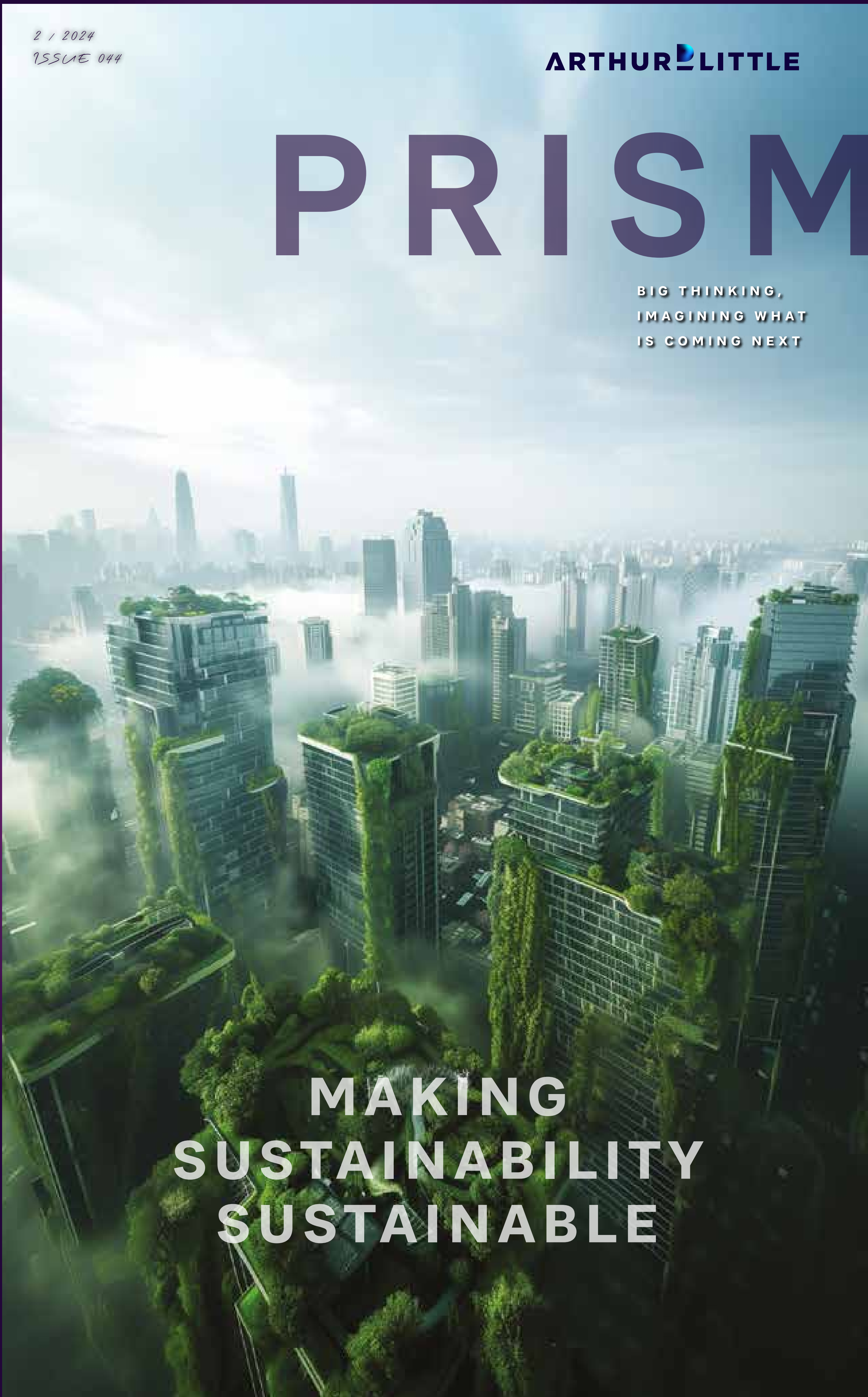
2 / 2024
ISSUE 044
ARTHUR D LITTLE
PRISM
BIG THINKING,
IMAGINING WHAT
IS COMING NEXT
MAKING
SUSTAINABILITY
SUSTAINABLE

THE PRISM BOARD

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Editing and design by Catalyst Comms, London: info@catalystcomms.co.uk.

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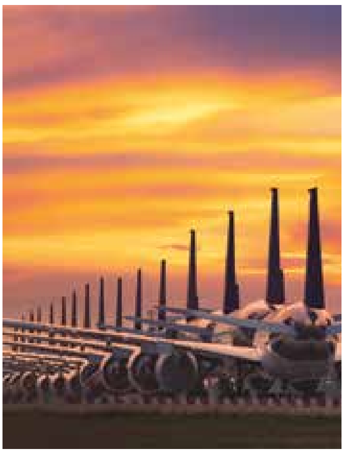

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Arnaud Siraudin, Matteo Ainardi, Amaury Klossa

EDITORIAL

DEAR READER

Last year saw a backlash against ESG investment and climate change regulation in the US, with similar examples of watering down or postponement of sustainability-related regulation in some parts of Europe. Despite this, businesses' evidence suggests a continued, and indeed increased, commitment to sustainability as it becomes more central to business strategy. But this also comes with a new realism about the massive challenges of achieving net zero and the huge costs involved. We have devoted this issue of *Prism* to exploring some of the challenges and how we can address them. As one might expect, there are no easy solutions, so be prepared for some in-depth content that hasn't been dumbed down!

Climate change adaptation is now finally coming to the fore, not as an alternative to mitigation but as an essential complement to it. Yet today, there is still very little adaptation regulation or investment. Based on a major in-depth study by Arthur D. Little's Blue Shift Institute, our first article explores the nature of the adaptation challenges across the industry, imagines scenarios for how it could unfold, and proposes what businesses should be doing now in response — before it's too late.

Lithium-ion (Li-ion) batteries are central to the green shift. Battery demand is forecast to increase sevenfold in the next decade. Creating a circular economy to recycle spent batteries is essential, yet circular models are currently unprofitable in many regions, such as Europe. We set out a blueprint for "urban mining" — how to successfully and profitably recycle Li-ion batteries locally, a template that can also be applied to other materials, such as electronics, plastics, and metals.

Carbon pricing has existed for over two decades, and today, national and regional schemes cover about one-quarter of all global greenhouse gas emissions. Many companies already use internal carbon pricing to help factor the economics of emissions into investment decision-making, but there are challenges in finding accurate data, and commercial pressures often push it to the periphery of the business. Our third article outlines a way for companies to get a better grip on internal carbon pricing to make it more effective and meaningful.

Our next three articles dive into different important domains for our future sustainability. The first is mobility. Transport accounts for around 15% of global CO2 emissions, the only sector with a steady increase since 1990. Despite the high hopes of 15 years ago, most journeys are still by private car. Our renowned Future of Mobility Lab and transport industry partner POLIS have made an in-depth study of what we need to do next to accelerate the shift toward sustainable, resilient, safe, efficient, and human-centric mobility systems in our cities. We offer a taster of the full results in this edition of *Prism*.

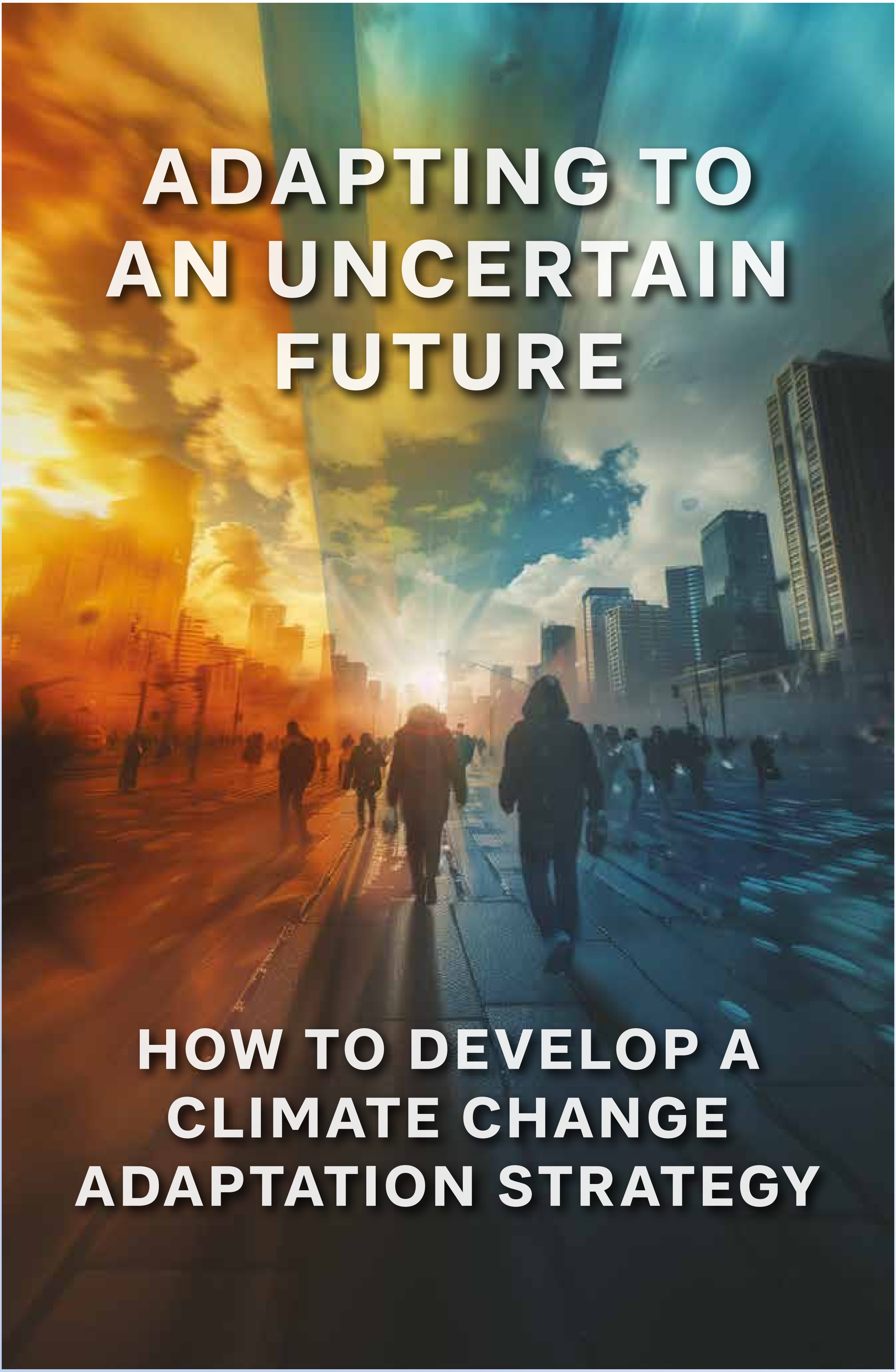
Next is steel production, which is responsible for a not-insignificant 5% of global CO2 emissions. Along with green electricity, hydrogen, and new production technologies, scrap recycling is the key to decarbonization, and we offer a strategic approach to making this more commercially viable.

Aviation needs to move to sustainable, low-carbon fuels. The main issue here is the lack of investment in building adequate green fuel production capacity. There are no easy answers, but we look in depth at what governments, producers, investors, and customers must do to unlock what we believe is a very attractive market.

To wrap things up for this issue, we bring you the latest developments in a promising energy-from-space technology — mirrors in the sky to increase the output of existing solar energy farms greatly. Once thought of as too costly, impractical, and even fanciful, this concept has suddenly started looking much more feasible. How it has developed provides us with some valuable lessons for approaching innovation for sustainability. Ultimately, we will only have a realistic chance of making sustainability sustainable through finding new ways of collaborating globally and harnessing the power of technological innovation.

We hope you enjoy the issue!

Rick Eagar
Chief Editor, *Prism*
Arthur D. Little



ADAPTING TO AN UNCERTAIN FUTURE

HOW TO DEVELOP A CLIMATE CHANGE ADAPTATION STRATEGY

AUTHORS

Dr. Albert Meige, Zoe Huczok, Rick Eagar

Mitigation gets most of the big headlines in the global discourse on the changing climate. However, no matter how successful — or not — the world is at mitigating global warming, many of the impacts of climate change are already underway and will greatly affect our future.

As well as efforts to reduce emissions and achieve net zero targets, businesses have an unavoidable need to adapt to climate change. Adaptation forms part of a broader set of sustainability goals, along with mitigation of climate impacts and improvement of resilience. Indeed, these concepts have many overlaps. For example, reducing water usage in a manufacturing process is an adaptation measure that also mitigates impacts. Protecting assets against severe weather events is an aspect of both adaptation and resilience. Businesses need to consider all three — being good at adaptation doesn't mean you can deprioritize mitigation, and vice versa. And there's more to adaptation than just becoming more resilient.

AS WELL AS EFFORTS TO REDUCE EMISSIONS AND ACHIEVE NET ZERO TARGETS, BUSINESSES HAVE AN UNAVOIDABLE NEED TO ADAPT TO CLIMATE CHANGE.

However, developing a strategy to help focus investment and development efforts for adaptation is particularly difficult. The technologies needed are, for the most part, specific, numerous, and fragmented. Adaptation solutions are diverse across different industries and often strongly driven by local circumstances, making scalability hard to achieve. At the same time, funding for adaptation tech remains low — less than 10% of all climate technology funding is estimated to have gone to adaptation in 2020–2021.

Furthermore, the suitability and viability of adaptation solutions in the future will be greatly affected by a range of uncertainties, such as competitive dynamics, regulation, and consumer behavior. This complexity leads all too often to decision paralysis or at least an extended "wait and see" philosophy, which many companies are pursuing today. Based on an in-depth study led by Arthur D. Little's (ADL's) Blue Shift institute, this article considers what adaptation means for businesses, future projections, some "no-regret" technology choices, and how to shape an adaptation strategy.

About the ADL Blue Shift study on climate change adaptation

The study was led by ADL's future technology institute, Blue Shift, in collaboration with the United Nations World Intellectual Property Organization (WIPO), which has established a green technology database comprising some 150,000 patents. It incorporated the results of 40 interviews with corporate executives, climate adaptation experts, venture capitalists, and start-ups, as well as two surveys covering 70 respondents.

One of the "elephants in the room" affecting the future course of adaptation is geopolitics, and clearly, issues such as international conflict and human migration will weigh significantly. Analyzing geopolitics is outside our expertise and mission, but we have sought to co-create a set of plausible projections together with our design fiction agency partners, Making Tomorrow, for which geopolitical events, both positive and negative, could be easily imagined as contributory factors.

4 KEY ASPECTS OF THE ADAPTATION CHALLENGE

A good place to start is to consider the range and extent of the challenges that adaptation poses for businesses. While these are many and diverse, they can be conveniently split into four generic business functions:

1. SOURCE: SECURING THE AVAILABILITY AND SUPPLY CHAIN OF CRITICAL RAW MATERIALS AND RESOURCES

Climate change will affect companies' raw materials and supply chains, such as decreasing agricultural yields and disruptions to supplies of critical materials due to severe climate events. For example, drought reduced the Panama Canal's capacity in 2023.

Companies need to consider how they can make their supply chains more resilient to disruptions.

2. MAKE: ADAPTING MANUFACTURING AND OTHER INDUSTRIAL PROCESSES TO A CHANGING CLIMATE

Energy and water shortages and grid instability are likely to be one aspect of climate that affects manufacturing processes. For example, in India, lower rainfall has reduced the efficiency of hydroelectric and nuclear power plants, causing greater grid instability. Fresh water is another critical resource with declining availability, hence the increased importance of solutions for water treatment, reuse, and recycling — or, in certain cases, desalination plants. Working conditions for employees, such as extreme heat, will also need to be addressed. Companies need to ensure that their processes can continue delivering the required product/service quality, volume, and continuity in a more extreme climate environment.

