the technologies and services that will enable the CCUS market to achieve its potential. Suppliers need to quickly ramp up capacity to deliver projects and meet growing demand along the CCUS value chain. Suppliers must closely monitor market growth and scale their operations; this will require large-scale investments that, given the early stage of the European market, will generate financial risk. To overcome this, suppliers should form strategic partnerships with relevant market players to underwrite their investments, safeguard capacity in planned projects, and jointly develop and innovate key technologies, sharing the risks and benefits.

- **Policymakers.** Policymakers play a key role in ensuring the CCUS market develops and grows in line with projections to deliver its decarbonization benefits. Given the relative immaturity (and cost) of CCUS, regulatory frameworks and subsidies are key to growth at both regional and country levels. These frameworks should focus on managing costs (especially investment requirements) until this still-immature technology is more cost-effective to deploy. One option is applying effective subsidies like those in the UK and the Netherlands, helping to unlock CCUS's decarbonization potential.

CONCLUSION

As countries struggle to reduce emissions, CCUS is becoming a key accelerator in the shift to net zero, particularly in sectors where emissions are proving stubbornly hard to abate. CCUS can act as a bridge to the developing hydrogen economy, reducing short-term emissions while infrastructure and capacity matures and providing a long-term solution in areas where hydrogen will not deliver effective emissions reduction.

The growth of CCUS promises a financial opportunity alongside an environmental one, delivering new revenues to players across the ecosystem. This is particularly true in Europe, which is shifting from a CCUS laggard to a leader, in part to meet the region's stringent climate targets. However, for the European CCUS economy to unleash its potential, every player, from utilities and technology suppliers to regulators and policymakers, must act now, putting in place effective strategies, building capacity, and forging partnerships across the ecosystem.

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About the authors

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BLUEPRINT FOR GERMANY'S ENERGY TRANSITION

THINK BIG, THINK GREEN

Author

Thorsten Kramer

Energy supply in Germany is in transition. And nowhere has the pressure to transform been as visible as at LEAG in Lusatia, Germany. Until recently, energy from LEAG (the country's second-largest electricity producer) was almost exclusively sourced from lignite. But in 2019, the government decided that Germany would phase out coal by the end of 2038 at the latest — LEAG faced a slow but steady demise.

When I started as LEAG's CEO at the beginning of 2022, I was immediately excited by the potential of the traditional eastern German company with its 7,000 employees. It quickly became apparent there was only one chance for the company to continue playing a key role in Germany's future energy supply: *LEAG must go green*.

We believe the inevitable end of conventional fossil fuel energy must be followed by a complete transition to renewable energy, with a focus on wind and photovoltaic (PV).

ENERGY SUPPLY UNCERTAINTY

Lusatia's position in this endeavor is unique. We have more than 33,000 hectares of post-mining land that is largely low conflict when it comes to setting up PV and wind systems. We also have four lines feeding into the transmission system, a long tradition of energy production in the region, competent specialists in our sphere, and a clear will to change (provided the plan is well thought out and solid).

Nevertheless, our announcement about turning LEAG into a pioneer of renewable energy that would be unique in Europe came at a time of uncertainty. The open-pit mining and power plant teams were already under extreme pressure from circumstances caused by the pandemic. Russia's war with Ukraine exacerbated the situation. To safeguard the country's energy supply, reserve units that had been shut down were brought back online. We sought, and found, hundreds of new employees, who gave their all and remained motivated against the backdrop of a planned coal phaseout.

For decades, Germans had enjoyed a reliable energy supply. Then, the state of electricity and gas supplies became the number one topic of discussion in the country. Hardly a day passed without mainstream media questioning whether Germany's energy supply was guaranteed. It was a common topic at conferences, in discussion groups, and on talk shows. Would we get through the winter? Might we experience a blackout?

At first, this did not seem like a good time to announce LEAG's transformation. In reality, it turned out to be an opportune moment to open a new, secure, long-term perspective for our company in the midst of global uncertainty.

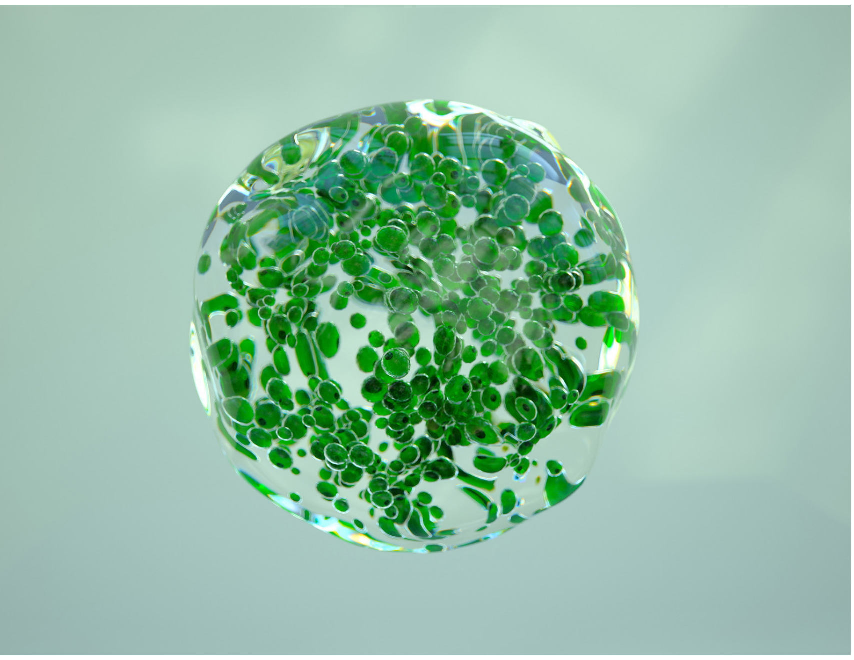
INTRODUCING GWF

By 2040, LEAG plans to produce up to 14 gigawatts of PV and wind energy, build H2-ready power plants with more than 4 gigawatts of output, have 3 gigawatt hours of storage capacity in batteries, and make electrolysis power available. This will create a high-quality, green energy pool of 20 gigawatts.