3. PROTECT: PROTECTING INDUSTRIAL SITES AND ASSETS FROM CLIMATE CHANGE IMPACTS

First, organizations must ensure they have better capabilities for prediction and early warning of climate-related disruptions. Second, they need to take physical measures to better protect their assets from floods, storms, and sea level rise, including new shielding or designs with built-in resilience. Third, they must improve their ability to respond rapidly to sudden damage or losses. Finally, they may need to consider wholescale relocation of assets away from high-risk locations, such as parts of China, Vietnam, and Bangladesh, which are vulnerable to sea level risk and flooding, or parts of sub-Saharan Africa, India, and Southeast Asia, which are vulnerable to droughts and heatwaves.

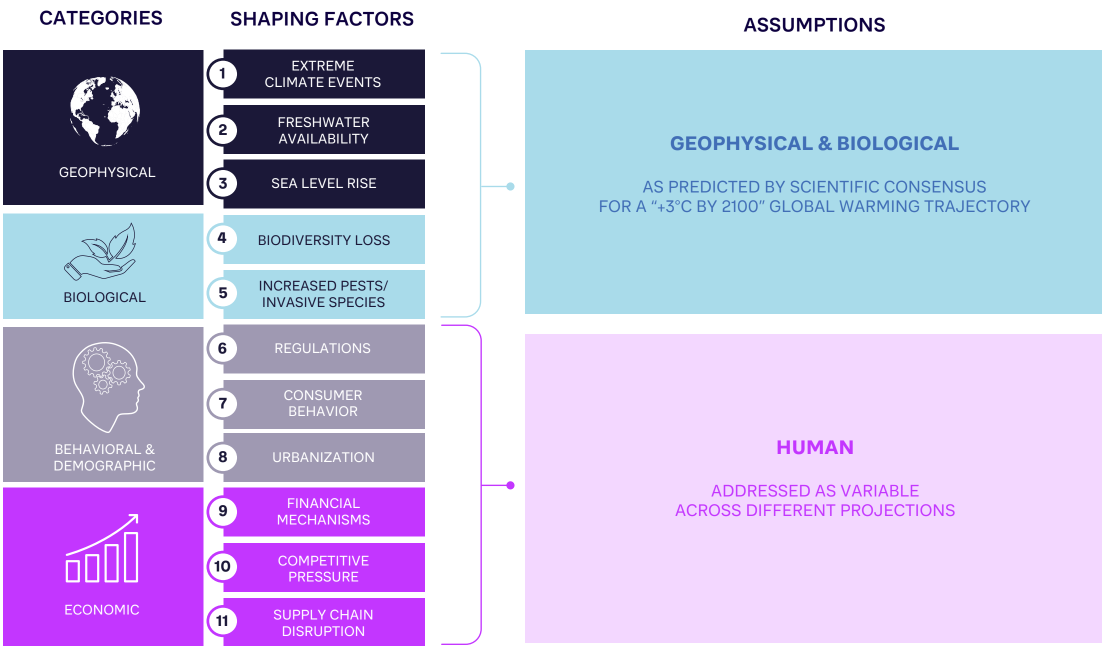
4. SELL: MARKETING COMPETITIVE AND DIFFERENTIATED GOODS AND SERVICES TO MEET THE NEEDS OF A CHANGING CLIMATE

Climate change will alter customers' needs for certain products and services and create new needs. For example, in late 2023, tire manufacturer Michelin started marketing a range of inflatable solutions for sun protection in large areas, including inflatable parasols to reduce heat islands in cities. New consumer expectations and sales and delivery channels may need to be considered, especially if consumer behaviors change because of ongoing climate-related events. Thus, social listening supported by natural language processing may help track changing and increasingly localized consumer preferences. Circularity and more sustainable ways of consumption may also become a higher priority, especially for B2B organizations.

Considering each of these generic business functions systematically helps ensure that an adaptation strategy is comprehensive, though some industries may be disproportionately affected by specific challenges (e.g., agrifood is particularly exposed to "Source").

DEALING WITH FUTURE UNCERTAINTIES

One of the biggest challenges in shaping an adaptation strategy is dealing with the significant uncertainties about the future environment. Our study identified 11 "shaping factors" that determine these uncertainties across four categories (see Figure 1).



Source: Arthur D. Little

FIGURE 1: SHAPING FACTORS FOR CLIMATE CHANGE ADAPTATION

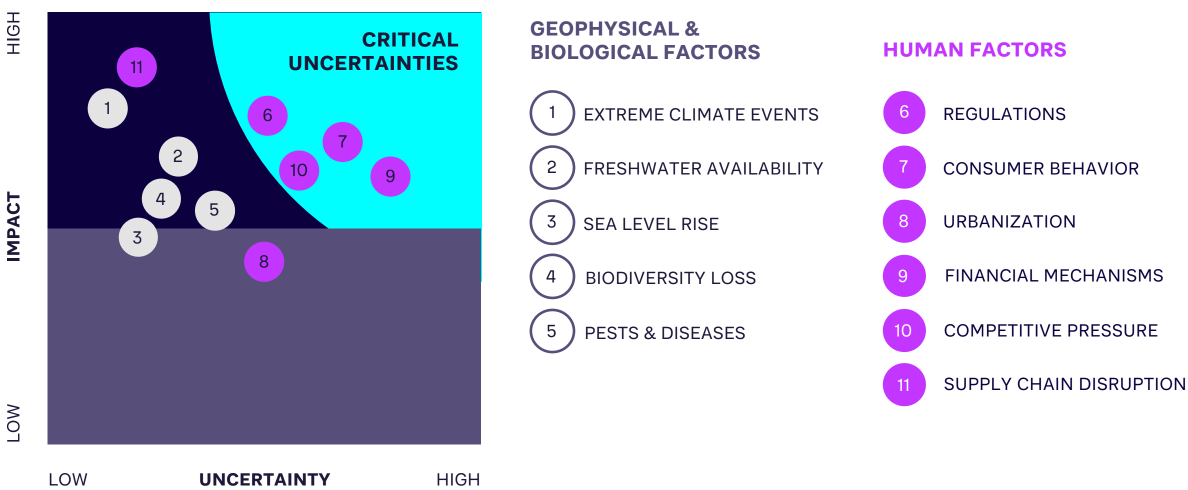
For geophysical and biological factors, we adopted a "+3°C by 2100" trajectory. This falls within the confidence interval for the Intergovernmental Panel on Climate Change's (IPCC's) Representative Concentration Pathway (RCP) 6.0, which predicts a temperature increase of ~+2.8°C versus pre-industrial levels, with a possible range between +2.0° and +3.7°C. This trajectory considers the likely target gap in 2030 based on the current delay in policy and climate action at large. Therefore, it allows for a cautiously pessimistic but realistic outlook against which to consider adaptation challenges. To understand what this future means, it is worth considering some representative impacts across our five relevant shaping factors (see Figure 2).

Source: Arthur D. Little

FIGURE 2: LIKELY CLIMATE IMPACTS FOR A "+3°C BY 2100" TRAJECTORY

Of course, uncertainties still exist regarding how these geophysical and biological factors will react and develop over time, but even at the most optimistic end of the range (+2°C by 2100), the need to adapt will be unavoidable.

Turning to the behavioral and economic factors (factors 6-11 in Figure 1), we can collectively consider these "human shaping." Using our survey of 70 experts, we ranked these in terms of level of uncertainty and impact on a 1-5 scale (see Figure 3).



Source: Arthur D. Little

FIGURE 3: HUMAN SHAPING FACTOR RANKING AND CRITICAL UNCERTAINTIES

Four factors emerge as the most critical because they have both high potential impact and high uncertainty on how adaptation will evolve:

1. Regulations refer to the extent to which new regulations will enforce or encourage adaptation, similar to how they drive mitigation today. It is by no means certain that this will happen for adaptation.

2. Consumer behavior means how far consumers will shift toward a preference for adaptation-related goods and services.

3. Financial mechanisms refer to public and private finance availability for adaptation. While adaptation finance for climate change hit a record US $63 billion in 2021/2022, increasing by 28%, it is still significantly below the $212 billion yearly need projected by 2030 for developing countries alone.

4. Competitive pressure is the extent to which market forces will drive adaptation. It is led by big industry leaders requiring all suppliers to comply. For example, today, Apple is demanding that its entire value chain reduce its impact on global warming.

By considering each "on/off" combination of these four factors, we generated 24 future projections, of which the following five are the most plausible, differentiating, and technologically relevant:

- **Green Communities:** This projection features a strong consumer behavior shift but limited finance. It characterizes a resource-scarce world where grassroots adaptation initiatives flourish without large-scale projects. It could happen if climate catastrophes start to change consumer opinion, yet ROIs for adaptation projects continue to be poor, and geopolitical or economic constraints limit public finance.
- **Lonely at the Top:** This projection features no consumer behavior shift but high competitive pressure. Here, adaptation is driven by global industry market leaders with deep pockets within a two-speed economy. Most less affluent consumers cannot support the higher price levels associated with adaptation, focusing instead on surviving in a tight economic environment.
- **Wild Green West:** This projection features strong finance but little regulation. There is a creative chaos in which adaptation initiatives sprout up everywhere, fueled by private capital but lacking any regulatory backbone. In this essentially neoliberal projection, governments fear imposing further heavy costs on industries to enforce adaptation, especially with the already huge mitigation costs, leading to a lack of globally agreed regulations and standards.

- **Don't Look Up:** This projection features limited finance and no consumer behavior shift. It is a pessimistic future in which neither customers nor financial institutions have adjusted to the new climate reality. This could be, for example, due to more pressing economic or geopolitical crises that have taken precedence over adaptation.
- **Adaptation Surge:** In this projection, all variables favor adaptation. It represents a relative utopia in which adaptation is the norm, resetting expectations, creating new markets and new needs, attracting finance, and being supported by appropriate national and international regulations.

The projections don't seek to describe a full world but rather illustrate a set of plausible tensions that may partly coexist in different regions or industries. Projections such as these are useful tools for companies wishing to develop long-term strategic plans.

FINDING YOUR WAY THROUGH ADAPTATION STRATEGIES

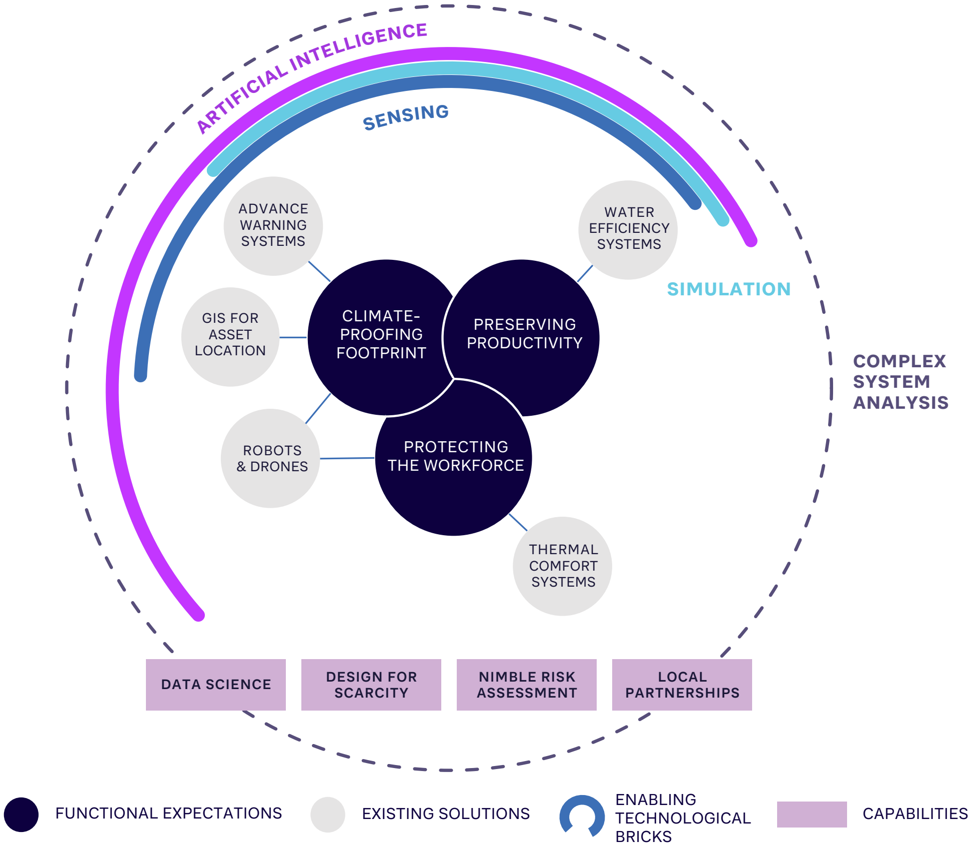
One of the challenges of developing an adaptation strategy is deciding which technologies to focus on: what will be needed, where and when, and what could be the best solution. Because adaptation is highly local, multivariate, and multidisciplinary, a huge range of technologies must be considered. Undoubtedly, this is one reason adaptation technologies have, up to now, remained in the shadow of mitigation technologies in terms of public debate.

Considering future projections such as those above is one way to help prioritize. Each future projection implies a partly different set of functional needs and priorities for which particular technological solutions are more or less relevant. For example, a Wild Green West future would favor less mature solutions with high potential ROI, such as synthetic biology for critical materials manufacturing and crop production and digital twinning for improving productivity and limiting vulnerability to climate events. Conversely, in a Green Communities future, the emphasis would be on low-cost, local solutions with more mature technologies, such as mini desalination plants for water supplies and modular designs for consumer products to reduce costs and improve reuse. In the full Blue Shift Report, we identify almost **100** of the most relevant technology families, mapped across the five future projections and the four key business functions (Source, Make, Protect, and Sell), all ranked by maturity and impact. (Readers wishing to understand in detail what is most relevant for their industry are urged to consult the main report.)

> ***BECAUSE ADAPTATION IS HIGHLY LOCAL, MULTIVARIATE, AND MULTIDISCIPLINARY, A HUGE RANGE OF TECHNOLOGIES MUST BE CONSIDERED.***

Overall, the value of adaptation technologies lies less in cutting-edge performance or breakthroughs than in applying existing technologies to solve specific and local problems **at an acceptable financial, environmental, and social cost** for all stakeholders involved. This is the key area for innovation. For example, reef balls, concrete structures that mimic marine reefs, are valuable because of their low cost, shape, marine-friendly material, and arrangement, which interact with local marine ecosystems to improve their resilience. Nevertheless, many technologies not developed for adaptation have a key role in this space, from advanced consumer sentiment analysis to digital twinning. There is no single best approach to solving adaptation challenges. Instead, a nuanced consideration of a business's ecosystem on its operations, and vice versa, is needed. Adaptation strategy is, therefore, best approached as an integral part of company strategy.

Looking across the whole adaptation technology space, some "no-regret" candidates are relevant for most industries, regardless of the projection. They address three major recurring functional expectations: **risk-proofing the industrial footprint, preserving productivity, and protecting workers** (see Figure 4).



Source: Arthur D. Little

FIGURE 4: NO-REGRET CAPABILITIES, SOLUTIONS, AND ENABLING TECHNOLOGIES

Existing no-regret solutions include advanced warning systems, thermal comfort systems, geographic information systems (GIS) for site location and relocation, drones for aerial imaging, robots for maintenance and automation of production, and water efficiency and recycling systems.

As with any technology forecast, it is valuable to consider not only technology solutions but also the key **enabling technology bricks** and underlying capabilities necessary to realize them.

From the study, three enabling technological bricks emerged as overall most relevant for these no-regret adaptation solutions:

1. Sensing technologies, including the Internet of Things (IoT), multispectral imaging, and light detection and ranging (LiDAR), provide granular, instant insights into specific metrics of interest without accessing locations — increasing safety and efficiency.

2. Deep neural networks, especially graph neural networks (GNN) — a branch of AI — have proven particularly apt at weather forecasting and, more broadly, identifying patterns across large numbers of variables. However, deep neural networks require large training data sets, and we only have one climate history.

3. Simulation via generative AI helps feed the training of neural networks by providing instances of climate events that could have happened (but did not). Digital twins allow the creation of a rich data set fully representing an asset or business. Augmented and virtual reality help visualize simulations, aiding decision-making and creating a sense of urgency.

Ultimately, the interaction of these technologies gives rise to a critical tenet of adaptation: **complex system modeling**. Complex systems are composed of many interacting units displaying emergent properties that cannot be understood in terms of the properties of their individual isolated components. Climate and human-climate interactions can be described as complex systems. Holistically modeling a company's interactions with its environment (including assets, operations, and people) and vulnerabilities to climate change will be a critical input into a sound adaptation strategy. Supply chain optimization is a proven use case. We predict that complex system modeling expertise will become increasingly important as companies have to make difficult choices and investment decisions in their adaptation strategies.

WE PREDICT THAT COMPLEX SYSTEM MODELING EXPERTISE WILL BECOME INCREASINGLY IMPORTANT AS COMPANIES HAVE TO MAKE DIFFICULT CHOICES AND INVESTMENT DECISIONS IN THEIR ADAPTATION STRATEGIES.

At the level of boosting or building underlying capabilities, four emerged as critical: **data science** because deep learning expertise will be critical to accurately predicting local climate phenomena and quantifying their impact; **design for scarcity** because the ability to design solutions in a resource-constrained environment will be key; **responsive risk assessment** because dynamic sensing and responding to rapidly changing risks will be important; and **local partnership** capabilities because climate adaptation solutions often have to be tailored to the local environment.

TAKING ACTION

Should companies take action now, or can it be postponed for a few years? In fact, some companies are already moving fast in adaptation strategy for good reasons. First, the no-regret solutions and technologies outlined above all deliver productivity and adaptation benefits. For example, IoT can help optimize the use of raw materials and utilities regardless of climate adaptation. Second, because climate adaptation is inevitable, early movers making carefully calculated investments are likely to build competitive advantage versus those who are forced to act in crisis mode. Adaptation is not just a matter of avoiding downsides — businesses with the right strategy have major opportunities. Finally, implementing many adaptation solutions requires long development lead times not least because climatic conditions cannot be controlled. In many cases, commitments to new technology development and testing must be made many years ahead of when they will be needed.

IN MANY CASES, COMMITMENTS TO NEW TECHNOLOGY DEVELOPMENT AND TESTING MUST BE MADE MANY YEARS AHEAD OF WHEN THEY WILL BE NEEDED.

A survey conducted as part of the study confirmed that lack of knowledge on the best course of action is the biggest hurdle to business adaptation, followed by resistance to change, lack of funds, and technology limitations. To move forward with adaptation strategies, companies need to consider four key questions:

1. How to predict: Decision makers should begin by creating their own global warming trajectory assumptions and identifying the shaping factors most critical for their industry and global footprint. They need to conduct site-by-site assessments of potential risks, both acute and chronic, and pilot improved risk-monitoring and modeling approaches, leveraging digital technologies such as digital twinning and AI.

2. How to decide: A suitable governance approach is needed to oversee the adaptation agenda, which often spans several functions. New metrics will likely be needed. Approaches such as heat maps can help allocate priorities. The key is thinking globally, acting locally, and enhancing customer listening.

3. How to finance: Mobilizing funding for adaptation requires updating financial metrics, including pricing climate-risk vulnerabilities in terms of damage to assets, production loss, and possible reputational effects. It may also involve the complex task of pricing positive externalities (productivity gains and employee retention) and potential market opportunities from adaptation (market share gains or new product-market fit). It also requires working with longer timelines (more than 15 years) than is customary for most corporate decision-making. Blended finance solutions, which combine concessional public funds with private capital, can be leveraged when corporate adaptation investments impact communities. Adopting a portfolio approach, balancing risks and returns, means various project types can be accommodated.

4. How to build: Because adaptation problems require local solutions, developing local ecosystems of partners is essential. As with any collaborative innovation effort, setting clear ground rules for intellectual property is important.

Ultimately, the effectiveness of adaptation to climate change will depend on how governments, businesses, local communities, and individuals collaborate to meet local, national, and global challenges. Climate change will become an increasingly consequential constraint on business strategy and forward planning. By 2040 and beyond, we may already be in a situation where “adaptation strategy” has become almost inseparable from “business strategy.”

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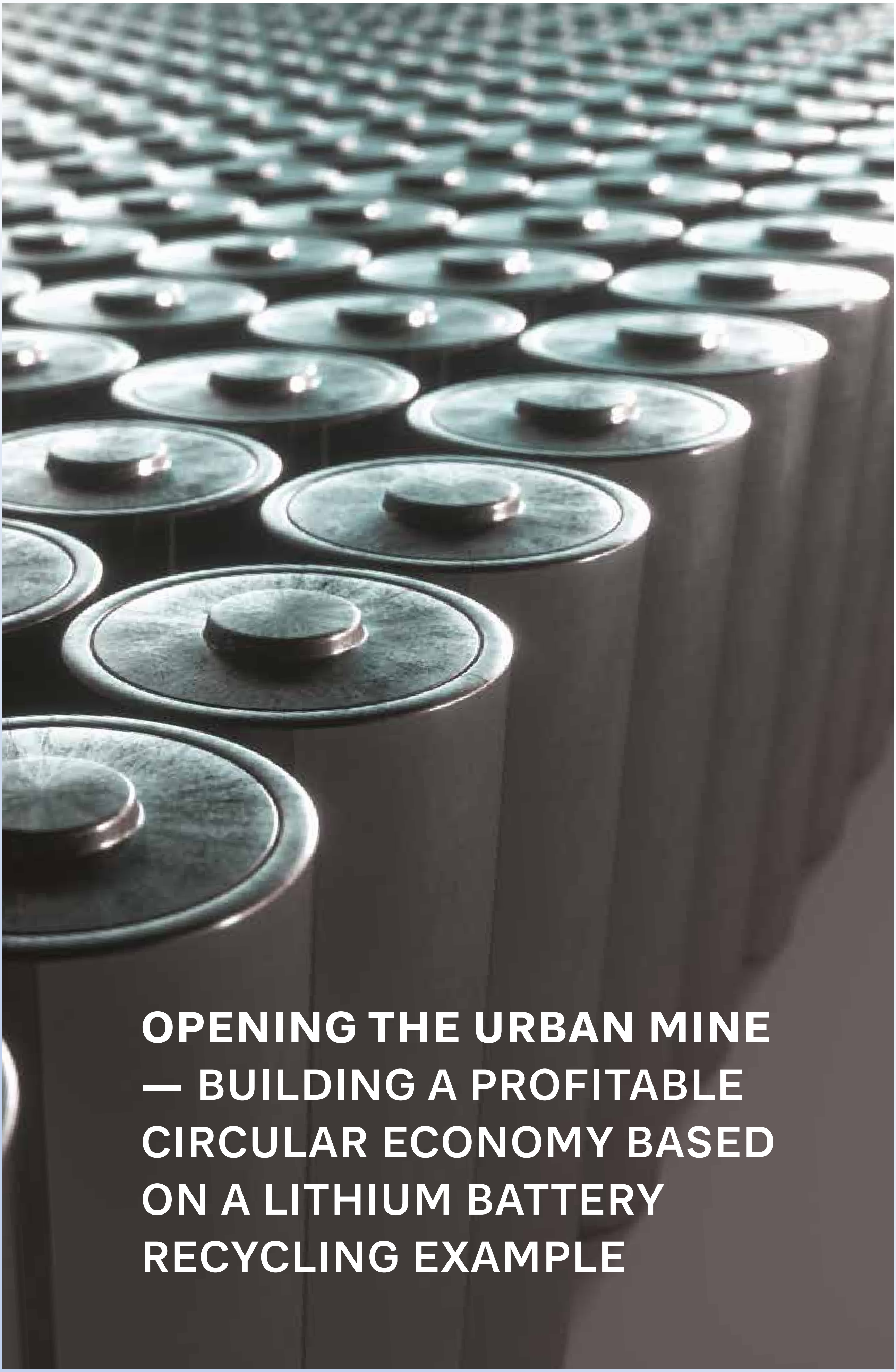


OPENING THE URBAN MINE — BUILDING A PROFITABLE CIRCULAR ECONOMY BASED ON A LITHIUM BATTERY RECYCLING EXAMPLE

AUTHORS

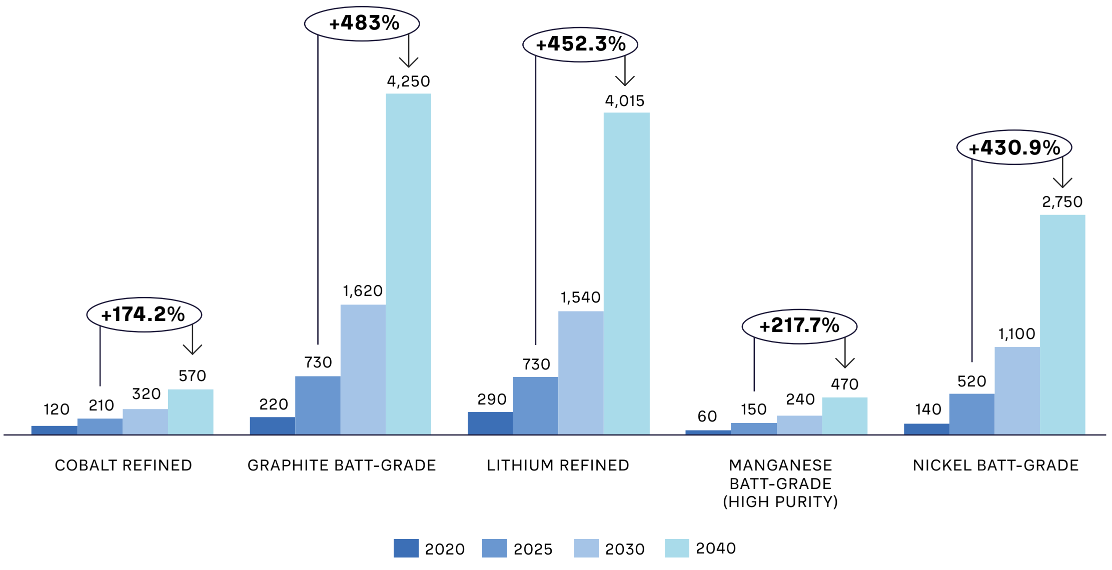
Dr. Michaël Kolk, Dr. Philipp Seidel, Felix Hoffmann

Creating circular supply chains is essential to the green transition, particularly when it comes to recycling and reusing rare materials. Yet, while many circular economy initiatives may be sustainable, they are not profitable, which hampers their wider development and holds back the achievement of sustainability goals.

Lithium-ion (Li-ion) batteries are a key case in point. Powering electric vehicles (EVs) and renewable energy storage are central to decarbonization and the green transition. According to Arthur D. Little (ADL) forecasts, after surpassing the 1 terawatt hour (TWh) threshold in 2023, global annual Li-ion battery demand will increase to roughly 5 TWh by 2030 and 7 TWh by 2035. However, battery production relies on large amounts of metals (e.g., lithium, manganese, cobalt, and nickel) that generate significant ESG (environmental, social, and governance) risks and carbon footprints when mined, processed, and manufactured. The EU Commission estimates that the global demand for active battery materials such as lithium, graphite, and nickel will double between 2025 and 2030 (see Figure 1). The decade after 2030 will see a further dramatic increase in material demand. However, since the lifetime of batteries in EVs and stationary storage can exceed 10 years easily, the availability of spent batteries for recycling will remain limited during the next decade. For example, in Europe, the material will hardly surpass 1 million metric tons before 2035.[1]

THE EU COMMISSION ESTIMATES THAT THE GLOBAL DEMAND FOR ACTIVE BATTERY MATERIALS SUCH AS LITHIUM, GRAPHITE, AND NICKEL WILL DOUBLE BETWEEN 2025 AND 2030.

1. "Lithium-Based Batteries Supply Chain Challenges." European Commission, accessed September 2024.



Source: Arthur D. Little, European Commission Joint Research Centre

FIGURE 1: FORECAST OF GLOBAL DEMAND FROM BATTERIES FOR PROCESSED RAW MATERIALS (IN KT)

Recycling end-of-life (EOL) Li-ion batteries (from laptops, consumer electronics, and, mainly, an increasing number of EVs) and reusing their components in new batteries should present a clear opportunity to marry sustainability and profitability. The EU Commission expects about half of the demand for nickel and cobalt for batteries in 2040 to be covered by output from recycling facilities.[2] However, in many regions, battery recycling business models are not profitable because of the need for high-CAPEX investments, low current volumes, immature technology, volatile raw material prices, and difficulties in scaling. Over three-quarters (77%) of experts in our analysis agree that recycling EOL Li-ion batteries in Europe is currently not economically viable.

This leads to the unsustainable practice of exporting black mass (partly processed EOL battery materials) to Asia, adding to transport emissions and impacting access to rare minerals required by the growing European battery industry. Global markets reflect this with lower prices for black mass in Europe due to lower local processing capacity, and thus demand, as well as the costs of shipping to Asia.

How can an economically viable circular model be put in place? Based on ADL research of industry players and our experience within client projects, this article sets out a blueprint for urban mining to successfully and profitably recycle Li-ion batteries locally. This template not only helps create a circular economy around batteries but provides best practices that can be applied to other recycling initiatives, such as electronics, plastics, and metals.

2. Maisel, Franziska, et al. "A Forecast on Future Raw Material Demand and Recycling Potential of Lithium-ion Batteries in Electric Vehicles." *Resources, Conservation & Recycling*, No. 192, 2023.

BUILDING A CIRCULAR ECONOMY AROUND BATTERIES

The growth of EVs focuses attention on the importance of Li-ion battery production to national and regional economic competitiveness. This leads to an increase in regulations designed to secure supplies of specific materials while governments encourage the creation of battery gigafactories through subsidies and incentives.

THE GLOBAL REGULATORY PICTURE

Regulations around battery recycling and sourcing rare materials vary worldwide but show an overall trend toward stricter standards. Asia, especially South Korea and China, was a notable first mover, with battery recycling regulations in place since 2013. This led to a current recycling rate of approximately 90% and a well-developed, profitable circular economy around batteries.

> ***REGULATIONS AROUND BATTERY RECYCLING AND SOURCING RARE MATERIALS VARY WORLDWIDE BUT SHOW AN OVERALL TREND TOWARD STRICTER STANDARDS.***

The EU's 2006 Battery Directive set a 55% recycling rate target. Realizing this was insufficient, its 2023 Battery Regulation marks a shift toward establishing a closed-loop battery value chain. This includes targets for both recycling particular materials and their reuse in the production of new batteries, including:

- Increasing lithium recycling rates from 50% to 80% between 2028 and 2032
- Increasing cobalt, copper, nickel, and lead recycling rates to 90% from 2028, rising to 95% by 2032

In the US, there is no overarching requirement for battery recycling. However, initiatives such as the Department of Energy's Lithium-Ion Recycling Prize and programs such as Call2Recycle actively promote and improve battery recycling practices. Furthermore, the Critical Minerals and Materials (CMM) Program indirectly encourages battery recycling by listing certain materials, including cobalt and nickel, as essential for clean technology.