We named the project GigawattFactory (GWF) because it is unique in Europe in its size and concentration of renewable onshore energy. We plan to invest up to €10 billion by 2030 (about US $11 billion) with the goal of delivering high-quality green energy on an industrial scale.

With large battery storage and electrolysis plants to produce green hydrogen, GWF will generate clean energy that can be used regardless of the season, weather, or time of day. This means baseload green electricity in new amounts and without lags or lulls. Hydrogen-capable gas power plants or pure hydrogen power plants are scheduled to go online by the end of the decade. Documents have been submitted for approval for a large part of these systems, so when important framework conditions (e.g., the power plant concept and electricity market design) are finalized by the government, we can get started.

The new power plants will be built at our existing lignite power plant locations so they can leverage infrastructure already in place, including transmission grid connections. Connection to the gas or hydrogen network in eastern Germany, which has yet to be built, is in the early planning stages. It will also be possible to use the green hydrogen produced for sector coupling for things like municipal public transport or district heating.



GWF combines large amounts of green electricity, storage options, and sector coupling to create a comprehensive, efficient green energy system for an entire region and far beyond. As Lusatia becomes a green energy powerhouse, it can carve out a unique position in Germany and Europe, becoming Europe's special green energy zone.

However, even with a convincing vision and favorable conditions, there are challenging years ahead. The project is complex, ambitious, and dependent on navigating our way through many regulations and external factors, including political decisions. All this takes place during a time of economic strain, tense discussions about secure energy supply, questions about the right energy policy for the future, and the comprehensive transformation of the German energy industry. That's why we need broad support from lawmakers, our workforce, and the general population.

OLD STRENGTHS FOR NEW CHALLENGES

What are the differences between the old and the new LEAG? What has changed? A lot, I believe.

WE ARE SUDDENLY IN DEMAND

For many decades, we were part of an infrastructure that was taken for granted. When Russia invaded Ukraine, everything changed. Suddenly, we, along with other energy producers, were on the speed dial of administrations in Berlin, Potsdam, and Dresden regarding energy supply security. Even though these issues seem more under control now, we continue to receive many questions regarding our business. What are you planning to do? Can you really do this? What do you need? It's a new experience for a company like ours that had generated safe, reliable electricity for decades with no fanfare.

OUTBOUND INSTEAD OF INBOUND

In the past, our business model was clearly defined, both inside our company and among external stakeholders. In this new era, we need a completely different type of dialogue with the public, local and national government, the media, and nongovernmental organizations. New contacts need to be convinced that our intentions and plans are feasible, real, and relevant. An established lignite company suddenly entering the green energy business in a big way leads to a paradigm shift for all stakeholders.

POWERED BY PARTNERSHIPS

We cannot operate many GWF trades and services ourselves, so we'll need suppliers committed to taking an active role. This will fundamentally change the way our company operates, moving from typical contracts to cooperation and joint idea development. Fortunately, eastern Germany has a strong, growing science and research community; many productive initiatives will undoubtedly spring from collaborations between business and academia.

LEARNING TO LIVE & WORK IN PARALLEL ENERGY WORLDS

When we presented our GWF plans in autumn 2022, many asked how LEAG could continue to operate lignite-fired power generation during the phaseout period (which runs until the end of 2038) while promising billions in investment in its green powerhouse. In truth, the two fit well together — coal-fired power generation can finance the transformation to GWF.

That means we are learning to live and work in parallel energy worlds, which poses some problems, especially for long-time employees. Fortunately, we have something that unites everyone, whether they work in lignite or with PV and wind: we supply safe, reliable energy. Indeed, LEAG must be competitive in both energy-production systems. Fulfilling this is hardly business-as-usual. Rather, it's an additional challenge some overlook in the midst of a transformation to newer, cleaner forms of energy.

One thing is certain: we can't afford to forget "old" energy. It's still our core business and is (as mentioned) financing our transformation. We must organize ourselves such that the traditional business can be managed in a highly professional manner and continues to receive the attention and resources it needs. Just because the new areas of our business are more talked and written about than our traditional ones does not mean our present is less important than our future. In parallel energy worlds, both are equally important, and we must clearly convey this to our employees.

A NEW STORY IN RESPONSE TO UNCERTAINTY

Of course, these parallel energy worlds will not last. We will remain an energy supplier, but our work will be completely different. We are simultaneously dismantling, building, and rebuilding. Anyone who does not understand the "why" and "how" of these changes might sow doubt, which will contribute to an environment of uncertainty, especially in an industry used to long-term planning and implementation cycles.

We must keep retelling our story and describing the GWF vision. This can be done with billboards, brochures, and social media, but the truth is that our most important audience is our employees. We need them to take our message home to their families, friends, and community organizations. If the conversations they have there reflect why we are repositioning ourselves, and if the majority of comments about our transformation are neutral or positive, we'll have achieved a major goal. We need the support and expertise of our employees — after all, they are the ones who will build and operate GWF.

It will take time for our story to take hold, just as it will take time for LEAG's transformation and the reasons for it to find its way into the conversations of our employees. But I believe in our story, and we will keep telling it.