THE LI-ION BATTERY RECYCLING PROCESS

Battery recycling broadly follows a three-stage process:

1. **Reverse logistics (collection/sorting):** Spent batteries are collected/transported to operating hubs and sorted.
2. **Pre-treatment:** Batteries are discharged, disassembled, and mechanically reduced through shredding. This results in black mass, a dark powder comprising all battery materials.
3. **Materials recovery:** Black mass is processed to extract metals by chemical or thermal processes or a combination thereof. Advanced process routes today deliver a greater than 90% recovery rate for elements including lithium.

CURRENT CIRCULAR ECONOMY BUSINESS MODELS

Batteries for recycling come from two sources: production scrap from battery gigafactories and EOL batteries from EVs, energy storage, cellphones, and laptops. The average life of EV batteries in first and (less demanding) stationary second-life applications is estimated to reach 10-15 years easily. That means most recyclers focus on batteries from production scrap, especially through closed partnerships between battery manufacturers and recyclers.

This will change in the medium term as EV numbers increase. In Europe, 2030–2035 is forecast to be the cross-over point when EOL volumes from EVs overtake production scrap to form the majority of recycling stock. This will enable new business models, such as vehicle OEMs or battery manufacturers, to retain ownership of the battery materials and use recycling companies as service providers to carry out the extraction process.

In Asia, where battery and EV production picked up earlier, recyclers have already built and begun operating large-scale hydrometallurgy facilities, processing black mass, including from Europe, at scale. This enables more economical operations and has stimulated a strong local market for black mass, resulting in prices around 20% higher than in Europe. The combination of these higher prices and a dearth of current hydrometallurgy operations in Europe leads to surplus black mass being exported to Asia, raising concerns about material security.

THE CHALLENGES TO URBAN MINING

To gain deeper insight into economic perspectives on current and future battery recycling, ADL conducted a research project with RWTH Aachen University in Germany. The project involved interviewing industry experts about the challenges and opportunities for urban battery mining. The results identified six key challenges and cost drivers that need to be overcome.

1. THE HYDROMETALLURGICAL PROCESS

The biggest obstacle to recycling in Europe is the cost of establishing and running hydrometallurgy facilities, as highlighted by two-thirds (66%) of experts. This covers the CAPEX investment required for building complex, specialized facilities capable of handling aggressive chemicals at scale and operating costs. Extracting valuable metals such as lithium, nickel, cobalt, and manganese in battery-grade quality requires precise controls and sophisticated procedures to ensure high-purity recovery. Residues and byproducts include toxic substances and heavy metals, requiring substantial (and expensive) treatment processes to ensure compliance with environmental regulations.

THE BIGGEST OBSTACLE TO RECYCLING IN EUROPE IS THE COST OF ESTABLISHING AND RUNNING HYDROMETALLURGY FACILITIES, AS HIGHLIGHTED BY TWO-THIRDS (66%) OF EXPERTS.

2. BATTERY TRANSPORTATION

There are stringent safety regulations around the transport and storage of EOL or waste Li-ion batteries, some of which are country-specific. Ninety-two percent of experts identified these requirements as challenging because of the high costs they add to battery transportation. A lack of transparency around the condition of batteries (i.e., whether they are simply EOL or have defects) further adds to transport expenses, requiring the greater, potentially unnecessary use of heavy and space-consuming metal containers. Long transport distances, especially over national borders, and lack of experience with safely transporting batteries also add to costs.

3. SITE SELECTION AND PERMIT ACQUISITION

Hydrometallurgical facilities require specific conditions, such as access to sufficient bodies of water, which complicates where they can be located, while the chemical intensity of their processes requires companies to obtain detailed permits for their operation. Securing the right permissions can take substantial amounts of time and requires complex negotiations with regulatory bodies and engagement with local communities and businesses. Permitting and regulations also vary between countries, adding further complexity and potentially leading recycling companies to set up operations in less regulated geographies.

4. SECURING A CONSISTENT SUPPLY OF BATTERIES AND MANAGING UPSTREAM/ DOWNSTREAM PARTNERSHIPS

Industry experts see demand increasing for EOL batteries as companies position themselves for the future. Just under half (43%) of respondents perceive securing future return volumes as a significant to enormous challenge because of growing competition. Two factors exacerbate this:

1. **EV OEMs significantly influence the market,** for example, by specifying quantities available for recycling and inviting bids for battery processing. This requires recyclers to navigate complex tender processes — often for short (one-year) contracts — limiting the ability to plan effectively.

2. **New players, often from Asia or North America, are entering the market.** Many have substantial financial resources or experience, meaning they will disrupt market dynamics, potentially through aggressive pricing strategies designed to gain market share.

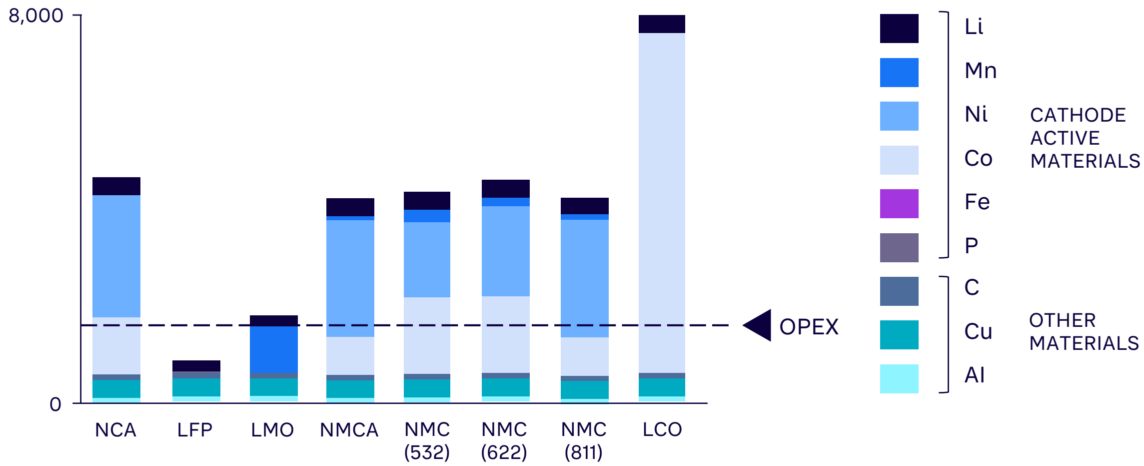
5. REGULATORY COMPLIANCE AND OPERATIONAL EFFICIENCY

Within the EU, the Battery Regulation mandates minimum recycling rates for specific battery materials, which will progressively increase. Experts believe achieving these targets is technically feasible but will pose a significant operational challenge to recyclers, requiring substantial effort and process optimization to comply. Conversely, increasing recycled content requirements in European batteries will drive the need for recycling.

6. CHANGING BATTERY CHEMISTRIES

Given the significant cost of rare metals, battery manufacturers are looking to alternative battery chemistries that require cheaper inputs. For example, expensive nickel, manganese, and cobalt (NMC) batteries are increasingly being replaced by cheaper new technologies such as lithium iron phosphate (LFP), which contain neither nickel nor cobalt (see Figure 2). LFP is expected to make up 50% of recycling feedstock by 2030. However, recycling profitability is much lower since lithium is the most valuable material that can be extracted from LFP batteries besides the lower-value iron and phosphate components. This is a particular challenge in Europe and North America; in Asia, there is an established, profitable market for LFP recycling. New, lower-cost batteries such as sodium-ion may further lower recycling profitability.

IN EURO PER TON OF RECYCLED BATTERIES BY CHEMISTRY



KEY ASSUMPTIONS

Commodity prices: Average 2021 material prices (before high-volatility period)
Battery component composition: Cathode (30%), anode (15%), electrolyte (10%), aluminum (20%), copper (15%), and others (plastic, binder, etc.) (10%)
Cathode material composition: Material mix dependent on battery chemistry
Component recovery rate: Cathode, anode, electrolyte, aluminum, and copper are recovered
Material recovery rate: Ni, Co, Cu, Li (aligned with regulations in EU)
OPEX: Assumption for average mechanical + hydro route

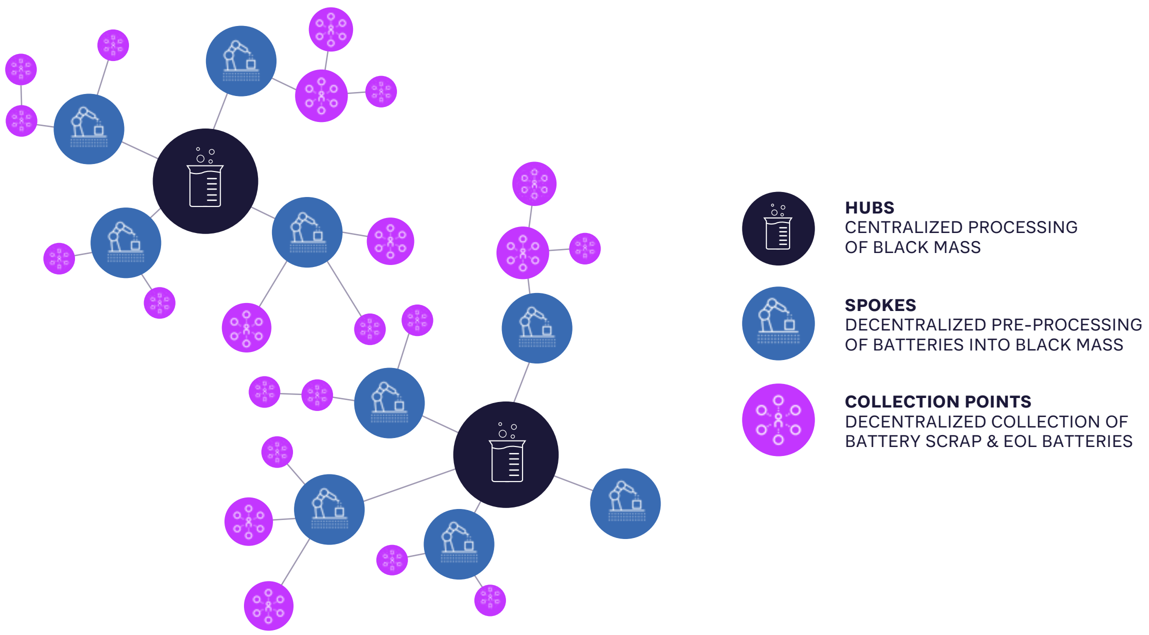
Source: Arthur D. Little

FIGURE 2: THE RECYCLING ECONOMICS OF DIFFERENT LI-ION BATTERY CHEMISTRIES

RECOMMENDATIONS FOR BATTERY RECYCLING PROFITABILITY

The creation of large-scale circular economies around battery recycling is vital to the green transition, particularly in Europe. While significant challenges exist, focusing on four recommendations helps overcome obstacles around profitability and provides lessons for businesses creating circular economies in other areas.

1. ADOPT A HUB-AND-SPOKE MODEL FOR LOGISTICS



Source: Arthur D. Little

FIGURE 3: OPTIMIZED HUB-AND-SPOKE MODEL FOR RECYCLING

Transporting EOL batteries over long distances is costly and raises safety concerns. By contrast, moving processed black mass is simpler and much less expensive. Consequently, recyclers should adopt hub-and-spoke models for their operations, with multiple local collection points for EOL batteries feeding spokes where initial mechanical processing is carried out (see Figure 3). The resulting black mass can then be transported to accessible central hydrometallurgy hubs for extraction. This model mitigates environmental impacts and bolsters economic efficiencies, streamlining collection, reducing transportation costs (and emissions), and improving safety. Required capital is reduced as the number of hydrometallurgy hubs is minimized.

The two main challenges to this approach are:

1. The significant costs of transporting EOL batteries across borders if spokes are located in different countries.

2. The reliance on a small number of large processing hubs. Hub failure or overload could paralyze operations, and securing suitable sites of sufficient size is vital to achieving economies of scale.

Case example: Li-Cycle

Li-Cycle, headquartered in Canada, is an international battery recycling company that applies the hub-and-spoke logic in its operations. Geographically distributed spokes pre-process packs and deliver black mass. Concentrated hubs continue with hydrometallurgical processing of black mass. Li-Cycle set up a North American hub in Rochester, New York, and has announced plans to install a European hub in Portovesme, Italy.

2. INNOVATE IN TECHNOLOGY AND PROCESSING

Improving current processing techniques and technologies can reduce costs, increase profitability, and optimize operations.

Two-thirds of experts see presorting batteries as an area that needs to be significantly improved. Currently, many recyclers don’t presort before starting to process, creating greater effort later. Presorting enables recyclers to:

TWO-THIRDS OF EXPERTS SEE PRESORTING BATTERIES AS AN AREA THAT NEEDS TO BE SIGNIFICANTLY IMPROVED.

- Distinguish between batteries with the same chemistry but different material percentages (e.g., NMC 111 batteries are significantly more valuable because of their higher cobalt content than NMC 811)
- Understand the battery’s condition so it can be processed differently, such as being repaired rather than recycled

Additionally, current recycling processes are not optimized for efficiency or material separation, adding to costs and meaning valuable metals are lost, such as lithium. Innovative technologies offer the possibility of:

- Improving yields
- Reducing energy consumption (and, consequently, costs)
- Substituting biological solvents for more aggressive/higher-emitting chemicals in the hydrometallurgy process, reducing environmental hazards and regulatory requirements

3. USE MACHINE LEARNING AND AI TO OPTIMIZE RECYCLING

Rightsizing operations and managing capacity and utilization are crucial for recycling profitability. AI supports planning optimization through more accurate short-/medium-term raw material price forecasting based on a much wider range of data inputs and advanced simulations. This enables recyclers to flexibly adapt their capacity planning, operations management, and procurement functions. AI also optimizes location planning for hubs and spokes and related transport and logistics.

In operations, better AI-powered analytics can help predict and diagnose battery health, value, and handling risks more accurately in conjunction with tools such as the EU's proposed battery passport. AI agents trained with large amounts of battery data can enable new recycling methods such as direct recycling of cells or cell components through better diagnostics on a more granular level. Machine learning also supports greater automation to reduce and remove recycling bottlenecks. Cameras for computer vision and robotics to identify packs, their designs, and conditions enable more automated disassembly processes. This will be critical when volumes of EOL batteries grow and recycling facilities are scaled for efficiency.

Case examples: Circu Li-ion and Li Industries

European start-up Circu Li-ion leverages AI applications in automated sorting combined with electrochemical techniques to improve efficiency in the recycling process. Batteries and cells that are fit for more direct recycling approaches than shredding and hydrometallurgy are detected and separately processed. Another example is Li Industries from the US. This cleantech company that focuses on developing next-generation Li-ion battery recycling developed a smart sorting solution with AI.

4. LEVERAGE ECONOMIES OF SCALE

Asian recyclers show the benefits of economies of scale regarding efficiency, yields, and higher profitability. For example, break-even in hydrometallurgy is achievable only with a capacity of at least 20,000 tons of black mass per year, as scaling up quantities doesn't proportionately increase plant and material costs. Six in 10 experts say European recyclers need to make large-scale adjustments to achieve similar economies of scale. Adopting hub-and-spoke models helps with scale, securing sufficient supplies of black mass to drive profitability.

Case example: BrunP Recycling

BrunP Recycling, a subsidiary of the world's largest Li-ion battery producer (China's CATL), is closing the battery materials loop globally with recycling operations in China and Indonesia and expansion plans for Europe. BrunP's recycling facilities in Hunan, China, are reportedly the biggest in the world, with the capacity to process 100,000 tons per year. In comparison, most operational Western facilities cope with amounts of 5,000-20,000 tons per year.