TRANSFORMATION INSTEAD OF CRUISE CONTROL

We plan to reorganize our company, bring new energy sources online, and work differently in just 10 years — a blink of an eye in the energy industry. If we achieve this, it will be a transformation of enormous magnitude. We know the destination, and we have a compass, but we don't yet know the exact path because conditions are constantly changing. Here are just three examples:

1. Without a new electricity market design, which determines the profitability of energy production, no manager or shareholder can make investment decisions that run into the billions.
2. Without the consent of local and state government, we cannot build the volume of renewables we need.
3. Without a hydrogen connection (or if that connection is implemented too late), we cannot use H2-ready power plants.

These external conditions will play a huge part in determining the success of our transformation and GWF. Although they are fundamental to our development, our options for exerting influence over them are limited. Fortunately, there are several crucial factors we *can* exert control over.

LEAG TRANSFORMATION SUCCESS FACTORS

Theory is gray; the reality of transformation is colorful. If you succeed in making people attentive and curious, and if you can bring them around to your way of thinking with regard to new goals (even partially), transformation can begin. This is both self-explanatory and crucial. It's why everything I describe below has to do with people and the possibility of winning them over to new ideas. Persuasiveness, equal exchange of ideas, productive debate and dialogue, and clear communications are prerequisites, and no one should underestimate the time and resources required.

AN IDEA WITH LEGS

There is room for debate about the details of how GWF will be implemented, but most people understand that GWF is a unique opportunity for LEAG, Lusatia, and Germany. GWF's purpose must be communicated again and again with both passion and intellect. We must concentrate on the big opportunity: green, safe energy on an industrial scale that will future-proof attractive jobs in the region, give manufacturing and processing companies a reason to locate here, and create a new level of green energy systems for communities in the area. It's important to talk about these opportunities and to refine them: that is what will create the energy needed for our transformation.

ACKNOWLEDGING PRESSURE

We know the lignite business is finite. We also know we can build what the region and Germany need: renewable energy of exceptional quality in large volumes. The need for a medium-term system change in energy supply is beyond question. External and internal pressures are present every day, but I believe piloting, exploring, and conceptualizing has gone on long enough. It is time for action.

At the same time, it is important to acknowledge current pressures and impatience. Employees are willing to fully concentrate on a topic or task if they understand why it is so important to our present and our future. Comprehensive communications and exchange is critical to this undertaking.

CELEBRATING PROGRESS & ALIGNING JOBS

We are all shaped by our experiences, so it's crucial to focus on challenges that have been successfully overcome and to celebrate progress, no matter how small. This is the simple, effective antidote to fear, insecurity, and paralysis. It is also why empirical knowledge is so important: it can strengthen basic confidence in our abilities and potential.

Because of the government's decision to phase out coal by 2038, many employees will leave LEAG, many young people will reorient themselves within the company, and employees with new skills will be added. Lusatia will receive billions of euros to compensate for the coal phaseout, but money alone does not buy a successful future. If LEAG and others can demonstrate how the transfer from the old energy world to the new one translates into job opportunities (some requiring training), we can inspire confidence in our plans. This is something we must work on tirelessly.

A CULTURE OF ERROR

Sometimes it is better to make a wrong decision than to freeze and make none at all. This has become known as a "culture of error," and it's a requirement in a dynamic transformation situation. Indeed, this viewpoint can give individuals and teams the strength to create exciting new things and move us all forward. It goes without saying that this type of culture requires strong, supportive (and demanding) leadership.

FLEXIBILITY IS KEY

Flexibility is crucial in a major transformation. Parameters change fast, sometimes daily. What seemed sensible four weeks ago may be wrong tomorrow or four weeks from now. That's why identifying trends, opportunities, and obstacles and reacting to them quickly is vital. This may mean reprioritizing projects with very little notice, so adaptability is essential. Ultimately, management must develop more options than will be needed. This can lead to irritation and disappointment both inside and outside the company, but it is essential — concentrating on just one path to a goal would be damaging. Of course, this way of working requires plenty of dialogue and mutual idea exchange at the management level, within teams, and to stakeholders.

COOL HEAD, WARM HEART

What sounds like a contradiction at first is a prerequisite for a successful transformation. Everyone should be passionate about the mission and encourage others to come along for the journey. At the same time, we must deliberately stop and make sure we are on the right path (does commitment X or investment Y still make sense for our goals?). This can lead to disappointment but is a reality in a major transformation. When it comes to costs and profitability, unbiased analyses are always necessary. LEAG's transformation is not just about a huge amount of money, it is about energy security in Germany. We are fortunate that our shareholders fully support us and our plans and share our vision of an energy company that is positioned for the future.

STAKEHOLDER MANAGEMENT

A project like GWF involves many stakeholders with legitimate expectations, demands, and interests. They include employees, shareholders, customers, suppliers, cooperation partners, legislators, and a variety of governmental organizations. All bring with them their own experiences, interests, and questions. It is essential to understand their expectations and opinions while helping them to truly understand GWF's potential. This falls squarely on the shoulders of the CEO, especially in the case of a heavily regulated market in the midst of a comprehensive transformation. An information and dialogue system must be quickly established and continuously updated to answer questions and communicate the project's progress.

FINAL THOUGHTS

In conclusion, I believe LEAG will succeed in this transformation. After all, the opportunities this challenging endeavor presents are simply too big, too important, and too fruitful to not give it our all.

About the author

Thorsten Kramer is CEO of Lausitz Energie Bergbau and Lausitz Energie Kraftwerke (LEAG), spearheading the company's transformation from a traditional, fossil-based energy supplier in Germany to a cutting-edge, sustainable powerhouse for renewable energies across Europe. This transformation poses complex challenges demanding the utmost utilization and exploitation of existing strengths to unlock novel, extensive, and sustainable opportunities for both the organization and its workforce. He has considerable experience in the field of renewable energies and change management. Prior to his appointment as CEO of LEAG, Mr. Kramer provided advisory services to a diverse range of globally operating companies, including both publicly listed and private equity–held firms in the industrial and energy plant construction sectors. Notably, he advised Bilfinger Engineering & Technologies, among others. Mr. Kramer also served as CEO of GES in Spain and Nordex Energy in Hamburg. During his tenure, he demonstrated his expertise in implementing significant restructuring initiatives and executing comprehensive strategic realignments, resulting in successes for both companies. Mr. Kramer earned a degree in mechanical engineering from Ruhr University Bochum, Germany. He can be reached at thorsten.kramer@leag.de.

ENERGY EFFICIENCY'S ROLE IN INDUSTRIAL DECARBONIZATION

Authors

Senthil Sundaramoorthy, Dipti Kamath, Sachin Nimbalkar, Christopher Price, Thomas Wenning, and Joseph Cresko

Around the world, efforts are increasing to drastically reduce greenhouse gas (GHG) emissions by 2050. The goal of the Paris Agreement is to hold the increase in global average temperature rise to below 2°C as compared with preindustrial levels, specifically aiming to limit it to 1.5°C. As of 2017, the global average temperature rise reached approximately 1°C. It is expected to hit the 1.5°C mark by 2040 if current trends continue. Limiting temperature rise to 2°C will require reaching net zero emissions in the latter half of the 21st century; GHG emissions would need to reach a near-zero value by 2050 to limit the rise to 1.5°C.[1]

The industrial sector represents a significant source of energy-related GHG emissions. For instance, in the US, it accounted for 33% of overall primary energy use in 2020 and was responsible for 30% of the nation's total energy-related GHG emissions (see Figure 1).[2] Reducing a sizeable portion of these emissions will play a key role in achieving the Paris Agreement's goals.

The focus of industrial decarbonization is on the energy-related CO2 emissions from fossil fuel combustion and specific processes, since they constitute the largest portion of industrial GHG emissions. Other GHGs, such as CH4 and N2O, have higher global-warming potential and should be reduced as well, but they are comparatively less in amount.

As of 2021, manufacturing was responsible for almost three-quarters of all industrial GHG emissions in the US.[3] The bulk of manufacturing energy-related CO2 emissions comes from iron and steel, chemicals, food and beverage, petroleum refining, pulp and paper, and cement (see Figure 2). Decarbonization efforts should therefore focus on these industries.

Over the past several years, strategies such as reducing carbon-intensive processes, switching from coal to gas and renewables, and increasing efficiency have been adopted by many industries to reduce energy intensity and related emissions. The US Department of Energy's (DOE) Industrial Decarbonization Roadmap identified four pillars as viable pathways to industrial decarbonization: (1) energy efficiency; (2) industrial electrification; (3) low-carbon fuels, feedstocks, and energy sources (LCFFES); and (4) carbon capture, utilization, and storage (CCUS) (see Figure 3).[4]

> **THE FOCUS OF INDUSTRIAL DECARBONIZATION IS ON THE ENERGY-RELATED CO2 EMISSIONS FROM FOSSIL FUEL COMBUSTION & SPECIFIC PROCESSES**

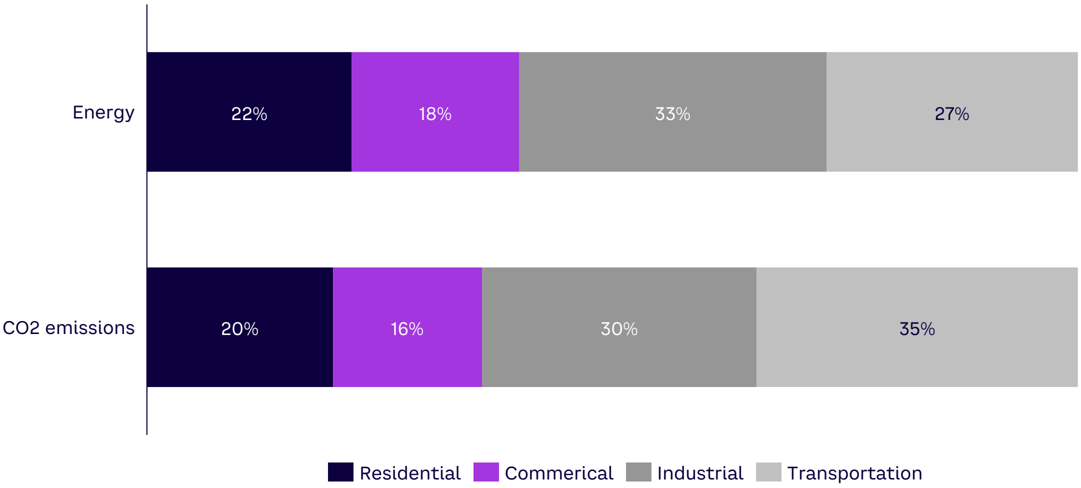


Figure 1. Carbon emissions and primary energy use by sector, 2020 (source: US Energy Information Administration [EIA])

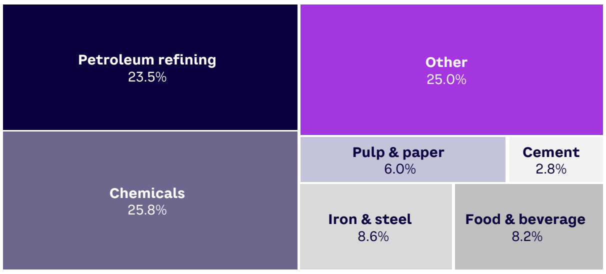


Figure 2. Percentage of energy-related CO2 emissions from manufacturing sectors (source: EIA)