INSIGHTS FOR THE EXECUTIVE

Embracing the circular economy for profitability, such as around battery recycling, requires businesses to focus on four key areas:

1. **Build partnerships across ecosystems, often with non-traditional partners:** This includes long-term relationships with all types of players along the battery lifecycle to stabilize supply and demand. It is vital not to limit partnerships to pure battery players but to look more widely; for example, to second-life users in the electricity infrastructure industry, providers of advanced battery analytics, suppliers of machinery, and experts in waste collection and logistics.

2. **Monitor and understand changing regulatory plans and potential subsidies that can help underpin investment:** One key driver of recycling businesses is regulatory requirements regarding batteries, such as the new European Battery Regulation. Beyond that, supply chain transparency rules or carbon footprint regulations indirectly impact the choice of processes and materials and can push demand for recycling output.

3. **Use AI to predict better demand and material prices, enabling more informed and accurate decision-making:** Operating and developing in a highly complex and competitive environment, profitable battery recycling operations rely on well-founded decisions. These require the best available data and capable tools to make better predictions and draw smarter conclusions. AI may boost the analytical capabilities of recycling businesses and deliver a decisive competitive advantage in the years to come.

4. **Plan and invest now when volumes may be low to gain a leadership position for when volumes increase:** The Chinese recycling ecosystem shows that starting early and establishing a footprint and credibility is a key requirement for success and profitability. Outside China, the first major materials and chemical incumbents and some large-scale entrants have started to stake claims. New, innovative businesses can still disrupt by finding better ways to deliver profitable and sustainable recycling in this dynamically evolving industry.

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GETTING A GRIP ON DECARBONIZATION WITH EFFECTIVE INTERNAL CARBON PRICING

AUTHORS

Pavel Kubička, Martijn Eikelenboom, Jiří Steif, Trung Ghi, Louay Saleh, Erik van der Wurff

Regulators and other stakeholders are increasing pressure on organizations to monitor, improve, and share information on their greenhouse gas (GHG) emissions. They want increased transparency around targets, timelines, and plans and are increasingly demanding actual results from decarbonization efforts.

The number of emission trading schemes (ETS) and carbon taxes is rising worldwide. In 2024, 75 carbon pricing initiatives were in place, covering 24% of global GHG emissions. Other countries are discussing implementing their own carbon pricing schemes.

As the world moves toward pricing carbon, organizations must respond by better managing and steering their carbon footprint. They need to start pricing carbon internally, using techniques such as internal carbon pricing (ICP), which contributes to better trade-offs in decision-making and considers the likely future price of externalities (as costs will be gradually internalized in products). Without ICP, procurement and other departments will never be incentivized to purchase and create more sustainable products.

> ***AS THE WORLD MOVES TOWARD PRICING CARBON, ORGANIZATIONS MUST RESPOND BY BETTER MANAGING AND STEERING THEIR CARBON FOOTPRINT.***

While many companies use ICP, most only deploy it in the margins of their operations. They are not leveraging its potential to become the core of their decarbonization approach, which could satisfy sustainability targets and deliver significant value to the organization. This is partially because providing effective programs in practice is not easy, thanks to the sheer complexity of organizations and their supply chains and an absence of reliable data (both from upstream and downstream emissions). Consequently, many organizations that have launched ICP programs have only applied them to selected Scope 1 (and 2) emissions and set carbon prices at conservative levels, with the actual weight of carbon pricing in decision-making not rigorously set.

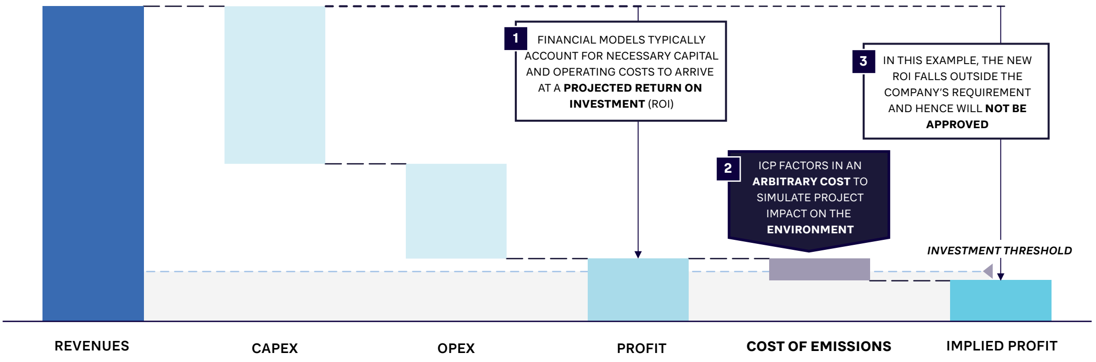
Now is the time for organizations to implement and step up their ICP programs to steer and mitigate their carbon emissions in line with their decarbonization strategies. This requires a much more holistic focus, putting in place a comprehensive, data-driven approach built on internal and external sources, starting small and growing to cover all material emissions across Scope 1, 2, and 3. It should enable granular and flexible emissions management by categories such as business unit, geography, type of emissions, or type of decisions, using parameters such as weight in decision-making or current and future carbon dioxide (CO2) price. This will give CEOs a much firmer grip on their decarbonization strategy, enabling them to guide it more confidently and effectively navigate a world where carbon will have an increasingly higher price.

THE NEED TO BETTER MANAGE EMISSIONS

Multiple factors are pushing companies to manage and decrease their GHG emissions:

- **Regulatory mechanisms:** Many governments have already implemented carbon-pricing mechanisms, such as carbon taxes, cap-and-trade systems (e.g., EU ETS), or the EU's Carbon Border Adjustment Mechanism (CBAM), to incentivize companies to reduce their GHG emissions. The direction of travel is clear, with new regulations, such as the EU Corporate Sustainability Reporting Directive (CSRD) and the International Sustainability Standards Board (ISSB) S1 and S2 standards, requiring companies to disclose their current GHG emissions, including Scopes 1, 2, and 3. Also influencing this direction are set targets and obligations to report on progress.
- **Market-driven mechanisms:** Businesses also face pressure from consumers, investors (e.g., ESG [environmental, social, and governance] funds or general investment funds with ESG criteria such as BlackRock), and business partners/customers that have committed to reducing their total emissions and mandate that their supply chains, therefore, better manage their own emissions.
- **Legal challenges:** Multiple large companies have been sued for damaging the environment through fossil fuel production or not keeping to their publicly declared promises around GHG emissions. For example, in 2021, a court in The Hague, the Netherlands, ruled that Shell must decrease its CO2 emissions by 45% by 2030 in line with Paris Agreement goals, covering both emissions from its operations and those from the use of fossil fuels it produces.
- **Voluntary initiatives:** Many companies have voluntarily committed to reducing their GHG emissions by setting internal targets or joining programs such as the Science Based Targets initiative (SBTi) or RE100. ICP is critical to monitoring and meeting these targets and engaging the entire business in reducing emissions.

HOW DOES AN INTERNAL CARBON PRICE WORK?



Source: Arthur D. Little

FIGURE 1: ILLUSTRATION OF AN INTERNAL CARBON PRICE

Figure 1 shows how an internal carbon price factors in an additional metric (the financial cost of emissions) when making investment and procurement decisions and generating a projected net present value (NPV). This is then used as part of the calculation to understand whether a project or purchase fits within company ROI thresholds and make a go or no-go decision.

It is important to understand that the ICP's impact on project approvals can be both negative and positive. It can rule out investments that add significantly to organizational GHG emissions; equally, factoring in the cost of avoiding emissions can enable sustainability projects to go forward, even if they would not have been approved using traditional profitability calculations that did not consider carbon prices.

In terms of legislative requirements, the use of ICP is currently voluntary. New legislation such as the European Sustainability Reporting Standards (ESRS), IFRS S2, and US Securities and Exchange Commission (SEC) Climate-Related Disclosures merely asks:

- If an ICP is used at all?
- If in place, what is the price/t CO2?

In addition, the ESRS and IFRS S2 (but not SEC climate-related disclosures) ask how the ICP is used in decision-making.

THE CURRENT CHALLENGES TO ICP USE

Extending ICP and making it the cornerstone of a more rigorous and effective decarbonization strategy faces two current challenges: the need for reliable data and prioritization among competing concerns.

NEED FOR RELIABLE DATA

Calculating realistic carbon prices for projects requires an accurate understanding of the emissions that an organization generates. This includes emissions created by the organization (Scope 1), emissions from purchased energy (Scope 2), and, increasingly, Scope 3 data from upstream and downstream emissions. Collecting this data and ensuring it is accurate and trustworthy, particularly from outside the organization, can be difficult. It requires a holistic approach and, importantly, relies on buy-in from different business units and external suppliers.

> ***CALCULATING REALISTIC CARBON PRICES FOR PROJECTS REQUIRES AN ACCURATE UNDERSTANDING OF THE EMISSIONS THAT AN ORGANIZATION GENERATES.***

To overcome the lack of reliable data, companies should begin by adopting an estimation method (e.g., spend-based, average data, or hybrid models), which provides an initial understanding of relevant GHG emissions. The weight given to ICP within decision-making should be proportionate to data quality. Suppose companies decide to give ICP greater weight. In that case, they need to gradually move to collecting primary emissions data, including through supplier engagement, and start with areas with a large impact and lower emission data point requirements, such as investments.

PRIORITIZATION AMONG MULTIPLE COMPETING CONCERNS

Companies face many serious issues, including high energy prices, inflation, and unstable supply chains. Given that ICPs are not mandatory, the temptation could be to avoid spending additional time and effort to develop one today. In fact, now is the optimum moment to start — as examples show, it takes time to build an optimal ICP that is fully aligned with the company’s strategy. Businesses can then use it to increase their resilience against future changes in regulations and mandatory carbon prices.

GETTING STARTED WITH ICP

Fully embedding ICP now gives companies greater control over carbon-reduction strategies, demonstrates transparency, increases efficiency, and delivers first-mover advantage, providing a framework for achieving future sustainability targets, as the success of leaders shows.

Successfully implementing ICP requires organizations to focus on the following five areas.

1. INVOLVE ALL KEY CORPORATE FUNCTIONS

Setting an internal carbon price and then using it effectively requires a holistic approach that stretches across key functions, especially:

- **Executive leadership:** Setting the strategic direction for the ICP initiative and providing necessary resources and commitment
- **ESG/sustainability:** Contributing expertise on climate change and carbon management, identifying opportunities for emission reductions, and ensuring that the ICP aligns with the overall sustainability strategy
- **Finance:** Taking a lead role in designing the ICP mechanism, integrating it into the company's financial systems, and tracking its financial impacts
- **Operations:** Implementing the ICP within the company's day-to-day activities, including projects to reduce carbon emissions, monitoring progress, and ensuring compliance
- **Procurement:** Modifying processes and incorporating the ICP into supplier contracts, ensuring partners are aware of the company's carbon-pricing policy
- **HR:** Communicating the ICP to employees and providing support in developing training programs and incentives
- **Legal and compliance:** Ensuring the ICP adheres to relevant laws and industry standards, managing any implementation risks
- **Communications/marketing:** Promoting the ICP both internally and externally, highlighting the company's commitment to sustainability

Getting buy-in from the entire business is vital to drive acceptance and support for the ICP.

2. CHOOSE A MODEL/BENCHMARK

ICP can be applied through a range of models. The most common are:

- **Shadow price:** This approach calculates the impact of mandatory carbon prices on future business operations and acts as a tool to identify potential climate risks. This approach aims to influence decision-making. About 80% of companies that report using ICP have chosen this approach, including Panasonic and Teijin.

- **Internal fee:** This approach takes carbon pricing a step further and involves the company charging itself a fee for every ton of carbon emissions it produces ("internal carbon tax"). Based on how it is implemented, it can provide a clear incentive for business units to reduce emissions through payment to the "corporate," thus generating revenues that can then be assigned to sustainability projects. It is more suitable for companies in low-carbon-intensity sectors, such as technology, financial, and professional services. Companies employing this methodology include Klarna and Swiss Re.

Early in the ICP process, senior leadership should decide strategically on the models and approaches to adopt to support their strategy. This will vary depending on factors such as the industry they are in, the level of current emissions, and how these will be reduced.

For example, in 2019, insurer Swiss Re committed to net zero emissions across the company and introduced an internal carbon price for operations, initially set at $8/tCO2e. This increased to $100/tCO2e in 2021, with a plan to gradually raise it to $200/tCO2e in 2030. As of 2023, Swiss Re's operational GHG emissions amounted to around 28,000 tons of CO2e, and the 2023 internal carbon tax price was increased to $123/tCO2e. Through this, Swiss Re has generated an estimated US $3.4 million to cover the costs of the carbon removal certificates, which it plans to use to compensate for its emissions while incentivizing business units to take concrete action on emissions reduction. The program is accompanied by other measures, including increasing energy efficiency, switching to 100% renewable electricity, and reducing business air travel.

> ***EARLY IN THE ICP PROCESS, SENIOR LEADERSHIP SHOULD DECIDE STRATEGICALLY ON THE MODELS AND APPROACHES TO ADOPT TO SUPPORT THEIR STRATEGIES.***

3. SET THE CARBON PRICE

ICP is being used across sectors with vastly different carbon prices. Therefore, one of the most important tasks for each company is to set its own ICP carbon price. Five key factors should be considered:

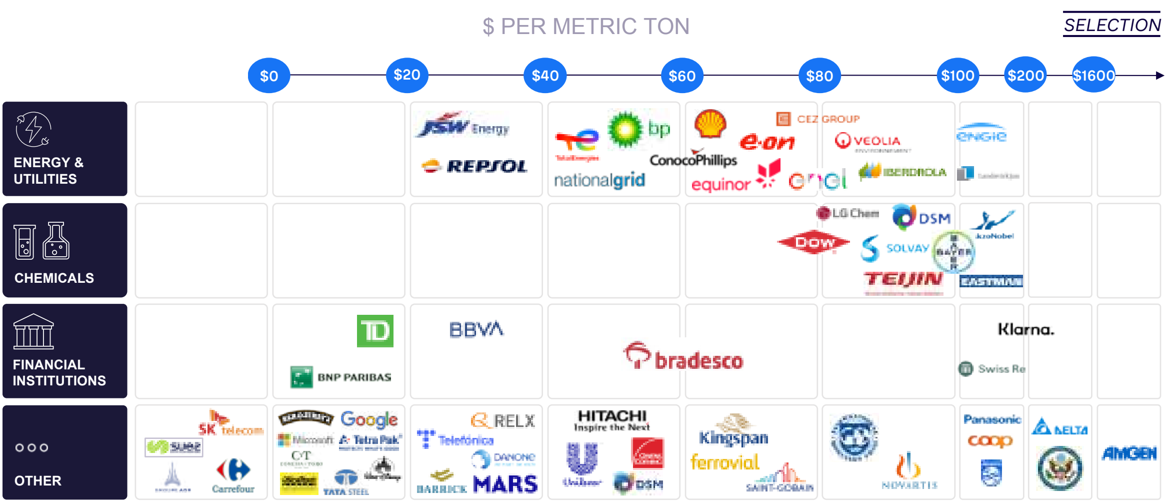
1. The social cost of carbon: This is based on externalities caused by emitting an additional ton of CO2e into the atmosphere. According to the UN Global Compact, the recommended carbon price should have been at least $100/tCO2e by 2020, the US Environmental Protection Agency (EPA) suggested $190/tCO2e in 2022, and the International Monetary Fund (IMF) sees an international carbon price floor as the only viable scenario that would limit CO2 emissions sufficiently and suggests at least $85/tCO2e by 2030.

2. Expected regulatory changes: Assess existing and anticipated carbon-pricing policies and regulations, including carbon taxes, cap-and-trade systems, and other market-based mechanisms. A sufficiently high ICP can help align with future mandatory/regulatory carbon price increases.