The *energy-efficiency* pillar focuses on lowering energy demand to reduce CO2 emissions from fossil fuel combustion. The *industrial electrification* pillar focuses on using electricity to replace the direct combustion of fossil fuels and lower the carbon intensities of both grid and on-site electricity-generation sources. The *LCFFES* pillar can further lower emissions associated with fossil fuel combustion by substituting fossil fuels, feedstocks, and energy sources with low- and no-carbon alternatives. Finally, the *CCUS* pillar aims to capture difficult-to-abate CO2 emissions at the source or directly from the atmosphere. Captured CO2 emissions can be used or stored for longer periods to prevent them from entering the atmosphere.[5]

Energy efficiency (near-term)	• Energy management • Adoption of smart manufacturing • Improved material & process efficiency • Utilization of combined heat & power
Industrial electrification (mid- to long-term)	• Electrification of process heating • Electrification of space heating • Electrification of hydrogen production • Development of electrified processes
Low-carbon fuels, feedstocks & energy sources (LCFFES) (mid- to long-term)	• Development of carbon-free alternative fuels • Adoption of low-carbon alternative fuels • Utilization of low-carbon feedstock materials • Development of biofuel infrastructure
Carbon capture, utilization & storage (CCUS) (long-term)	• Direct air carbon capture • CCUS • C02 distribution infrastructure • Chemical utilization

Figure 3. Four pillars of industrial decarbonization with example approaches (source: DOE)

To achieve net zero emissions by 2050, the US industrial sector must decarbonize by adopting emerging and transformative technologies like electro-technologies, LCFFES, and CCUS and by focusing on energy-efficiency efforts. Although almost half of the emissions reductions in 2050 are expected to come from transformative technologies, most emission reductions through 2030 would come from energy-efficiency technologies already available and proven effective.

In total, 66% of the on-site manufacturing sector's CO2 emissions are from process energy use and are mostly attributable to process heating, steam, and motor-driven systems.[6] Energy efficiency remains the most cost-effective option to reduce these GHG emissions. However, with the emergence of other decarbonization strategies, energy efficiency has recently taken a back seat for many manufacturers, especially in energy-intensive sectors. The surplus of oil and gas in the US, coupled with low natural gas pricing, is also making energy efficiency a lower priority.

To strengthen the role of energy efficiency in decarbonization, the industrial sector needs to better understand the approaches it can leverage. This article addresses this knowledge gap and details energy-efficiency opportunities for the industrial sector in general and the six most energy-intensive industries.

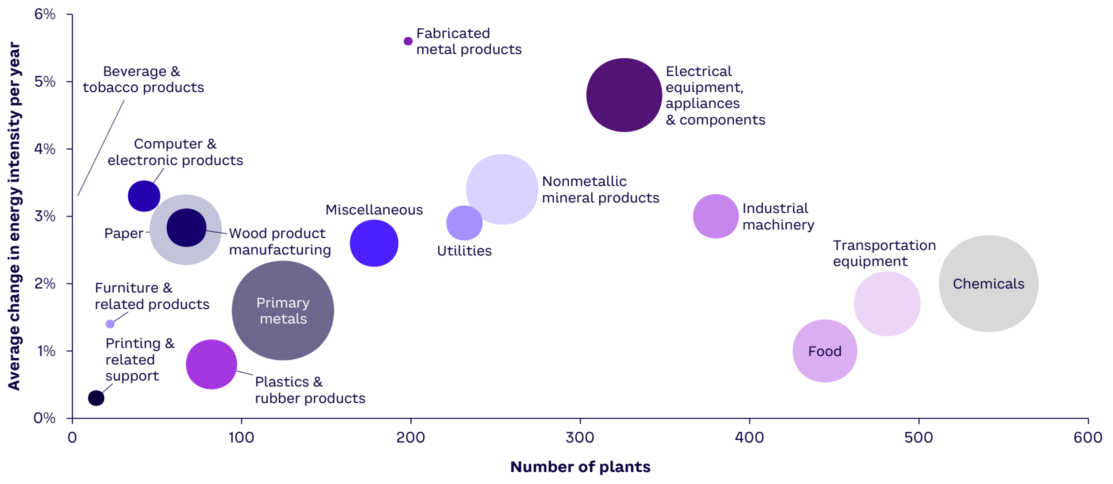
Our 2023 paper featured in "Renewable Energy Systems and Energy Efficiency for a Decarbonized Sustainability," a special issue of *Sustainability*, provides a thorough literature review of studies across the globe addressing energy efficiency's potential to reduce carbon emissions in these industries and the industrial sector in general.[7] This article serves as a preliminary guide to support the selection of specific energy-efficiency technologies.

ENERGY EFFICIENCY FOR INDUSTRIAL DECARBONIZATION

Energy-efficiency improvement is a feasible, low-cost approach that, in most cases, does not require any major change to industrial processes and can bring immediate emissions reductions. Since 2010, through the Better Buildings, Better Plants program, DOE has worked with more than 270 manufacturers and water and wastewater utilities across the US to accelerate the adoption of energy-efficient practices, highlight innovative technologies, and spur change at an organizational level.