3. Organizational incentives: To fully leverage the potential of ICP, the chosen carbon price needs to be high enough to influence decision-making. Furthermore, the entire ICP structure needs to be set up to encourage innovation and efficiency.

4. Industry benchmarks and market trends: Consider carbon prices adopted by competitors, industry leaders, and other organizations with similar operations and emissions profiles. Figure 2 shows examples of internal carbon prices set by specific companies — these examples are based on CDP data and information from company websites. Monitor global carbon market trends, including the prices of carbon credits and allowances and the direction of carbon-pricing policies.

5. Cost of abatement: Estimate the cost of implementing emission-reduction measures. The internal carbon price should be set at a level that incentivizes investments in these measures and technologies.



NOTE: EQUINOR USES AN INTERNAL CARBON PRICE OF $80/T FOR PROJECTS IN NORWAY AND $55 PER METRIC TON GLOBALLY;
AMGEN USES $1000 ICP FOR PROJECTS THAT GENERATE SUBSTANTIAL CO2E. MORE EXPENSIVE PROJECTS WITH CO2E COST OF <$1600/T ARE CONSIDERED "REASONABLE"

Source: Arthur D. Little, CDP, World Bank Group, S&P, FD

FIGURE 2: INTERNAL CARBON PRICES DISCLOSED PUBLICLY BY LARGE ORGANIZATIONS

The internal carbon price should evolve over time, aligning with external developments and internal capabilities' growth. Japanese chemical, pharmaceutical, and information technology company Teijin launched an ICP focused on Scope 1 and 2 emissions in capital investment in 2021, with a carbon price set at €50/tCO2. In 2023, it expanded to add M&A projects, renewable energy sourcing, and supply chain emissions (Scope 3, Category 1) while doubling the carbon price to €100/tCO2 (see Figure 3).

CATEGORY	INITIAL SETUP (SINCE 1/2021)	ROLE & SCOPE EXPANSION (SINCE 4/2023)
IN-HOUSE CO2 EMISSIONS (SCOPES 1 AND 2)	CAPITAL INVESTMENTS	• CAPITAL INVESTMENTS • (NEW) M&A PROJECTS • (NEW) LONG-TERM SOURCING OF RENEWABLE ENERGY, ETC.
CO2 EMISSIONS IN SUPPLY CHAIN (SCOPE 3 CATEGORY 1)	N/A	• (NEW) CAPITAL INVESTMENTS
PRICING (WORLDWIDE)	EUR 50/TON-CO2	• (REVISED) EUR 100/TON-CO2

Source: Arthur D. Little

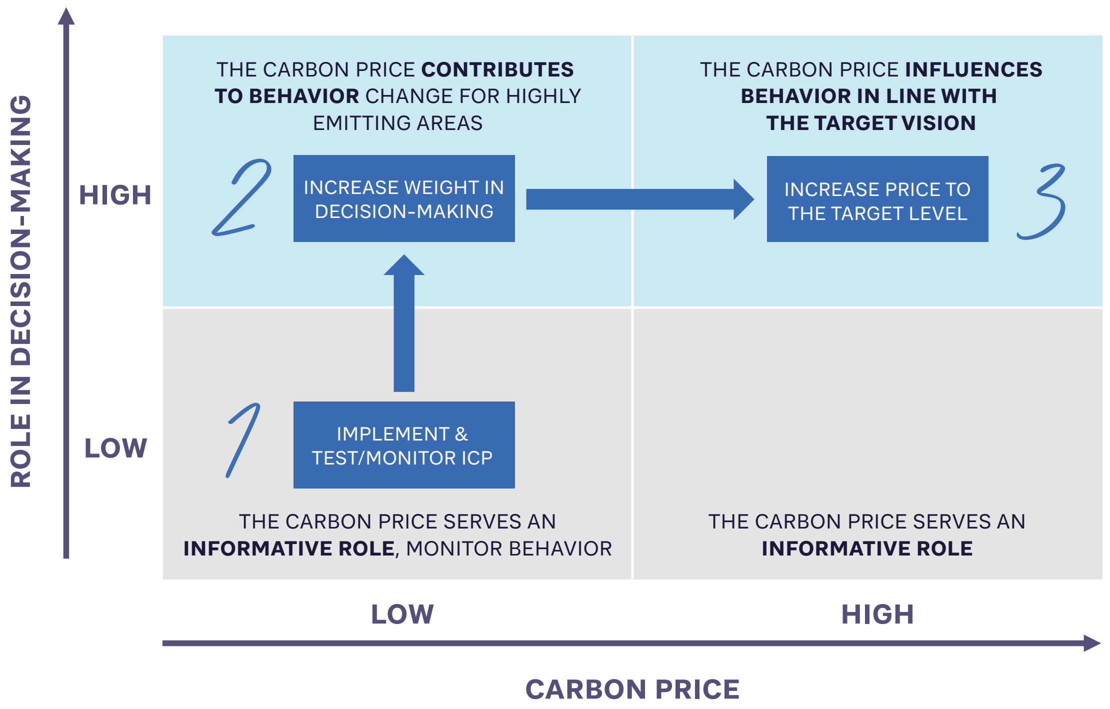
FIGURE 3: TEIJIN'S NEW ICP SYSTEM

4. START SMALL AND BUILD

Depending on the organization and its structure, ICPs can be complex to implement, particularly given the often-large range of operations across geographies, legislations, and products; complex and lengthy supply chains; and the volume and quality of data required for all material emission sources. However, rather than risking project failure through overlong implementation time frames, organizations should focus their approach, starting small, piloting, and building from there. For example, they can begin by applying the ICP to major capital investments and move on to major purchases, gradually decreasing the emissions thresholds for inclusion. Starting with the areas that create the largest emissions delivers the greatest scope for improvement.

Companies should not stop with carbon price–adjusted CAPEX decisions. If the impact of carbon emissions did not adjust the relevant future cash flow, EBITDA, or KPIs, a negative effect on their KPIs and bonuses could make executives reluctant to invest. Therefore, a clear and transparent framework for how carbon pricing will impact financial metrics and compensation needs to be developed. For example, Microsoft's internal carbon fee model impacts operational decisions and is reflected in the financial performance of different business units.

ICP rollouts can be phased. Once the initial framework is in place, ensure everyone is comfortable using it, starting with a low price and low decision-making weight for carbon. This pilots the ICP, making everyone aware of it and providing the ability to check data quality and other processes. After the system has bedded in, move on to monitoring its impact on key areas before increasing the carbon price and its weight in decision-making to the desired level (see Figure 4).



Source: Arthur D. Little

FIGURE 4: A PHASED APPROACH TO ICP ROLLOUTS

Panasonic provides a strong example of this gradual approach. The company emits approximately 110 million tCO2e/year across its value chain. It implemented an ICP system on a trial basis starting in fiscal 2024, focusing on investment decisions in its Living Appliances and Solutions business, with the carbon price set at ¥20,000/tCO2 (around US $143). From fiscal year 2025, the pilot ICP system will be rolled out more widely, adapting to the characteristics of each business unit. In addition to Scope 1 and 2 emissions, for which its goal is net zero by 2030, Panasonic is using its ICP to target Scope 3 emissions to achieve complete net zero by 2050.

5. MONITOR, STEER, AND ADAPT

ICP models must be designed and tailored to support individual company strategy and objectives. By establishing a comprehensive monitoring view (see Figure 5), companies can then amend key parameters (e.g., the price of carbon in the business units or geographies where it is applied and its weight in decision-making) to steer their strategy in line with wider business goals. For example, they can apply higher costs on some business units or geographies or tighten or loosen particular parameters based on other economic or corporate priorities.

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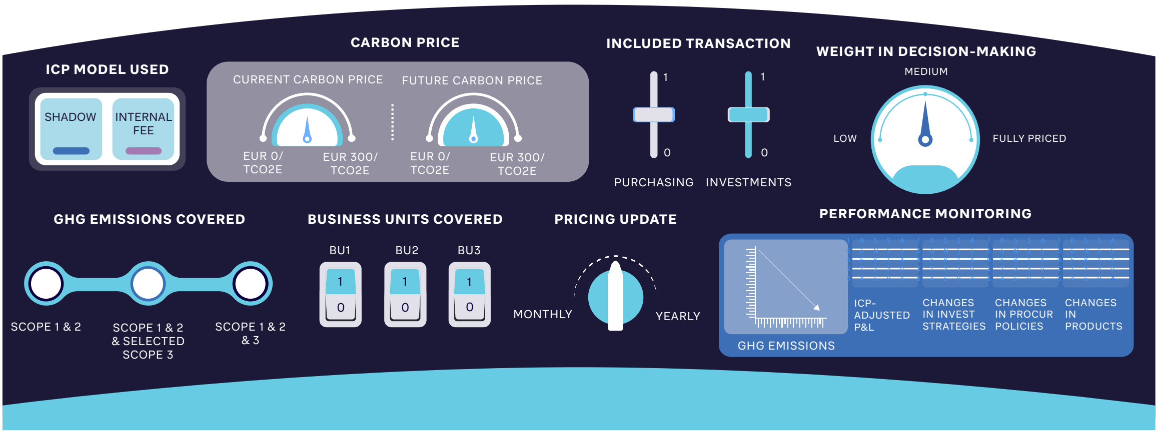

Source: Arthur D. Little

FIGURE 5: COCKPIT VIEW OF ICP

Swedish fintech company Klarna illustrates this ability to adapt. It has set a target of achieving net zero by 2040, with ICP central to its strategy. In 2020, it set a carbon price of $100/tCO2 for its Scope 1, Scope 2, and Scope 3 travel emissions, with remaining Scope 3 emissions priced at $10/tCO2, intending to create accountability and incentivize emissions reduction. In 2024, it increased the price for Scope 1 and 2 to $200/tCO2e. This has generated $7 million since 2021, with Klarna investing much of this money in around 20 climate technology start-ups. Klarna also allows its customers to donate to these start-ups through its app, adding new offerings to its portfolio.

INSIGHTS FOR THE EXECUTIVE

Achieving decarbonization is a journey — and organizations need to ensure that they are moving forward and accelerating their efforts if they are to reach objectives such as becoming net zero by 2050, as well as prepare for ever-tightening regulation. Establishing an internal carbon price and monitoring mechanism delivers robust support to investment and procurement decision-making, steering the organization now and in the future. To ensure success in this complex program, CEOs should:

- **Set overall strategic direction around carbon reduction:** If decreasing emissions is important, or the growing price of carbon or current or future regulations would significantly impact your company, make ICP the cornerstone of your decarbonization approach.
- **Set overall aspirations for ICP:** What are the key aims and objectives? Are they to influence decision-making or also to raise money to launch decarbonization projects? This will drive the models and approaches used.
- **Start now to give visibility for the future:** This is particularly true when planning major long-term investments, such as new factories or facilities, with significant carbon risks and lengthy project timelines.
- **Get buy-in from across the business and create cross-functional teams** to deliver a cohesive implementation.
- If you opt for an ICF approach, **define and communicate early how you will use the funds collected** to create additional benefits, including investments in climate technologies.
- **Start small and build:** First, put the framework in place, then extend it to other key areas, gradually increasing data quality, prices, and weighting to make it an intrinsic part of all investment and procurement decision-making. Develop a clear and transparent framework for how carbon pricing will impact financial metrics and compensation. By the end, you will need a flexible steering tool to help you manage the company into the future based on strategy.
- **Finally, additional externalities should be considered in decision-making:** For example, water is increasingly becoming a critical issue in many areas, so representative freshwater use and water pollution costs should be factored into relevant decision-making. Social externalities can also be considered and monetized. Companies with mature sustainability strategies consider the costs of over 20 externalities in their decision-making.

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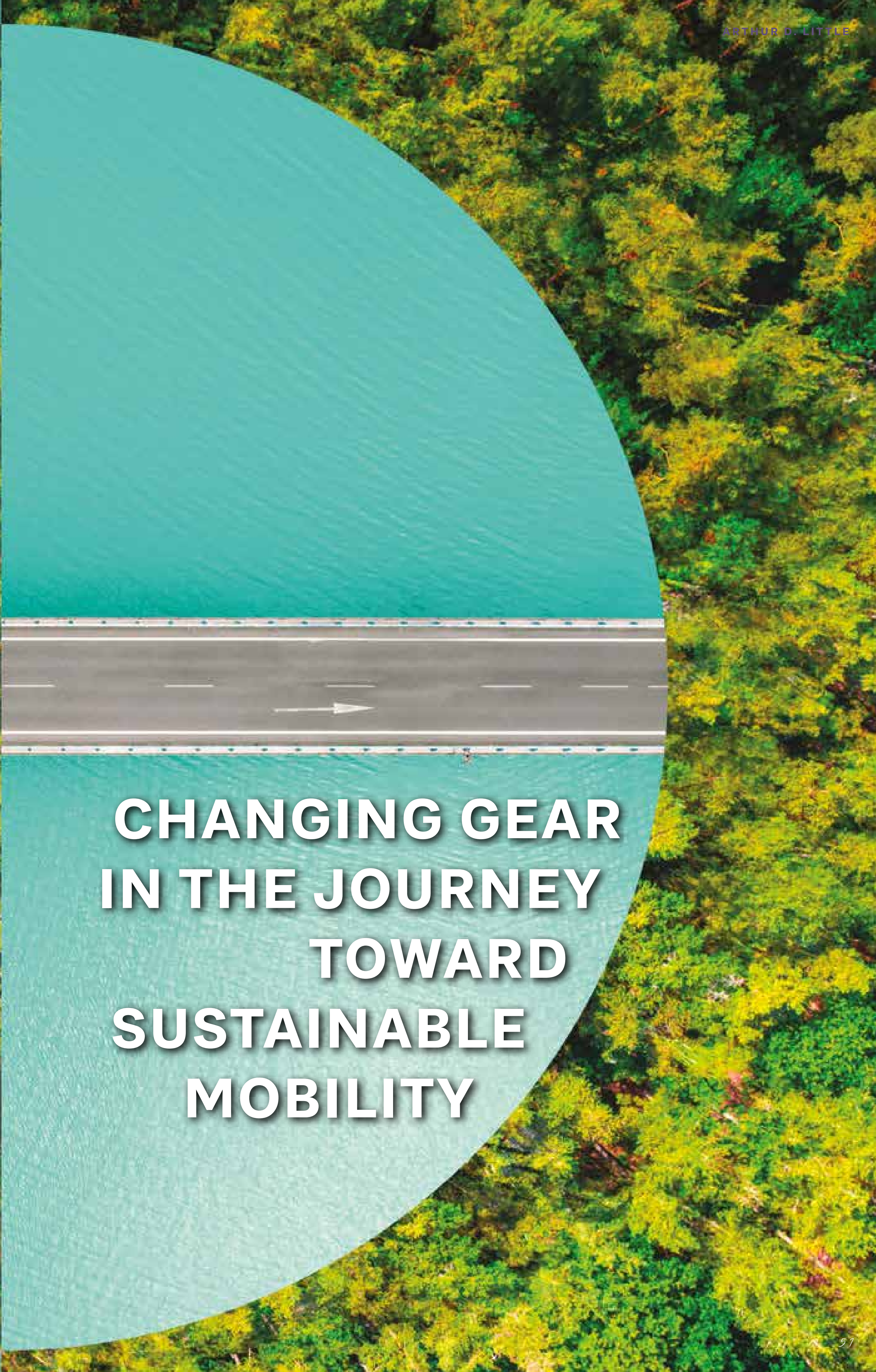
MAKING THE SHIFT —



CHANGING GEAR IN THE JOURNEY TOWARD SUSTAINABLE MOBILITY

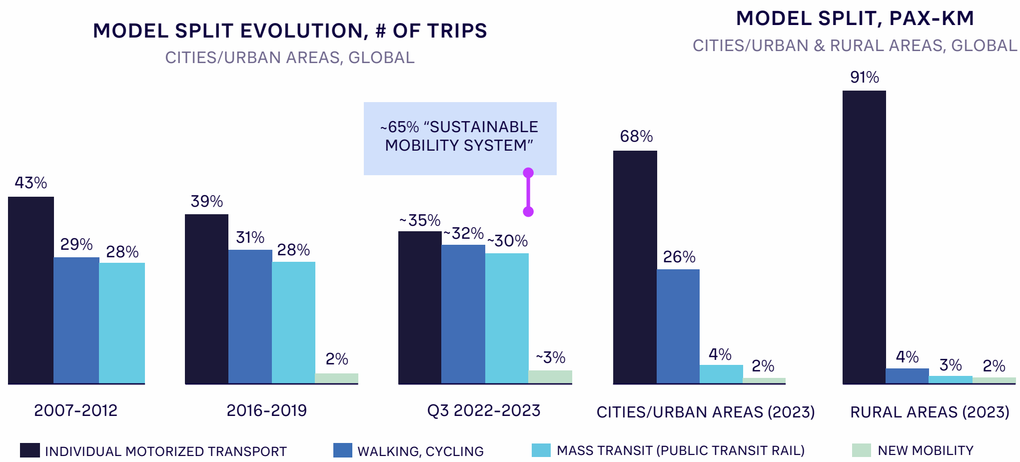
AUTHORS

Francois-Joseph Van Audenhove, Mickaël Tauvel, Arsene Ruhlmann, Vadim Panarin, Dr. Philipp Seidel, Alexander Hensler, Rick Eagar

When Arthur D. Little (ADL) first set up its Future of Mobility Lab in 2010, there was much optimism that by now, we would have made significant progress toward the goal of more sustainable, resilient, safe, inclusive, efficient, and human-centric mobility systems in our cities. Technological developments — particularly the rapid advances of digitalization, connectivity, and automation — promised the ability to deliver tailored, diverse, and convenient mobility solutions to customers that would be attractive enough to prompt a major shift away from private cars.

Fourteen years on, things haven't quite happened the way many expected, though there has been progress in some areas. In today's city centers, for example, we have seen growth in public transport and active mobility (walking and cycling), as well as the introduction of "new mobility" solutions, such as shared and owned micromobility devices (e-bikes and e-scooters) and car sharing, ride hailing, and electric-powered personal mobility devices.

However, the bigger picture is less rosy. If we consider that mass transit, walking/cycling, and shared mobility modes were collectively sustainable over the 15 years leading up to 2023, the share of these modes has only grown from some **57%** to around **65%** globally, while the remaining **35%** of trips are still made by private car. And if we look at pax-km instead of trips, we see that private cars still represent about **70%** in urban areas and **90%** in rural areas (see Figure 1).



Note: (1) New mobility includes shared and micromobility (car sharing, bike sharing, e-scooter sharing, etc.); individual motorized transport includes taxi and ride-hailing; private mobility devices are not accounted for
Source: Arthur D. Little

FIGURE 1: EVOLUTION OF MODAL SPLIT (# OF TRIPS) AND % PAX-KM

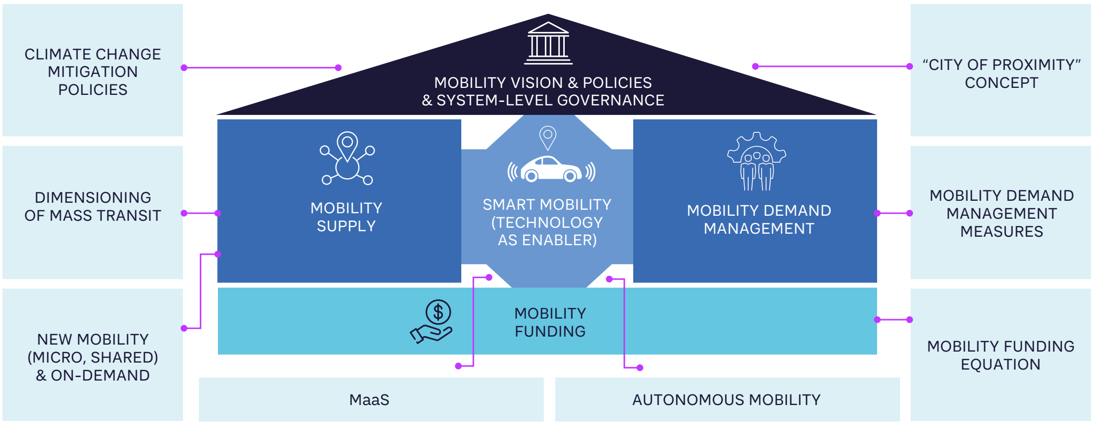
ADL's Q4 2023 "Future of Mobility" survey of more than 16,200 respondents globally[1] confirms the trend: more than **70%** of citizens use private cars for their daily commute. However, on a more optimistic note, the survey also shows that **42%** of citizens would consider forgoing at least one of their cars if sufficient mobility alternatives were made available to them.

This lack of progress has implications for transport externalities. For example, transport still accounts for 25-40% of national CO2 emissions in Europe, the only sector with a steady increase since 1990. Transport still leads to many casualties, and, despite less congestion post-COVID-19 due to increased working from home, levels have been growing again since 2023, and the average commuting time to work has not improved.

At best, we can talk of an evolution toward more sustainable mobility but certainly not a revolution. Why is this the case, and what should stakeholders such as transport authorities, mobility operators, and investors do to shift gear and accelerate? Drawing on a recent major joint ADL/POLIS[2] study, this article offers a quick overview of the challenges and solutions to sustainable mobility. The full study, "The Future of Mobility 5.0,"[3] addresses the various issues and solutions in depth.

As part of the study, we undertook eight deep dives into key challenges and promising solutions to overcome them. We mapped these against the framework ADL uses to describe the key building blocks of a virtuous mobility system[4] (see Figure 2).

1. "Future of Mobility Worldwide Survey (Q4 2023)." Arthur D. Little, September 2024.
2. POLIS is a network of European local and regional authorities cooperating on innovative and sustainable urban mobility.
3. "The Future of Mobility 5.0." Arthur D. Little/POLIS, September 2024.
4. This framework was first introduced in the 2014 ADL/UITP (International Association of Public Transport) study, "The Future of Urban Mobility 2.0: Imperatives to Shape Extended Mobility Ecosystems of Tomorrow."



Source: Arthur D. Little

FIGURE 2: EIGHT SOLUTIONS REVIEWED AS PART OF "THE FUTURE OF MOBILITY 5.0" STUDY

Our analysis led us to conclude that, with comprehensive implementation, appropriate funding, and robust governance at the system level, the following **high-impact solutions could potentially double the global share of sustainable mobility from approximately 30-60% of pax-km** within the next decade.

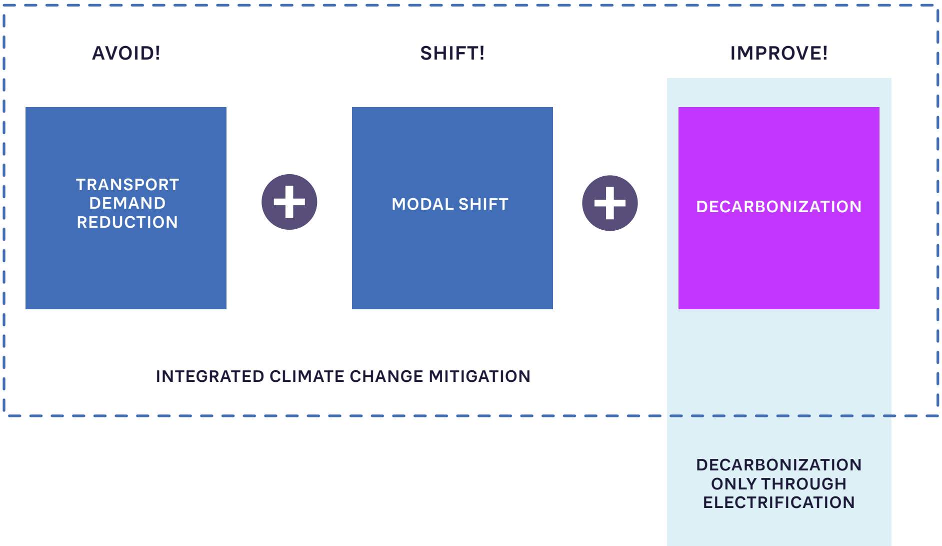
MOBILITY VISION AND POLICY

CLIMATE CHANGE MITIGATION

Recent years have seen significant progress in the development of long-term mobility visions and policies and their integration within wider urban strategies. This trend is especially pronounced in Europe, driven by the implementation of sustainable urban mobility plans (SUMPs). These plans strive to establish holistic urban mobility policies that enhance quality of life and are developed through a collaborative process involving a broad spectrum of stakeholders from both public and private sectors.

This certainly moves us in the right direction, but there are still difficulties in adopting adequately integrated policies to secure progress on climate mitigation, and the move toward net zero is still challenging. For example, many policies center on electrification. However, the electrification of private cars is not enough on its own, and in any case, its contribution is slow because of cars' long replacement cycles.

Mitigating climate change's impact requires a more joined-up policy approach, whereby electrification is complemented with other key levers, particularly modal shift and transport-demand reduction, to maximize overall impacts (see Figure 3).



Source: Arthur D. Little

FIGURE 3: KEY LEVERS FOR ACHIEVING NET ZERO IN TRANSPORT

As shown in Figure 3, an effective transport emission strategy needs to focus on three levers:

1. **Transport demand reduction:** Historically, the surge in car usage has been a primary contributor to increased emissions. However, the COVID-19 period demonstrated that significant changes are achievable with sufficient determination. Reducing demand can be accomplished by eliminating unnecessary trips, shortening travel distances, and employing behavioral change strategies. Restricting measures for solo car driving can also be considered where other competitive options are available to enhance vehicle occupancy rate.

2. **Modal shift:** This is about promoting a shift to less energy-intensive mobility modes, away from private cars toward mass public transport, active mobility, and new mobility modes such as micro, shared, and on-demand mobility. As is clear from individual car usage trends, making progress has been difficult and is partly driven by a lack of political will.

3. **Decarbonization through electrification:** This approach aims to achieve very low CO2 emissions thanks to electricity from low-carbon sources (kg CO2/kWh), as well as better energy efficiency per km traveled (kWh/km). This can be only partially achieved over the short term with better internal combustion engine (ICE) fuel efficiency and use of alternative fuels including biofuels, as long as the potential negative impacts of crop-based biofuels (land use and food price increases, among others) are minimized.

France offers a good illustration of the need for an integrated strategy. Between 1990 and 2018, energy efficiency and carbon intensity improved by 40% and 10%, respectively, mainly through electrification. However, a 24% modal shift to private vehicle usage and a 30% decrease in vehicle occupancy rate meant that, overall, CO_2 emissions climbed almost in step with transport demand.

"CITY OF PROXIMITY" CONCEPTS

First, we shape the cities — then they shape us. Reshaping mobility behaviors also requires reshaping public spaces away from a century of car-centric transport policies. Implementation of the "city of proximity" urban spatial-planning concept, the most famous of which is the "15-minute city" introduced by Carlos Moreno in 2016, aims to enable more sustainable, livable, and healthier cities by considering the closeness of services needed by citizens. Many examples of partial implementation of such concepts can be seen worldwide in cities such as Paris, France; Portland, Oregon; Melbourne, Australia; Glasgow, Scotland; and Copenhagen, Denmark, with good local results in improved congestion, pollution, and quality of life.

Overall, the concept of the city of proximity has great potential to contribute to sustainable mobility. In the future, city authorities should pursue efforts to deploy the concept at a larger scale, with possible adaptations to cater to how digitalization has changed citizens' needs for proximity and with a stronger emphasis on measuring systemic impacts.

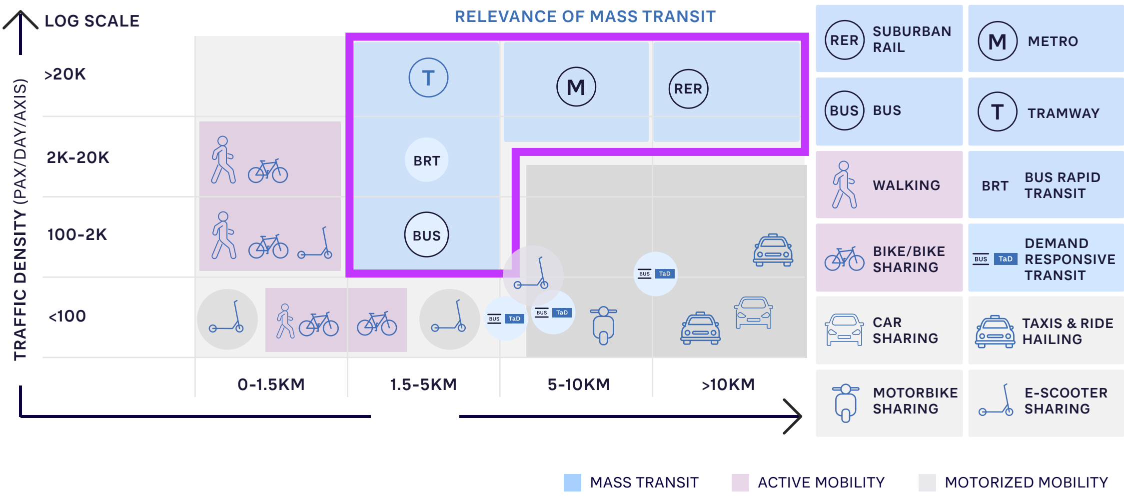
MOBILITY SUPPLY

DIMENSIONING AND MATURITY OF PUBLIC TRANSPORT

Improving mobility supply is about ensuring that the right mix of mobility services, modes, and infrastructures is available to meet evolving user needs, achieve sustainable mobility policy objectives, and ensure that flows of people and asset utilization are optimized within and around cities and regions.

OVERALL, THE CONCEPT OF THE CITY OF PROXIMITY HAS GREAT POTENTIAL TO CONTRIBUTE TO SUSTAINABLE MOBILITY.

Authorities should become smarter with transport mode allocation by developing multimodal masterplans and prioritizing transport services according to their performance and affordability. That means further development of mass transit as the "backbone" of the virtuous mobility system whenever traffic density justifies the investments. It also means encouraging the use of active and micromobility services for under 5 km trips and shared and on-demand motorized mobility, such as car sharing, taxi, and ride hailing, for longer-distance travel and in lower-density areas where investment in mass transit is not justified (see Figure 4).



Source: Arthur D. Little

FIGURE 4: OPTIMAL ALLOCATION OF TRANSPORT MODES

NEW MOBILITY (MICRO, SHARED, AND ON DEMAND)

Micromobility services, especially e-scooters, e-bikes, and e-Scooters (either shared or owned), are services with relatively high demand/willingness to pay and are often used together with public transport to cater to door-to door intermodal trips use-cases. There also seems to be demand for car-sharing and ride-hailing mobility services to support multimodal life use cases, which involve using different modes for different journeys and needs, both within and outside of cities. Mass-transit operators and shared new mobility services providers thus have a shared interest in bringing about the shift away from private cars. Authorities must cultivate new mobility as part of the mobility menu and foster partnerships with new mobility service providers rather than merely seeking to regulate them. That also means new mobility service providers must be more interested in “ecosystem plays” to maximize success and improve their economic viability.[5]

SMART MOBILITY (“TECHNOLOGY AS ENABLER”)

Technological innovation is essential and can serve as a powerful catalyst to deliver on the promise of a more virtuous mobility system. However, it can also be a double-edged sword and must be carefully guided to ensure it addresses genuine needs instead of promoting solutions in search of a problem.