Through the program, DOE supports 3,600 facilities, corresponding to 14% of US manufacturers. Collectively, these firms have reported savings of 2.2 quadrillion BTUs (British thermal units) of energy. That is equivalent to 131 million metric tons (MMT) of CO2 emissions reductions and a savings of US $10.6 billion.[8]

Figure 4 shows the average energy-intensity improvement in terms of the number of plants and



Note: Bubble size denotes unadjusted baseline energy consumption as of fall 2022

Figure 4. Average energy-intensity improvement in terms of number of plants and program energy footprint for selected sectors (source: DOE)

the program's energy footprint for selected sectors since 2010. Current energy-efficiency measures in the US industrial sector can potentially save 6.25 quads of energy (6.5% of baseline energy use in 2050) and reduce CO2 emissions by 244 MMT (5.6% of baseline energy CO2 emissions in 2050) through 2050.[9]

Similar studies have been conducted around the world. In 2015, the UK government released a series of reports that assessed the potential for a low-carbon future and developed decarbonization roadmaps for eight of the UK's most heat-intensive industrial sectors.[10] Per the study, combined max tech pathways (CCUS, electrification, material efficiency, energy efficiency, and other approaches) can reduce emissions from 81 MMT CO2 in 2012 to 22 MMT CO2 in 2050. Energy efficiency combined with heat recovery alone potentially contributes to a reduction in total emissions of 8 MMT CO2 (13% of the overall reduction) in 2050. The main contributors to emissions reductions are the refining industry (43%), the pulp and paper industry (41%), and the food and beverage industry (36%).

> STRATEGIC ENERGY MANAGEMENT IS A SYSTEMATIC APPROACH THAT EMPOWERS AN ORGANIZATION WITH CONTINUAL ENERGY MANAGEMENT PRACTICES

Similarly, industrial energy consumption in the EU is projected to drop by 25% in 2050 compared to 2015 levels through energy-efficiency improvements, with waste heat–recovery applications as the primary driver. The energy-efficiency improvements are also expected to reduce energy-related CO2 emissions by 22% in iron and steel sectors, 22% in chemical sectors, 35% in the nonmetallic minerals (e.g., cement, lime) sector, 15% in the nonferrous metals sector, and 32% in refineries in 2050 compared with the baseline scenario.[11] In Australia, energy efficiency in the manufacturing sector could cause a 40% reduction in energy intensity by 2050 compared to 2010 levels.[12]

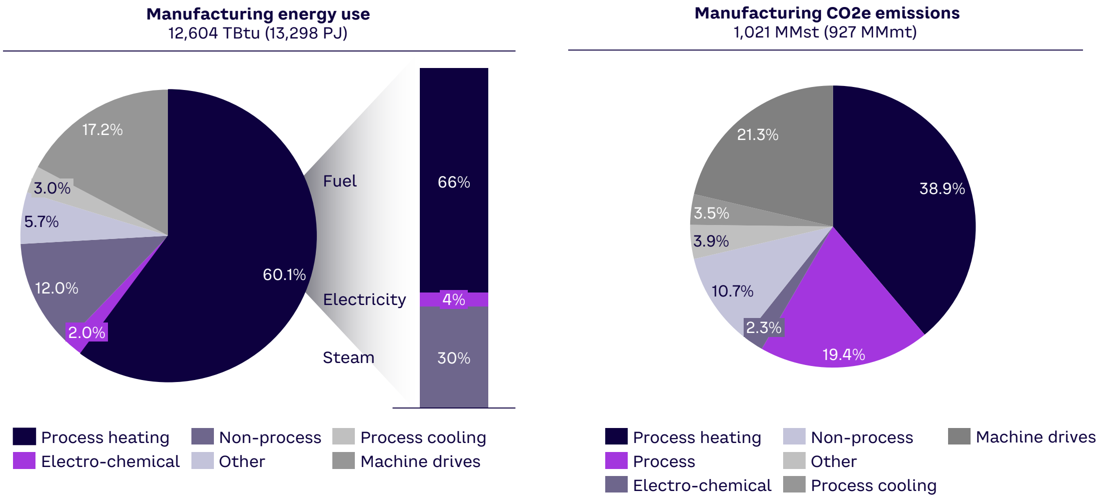
The following sections describe specific strategies for achieving energy efficiency. (For further details, see "Energy Efficiency as a Foundational Technology Pillar for Industrial Decarbonization," which includes informative tables showing energy-efficiency strategies for the six most energy-intensive sectors.)

STRATEGIC ENERGY MANAGEMENT

Strategic energy management is a systematic approach that empowers an organization with continual energy management practices. It supports energy and emission reductions by providing the tools necessary to integrate energy management into a facility's daily operation. There are three vital elements to strategic energy management: the organization's commitment, the identification and implementation of energy-efficiency projects, and the tracking and reporting of performance.[13] Strategic energy management also includes using energy management information systems and adopting energy management standards and protocols (e.g., ISO 50001). DOE has developed 50001 Ready Navigator for manufacturers, an online application that provides step-by-step guidance for implementing and maintaining an energy management system in conformance with ISO 50001.[14]

SYSTEM EFFICIENCY

The energy efficiency of industrial systems can be improved by evaluating the performance of energy end uses (e.g., process heating, process cooling, steam, compressed air, pumps, fans, and other systems) and taking action to reduce energy consumption. Some of the highest energy-use requirements come from a few systems. Process heating (fuel-based, steam-based, and electricity-based) and machine drives play a dominant role and are responsible for more than 77% of total energy use and 60% of total emissions in the US manufacturing sector (see Figure 5).



MMst = million short tons; MMmt = million metric tons

Figure 5. Total energy and emissions in manufacturing sector by end use, 2018 (source: DOE)

Process-heating operations (heating, melting, curing, heat treating, drying, and smelting) are essential to a number of industries. A variety of process-heating equipment (e.g., furnaces, ovens, dryers, kilns, and incinerators) operate under the same principle of transferring thermal energy from fuel combustion directly or indirectly to the load or the material. Thus, using high-efficiency systems provides significant savings in energy and CO2 emissions. For example, a high-efficiency boiler can deliver 350 trillion BTUs of energy savings and a 20 MMT CO2 reduction annually in the US.[15]

In 2018, process-heating systems used 7,576 trillion BTUs of primary energy, contributing to about 360.4 MMT of CO2-equivalent (CO2e) GHG emissions in the US manufacturing sector.[16] Most of the energy-savings opportunities in process heating are reducing, recycling, and recovering waste heat losses.

In 2006, DOE initiated Save Energy Now assessments to evaluate the energy efficiency of industrial steam and process-heating systems in energy-intensive US facilities.[17] The results from assessments conducted between 2006 to 2011 indicated that process-heating and steam systems combined could save approximately 480,000 million BTUs per plant per year, a CO2-reduction potential of about 31,000 metric tons per plant per year, with most of the savings coming from the recovery and reuse of waste heat.

Motors and machine drives (e.g., pumps, fans, and compressors) are used in a wide variety of manufacturing applications, including fluid handling, material handling, processing, and HVAC systems. Industrial motors and machine drives accounted for about 17% of US manufacturing's total energy use and 21% of carbon emissions (see Figure 5). Inappropriate equipment sizing and poor system design result in inefficiency, increased maintenance, reduced control, and decreased energy performance.[18] These inefficiencies can be countered by using high-efficiency or premium-efficiency motors, installing adjustable speed drives, power conditioning, developing better system designs, and properly sizing equipment.[19]

In addition, matching drive systems (pumps, fans, and compressors) with end-use requirements will reduce energy use. The implementation of energy-efficiency technologies for industrial motor drives in six countries showed an average potential of 28%-38% energy savings compared to the 2008 electricity use of these systems; the potential electricity savings were found to be 25%-35% in the US.[20] Optimizing performance, regular system maintenance, continuous monitoring, and upgrading ensure highly efficient systems and lower energy consumption and carbon emissions.

MATERIAL & LIFECYCLE EFFICIENCY

Material and lifecycle efficiency involves using less material to produce the same set of products, extending the life of a product, and increasing product utilization rates without compromising the end-use benefits of the product. Material efficiency, additive manufacturing, material substitution, and a circular economy (CE) are crucial to reducing material waste, energy demand, and GHG emissions in the manufacturing sector.

Heavy industries, such as iron/steel and cement, are leading contributors to global industrial-process CO2 emissions and can benefit significantly from material efficiency, especially since demand is expected to increase by 12% to 23% for cement and 40% for steel by 2050.[21,22] Material efficiency can lead to significant CO2 emissions reduction by 2060, potentially reducing the total emissions by approximately 20% for steel, 70% for cement, and 30% for aluminum.[23]

In a circular economy, a material's end of life is extended by reuse, remanufacturing, repair, or refurbishment, followed by recycling and clean disposal when the material can no longer be circulated across its lifecycle. CE strategies can be used to enable decarbonization, increase resource productivity, ensure sustained access to scarce resources, and extend the economic value of materials and products.

The Ellen MacArthur Foundation estimates that a CE approach can reduce global CO2 emissions from cement, steel, plastics, and aluminum by 40% annually by 2050. Waste elimination accounts for 24% of the emission reduction, and extending lifetimes by reusing and recirculating the material accounts for 30% and 50%, respectively.[24] In Europe, the CE model is expected to reduce emissions by 56% annually until 2050 in energy-intensive sectors.[25]

SMART MANUFACTURING

Implementing smart manufacturing technologies can create energy savings through improved process control, reduced waste, a shorter downtime, and improved performance and productivity. Smart manufacturing involves using advanced sensors, monitoring and control systems, and optimization technologies to gather and process data and provide actionable insights to manufacturing personnel while improving decision-making across facilities and supply chains. Big data, the Industrial Internet of Things, and machine-to-machine communications are all driving forces for smart manufacturing. The benefits of smart manufacturing include reduced cost, production flexibility, shorter time to market, greater energy efficiency, reduced environmental impact, and increased productivity.[26]

DOE estimates average energy savings of more than 20% across all industries based on a review of several sets of studies.[27] The feasibility of smart manufacturing technologies depends on several factors, such as energy use, capital, operations and maintenance costs, increased revenue from increased productivity, education and training, cybersecurity, and energy savings. Smart manufacturing feasibility for energy productivity can be determined using the cost of a conserving energy framework, which balances some of these factors against changes in energy use.

COMBINED HEAT & POWER

Combined heat and power (CHP) generates electricity or mechanical power and captures the heat that would have otherwise been wasted to provide valuable thermal energy.[28] CHP is a type of distributed generation located at or near the point of use. CHP improves efficiency and reduces GHG emissions by reducing or replacing the purchase of electricity from the grid and thermal energy produced by boilers, typically fueled by natural gas. In addition, electricity generated by CHP does not have any transmission and distribution losses, unlike conventional electricity generation.

CHP systems have been used to generate electricity for decades and continue to be relevant as industries seek to reduce their environmental impact while maintaining a reliable energy supply with high efficiency and low emissions. Industrial CHP systems, through both topping and bottoming cycles, can provide needed energy services for some sectors with overall energy efficiencies of 65%-85% (compared to the separate production of heat and power, which collectively average to 45%-55% system efficiency).[29]

CHP has historically relied on fossil fuels, but newer CHP technologies use low-carbon fuels like biogas, renewable natural gas, and hydrogen, which can further reduce GHG emissions. Renewable natural gas and hydrogen CHP systems can be a long-term path to decarbonizing industrial thermal processes that are resistant to electrification because of technology or cost barriers, as well as critical operations where dispatchable on-site power is needed for resilience and reliability.

ENERGY EFFICIENCY FOR ENERGY-INTENSIVE INDUSTRIAL SECTORS

The majority of industrial emissions come from energy-intensive sectors. DOE's Advanced Manufacturing Office (AMO) conducted energy-bandwidth studies to analyze energy use and potential energy savings for selected manufacturing sectors (see Figure 6).[30]

As identified in a French report on this subject, energy-intensive industries have traditionally been difficult to decarbonize due to the difficult-to-abate, fossil fuel–driven, expensive process-heating infrastructure.[31] As a result, they have been reluctant to join government decarbonization programs. Figure 7 shows the results of a brief review of programs around the world for decarbonizing the industrial sector.

The uptake of these programs was dominated by the food and beverage industry — to the point where the Australian government launched a separate program focused on this sector. Canadian programs have seen petroleum-refining industries participate more frequently than in other parts of the world, which can be attributed to Canada's unique sector-specific characteristics.

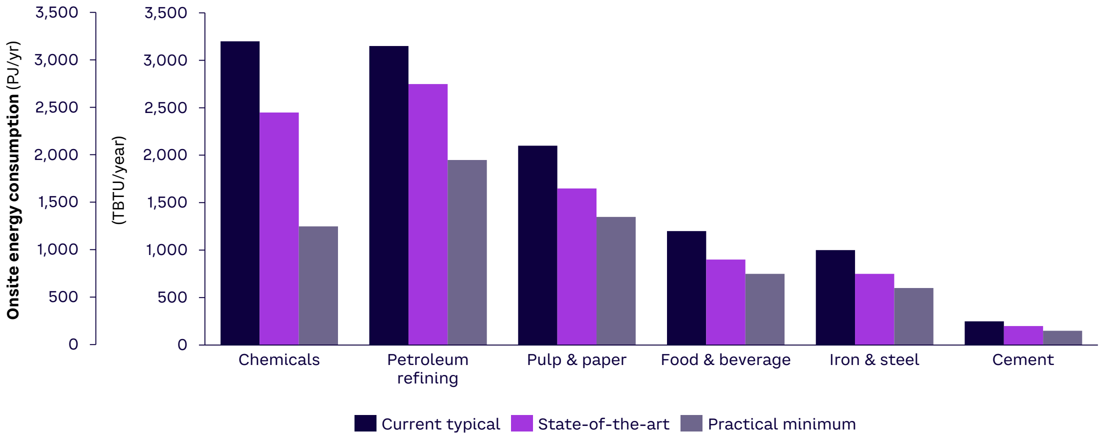


Figure 6. Energy use of select energy- and carbon-intensive industries in the US (source: DOE)

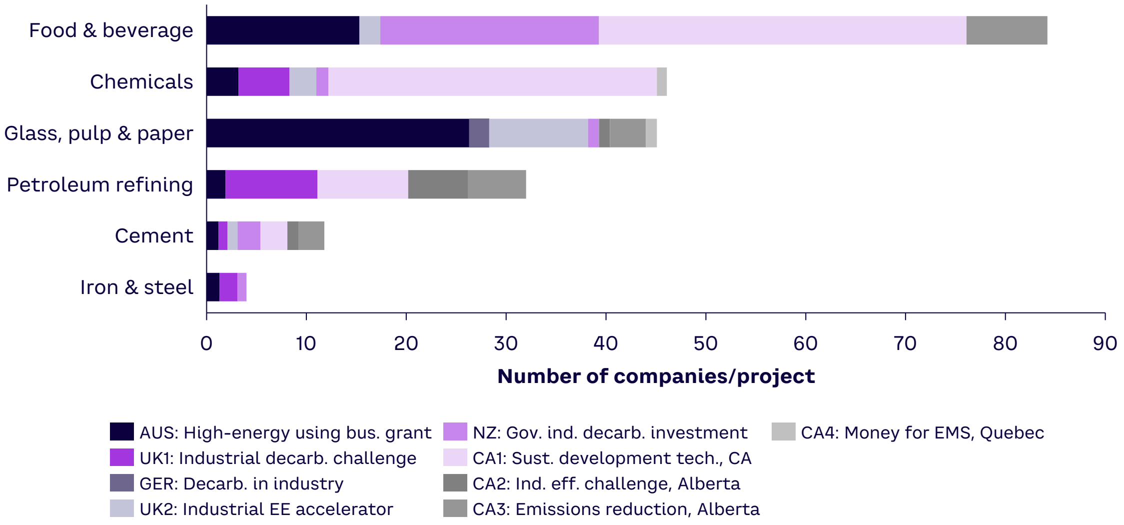


Figure 7. Uptake by company or project to programs from around the world for decarbonizing the industrial sector (source: DOE)

Iron and steel industries had relatively less participation. These results can be leveraged further to identify the reasons behind the reluctance in participation and to develop programs catered toward specific sectors. For a table showing details on these programs, please see "Energy Efficiency as a Foundational Technology Pillar for Industrial Decarbonization."

Government-backed programs are focused not only on funding, but also on providing technical assistance and various types of assessments. In fact, compared with the larger investments in electrification, switching to low-carbon fuels, and CCUS, energy-intensive industries seem to be enthusiastic about implementing energy-efficiency projects.

CONCLUSION

The industrial sector plays a crucial role in many economies, and decarbonizing it can lead to significant emissions reductions. If the US and other countries are to achieve their long-term climate goals, immediate action must be taken to decarbonize manufacturing.

This article describes the potential of the energy-efficiency technology pillar and its pathways for decarbonizing the industrial sector, with special attention paid to energy-intensive industries. It shows how energy-efficiency strategies implemented at the system and process level can bring both short-term and long-term reductions in carbon emissions.

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