5. Van Audenhove, Francois-Joseph, et al. “Sharing in Success: How Car Sharing Can Deliver on Its Potential in an Ecosystem Play.” Arthur D. Little/movmi/The Mobility Cooperative, 2024.

MOBILITY AS A SERVICE

The mobility as a service (MaaS) concept, which allows consumers to plan, book, pay for, and access various mobility services through a single digital platform, has been a prominent innovation in mobility over the last decade. It promised to facilitate a shift from ownership to usage of mobility devices and reduce reliance on private cars. However, despite some progress, the overall expansion of MaaS has been sluggish and largely failed to fulfill these promises. A primary reason is that most MaaS implementations have adopted a one-size-fits-all, technology-centric approach without adequately addressing the specific needs of users, service providers, or authorities. In terms of the Gartner hype curve, with less than 5% of the potential audience adopting it, we are probably close to the "Trough of Disillusionment."

MaaS is certainly part of the solution to achieving a more "virtuous mobility system," but it needs to evolve beyond merely serving as an "umbrella app" for existing services. It should offer added value, such as enhanced system-level functionalities that benefit both customers and cities, cater to specific target groups such as tourists and private car owners, and support broader mobility goals (for instance, by suggesting routes that favor sustainable modes). Furthermore, improved collaboration within an open data ecosystem is essential for the effective realization of MaaS.

AUTONOMOUS MOBILITY

Automation of mobility services will be part of our cities and regions in the not-so-distant future, and its deployment could help solve some of today's pressing issues, such as lack of drivers, safety, and how to service remote areas. However, autonomous L4[6] technology is progressing more slowly than predicted and has not yet achieved the breakthrough needed for general application in mixed traffic, even if it is now expected sooner rather than later. We expect the benefits of autonomous not to be realised through individual automated vehicles but through connected vehicles in smart traffic systems. Vehicle manufacturers need to prepare technology for integrated mobility systems rather than just individual vehicle solutions. The right use cases and applications must be selected for the post positive impact at overall system level (rather than talking about technology readiness). Today, low-hanging fruit can be found in traffic, such as automated bus rapid transit systems on dedicated lanes or remote-controlled vehicles, as well as within premises, such as automated bus driving in depots.

> ***TO MEET MARKET DEMANDS, MAAS MUST EVOLVE BEYOND MERELY SERVING AS AN "UMBRELLA APP" FOR EXISTING SERVICES.***

6. L4 refers to autonomous vehicles that are fully self-operational within set boundaries and require no attention or assistance from a human driver.

MOBILITY DEMAND

MOBILITY DEMAND AND ACCESS MANAGEMENT MEASURES

Prioritizing a shift toward sustainable mobility behaviors is crucial for enhancing transportation systems. Our latest "Future of Mobility" survey[7] study shows that the availability of alternative mobility services influences only about 30% of potential readiness to abandon personal cars. The other 70% needs to be addressed through effective demand management strategies.

Mobility demand and access management strategies can be diverse and must be supported by thorough cost-benefit analyses that include externalities and are carefully tailored to each unique context. Our study examined 40 potential measures and found that while some high-impact options — such as urban planning, land-use models, and dynamic tools such as congestion charging — can be challenging and expensive to implement, other effective measures are more feasible if there is sufficient political will and courage. We refer to these as "sweet spots." They include regulatory actions aimed at reducing cars and freight in urban areas, such as low-emission zones, freight transport restrictions, and parking regulations and pricing; specific infrastructure initiatives such as intermodal mobility hubs; personal travel management measures including smart parking solutions or MaaS apps; and marketing strategies that promote sustainable mobility. The importance of effective marketing cannot be overstated, particularly when considering the marketing spend by the automotive industry. private companies and public organisations can also play a key role in promoting sustainable mobility behaviors among their employees through initiatives such as mobility plans or mobility budgets.

PRIORITIZING A SHIFT TOWARD SUSTAINABLE MOBILITY BEHAVIORS IS CRUCIAL FOR ENHANCING TRANSPORTATION SYSTEMS.

RETHINKING THE MOBILITY FUNDING EQUATION

Expanding mass transit, especially into less densely populated areas, requires significant investment because of higher marginal costs per passenger. Similarly, transitioning to net zero and enhancing resilience require considerable financial resources for fleet electrification, new e-vehicle infrastructure, and the maintenance or replacement of existing infrastructure. Solving the financing gap will require concerted efforts on both sides of the "mobility funding equation" — identifying new funding sources and enhancing the effectiveness and efficiency of expenditures.

7. "Future of Mobility Worldwide Survey (Q4 2023)." Arthur D. Little, forthcoming 2024.

On the expenditure side, transport authorities must focus on maximizing the cost-effectiveness (value for money) of capital investments. This involves prioritizing funding toward the most efficient transport modes based on their usage rates and cost-effectiveness. Additionally, cultivating new mobility as part of the menu might necessitate partial public funding, especially in areas where these services enhance the overall mobility system but may not yet be commercially viable. This must be complemented by operational efficiency measures to reduce operational costs.

Effective revenue management is crucial, particularly in fare policies, which typically generate 30-50% of total revenues. Exploring subscription models (including within a broader MaaS framework), enhancing service appeal by improving time competitiveness, and increasing the cost of car usage are viable strategies. Diversifying to identify new sources of revenue is also relevant. Additionally, exploring all available public financing options (e.g., the European Investment Bank in Europe) and fostering innovative public-private partnerships can provide both financial resources and operational benefits. However, it is essential to recognize that revenues ultimately come from only two sources: users and taxpayers. Successful public-private collaborations require a mutual understanding and acceptance of private sector expectations for a reasonable ROI.

PUTTING IT ALL TOGETHER — OVERALL CONCLUSIONS

The potential for transformation is evident, **yet the real challenge lies in putting it into action**. Insights from our Q4 2023 survey of mobility leaders[8] reveal significant discrepancies between the acknowledged importance of these solutions (an average importance rating of **81%**) and the current readiness of the ecosystem to implement them (an average readiness rating of below **60%**). Therefore, system-level coordination and enablement are imperative to bridge this gap and turn potential into reality — there are no shortcuts.

Local and regional authorities must reevaluate their roles in shaping and guiding mobility ecosystems. This means moving beyond their foundational **"framing"** activities, such as putting in place a forward-looking mobility vision and suitable regulatory frameworks/ policies, toward **"enabling"** activities. This includes steering and orchestrating roadmaps to facilitate the implementation of solutions that necessitate a multi-stakeholder approach guided by users' actual problems and needs and requiring innovative public-private partnerships. For example:

8. Ibid.

- Roadmaps to facilitate the setup and implementation of a MaaS ecosystem.
- Adopting a comprehensive, system-level approach to autonomous transportation, integrating automated public transport with individual transport modes such as robo-taxis.
- Undertaking specific roles or actions that serve the wider public interest. An example of this is the future necessity for a "control tower" role in urban centers, which will be essential for the real-time management of traffic flows and transportation assets.

Achieving this will require expanding mandates and capabilities for authorities and developing more agile operational methods.

The solutions necessary for a transformative shift toward a more virtuous mobility future are already within our grasp, with clear "game changers" already identified to accelerate the transition. Making it happen demands political will, courage, and determination. Increased collaboration among public and private stakeholders within the extended mobility ecosystem is key. Transport authorities in cities and regions, in particular, play a crucial role in accelerating the shift.

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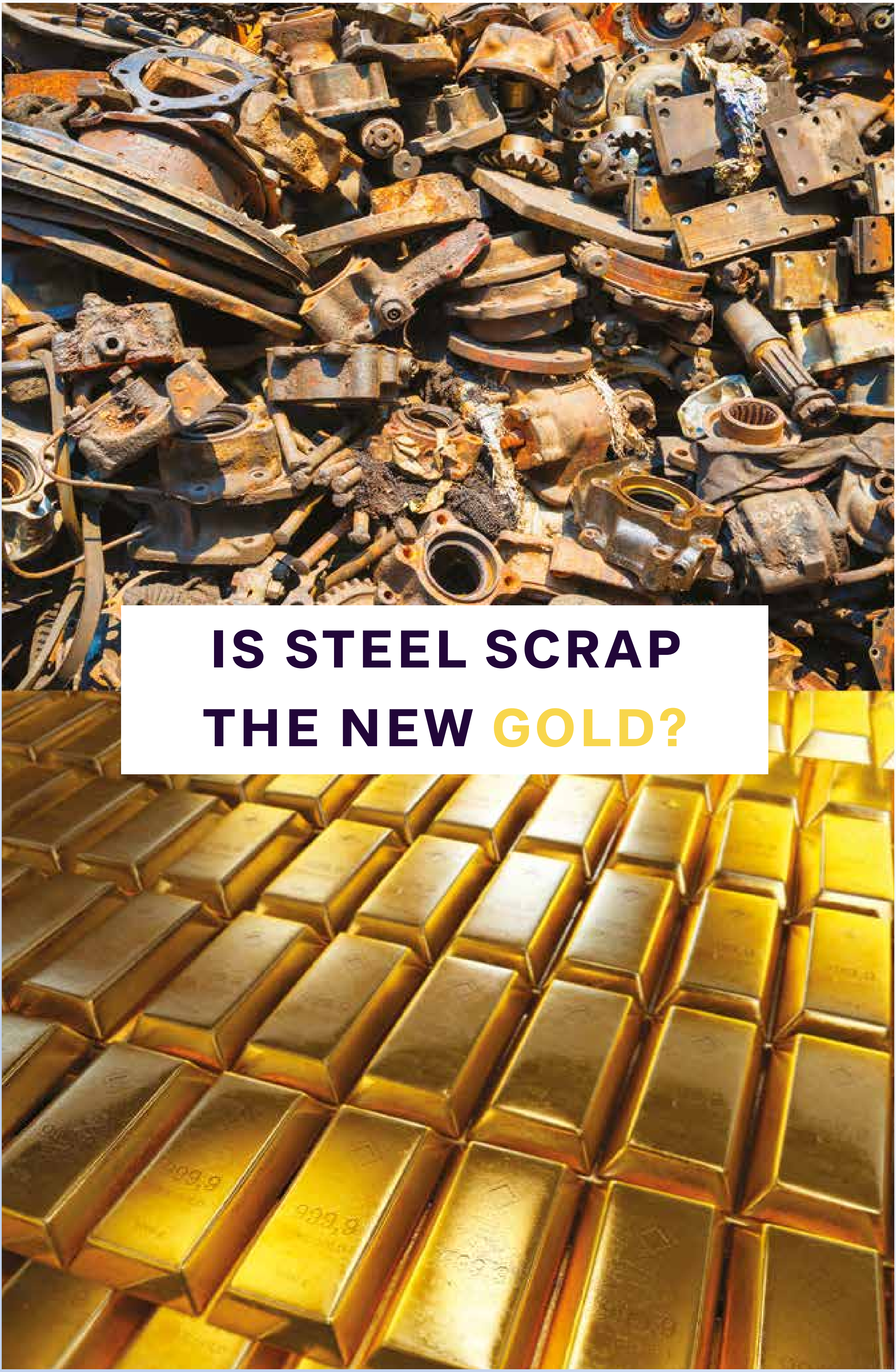
IS STEEL SCRAP THE NEW GOLD?



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Steel production is responsible for 7%[1] of global carbon dioxide (CO2) emissions, underscoring the urgency of reducing its carbon footprint to meet net zero targets. Regulators are intensifying their efforts; for instance, Europe aims to cut CO2 steel production emissions by nearly 25% by 2030.

Steel is integral to the global economy, playing a crucial role in the construction, automotive, and industrial machinery industries. It is also essential for green technologies such as wind turbines, electric vehicles, and advanced manufacturing processes. Despite volatility, steel demand is projected to rise, making its decarbonization pivotal for achieving a greener economy.

Two key technologies promise a more sustainable future for steel production: direct reduced iron (DRI) for primary steel and electric arc furnaces (EAFs) for secondary production, which reuse scrap steel. Deploying these green steel technologies is crucial for reducing emissions and replacing traditional, coal-fired blast furnaces.

STEEL IS INTEGRAL TO THE GLOBAL ECONOMY, PLAYING A CRUCIAL ROLE IN THE CONSTRUCTION, AUTOMOTIVE, AND INDUSTRIAL MACHINERY INDUSTRIES.

However, successfully building and running DRI and EAF steel mills requires substantial investments, a supply of competitively priced green energy, and — the primary lever for EAF — acquiring sufficient scrap steel. In 2022, out of the 1,885 metric tons (Mt) of crude steel production, 1,340 Mt were produced using blast furnaces (around two tons of CO2 per ton of liquid metal), which should be replaced by DRI and EAF. EAF production was 538 Mt in the same period. This will drive large-scale demand growth in the scrap market. Scarcity will probably drive prices higher, particularly for clean scrap generated by manufacturing processes.

1. According to IRENA ("Towards a Circular Steel Industry," July 2023), steel production accounts for roughly 7% of global CO2 emissions.

To secure their futures and meet the need for this vital material, steelmakers must transform to create more circular economies to secure and effectively use scrap. They need to move from digging in the ground for materials to digging in recycling sources. That requires closer collaboration with recyclers and manufacturers across the ecosystem that create scrap as a byproduct of their activities, such as automotive manufacturers, to collect sufficient volumes to power their new mills.

These changes are prompting steel producers to look globally for scrap, sourcing this new "gold" from Africa, China, Latin America, Europe, and North America. This expansion necessitates new strategies and operational models.

How can steel producers manage the green transition, and what are the lessons for other sectors as economies become more sustainable and circular?

MEETING THE GLOBAL IMPERATIVE TO DECARBONIZE STEEL

REGULATORY PRESSURES

Traditional steel production methods involve blast furnaces that use coking coal as fuel and inevitably produce large amounts of CO2. Around 85% of steel production was powered by fossil fuels in 2022, according to the World Economic Forum.[2] While efforts are ongoing to reduce or capture emissions, such as by carbon capture and storage (CCS), large-scale deployment remains limited because of economic, technical, and infrastructural challenges. Many projects are still at the proof-of-concept stage, such as ArcelorMittal's Steelanol Project in Belgium, which aims to capture CO2 from steel production and convert it into ethanol through a biological process.

TRADITIONAL STEEL PRODUCTION METHODS INVOLVE BLAST FURNACES THAT USE COKING COAL AS FUEL AND INEVITABLY PRODUCE LARGE AMOUNTS OF CO2.

Meanwhile, the regulatory clock is ticking. Annual emissions from steel production represent 5% of the EU's total CO2. This has led EU regulators to target reducing emissions from 191 Mt in 2021 to 150 Mt by 2030. Individual firms have also set their own targets; for example, US Steel aims to reduce greenhouse gas emissions intensity by 20% by 2030 and achieve net zero emissions by 2050. Regulatory change is being driven by a combination of targets, carbon taxes (including the EU's Carbon Border Adjustment Mechanism [CBAM], which aims to ensure imported materials such as steel are produced sustainably), and national/international subsidies for the switch to cleaner technologies such as DRI and EAF.

2. "Net-Zero Industry Tracker 2023." World Economic Forum, 28 November 2023.

CUSTOMER PRESSURES

Major customers are also increasingly demanding low-emission steel, driven by their own sustainability targets. For example, leading US automotive manufacturers such as Ford and General Motors have joined the First Movers Coalition, a global group committed to decarbonizing supply chains, including steel.

THE IMPORTANCE OF TECHNOLOGY INNOVATION

Together, these regulatory and customer pressures are driving a need for change in the steel industry, which is manifested in a shift away from emissions-heavy blast furnaces to cleaner technologies that rely on three elements:

1. Green energy
2. Hydrogen
3. Sufficient supplies of scrap

DRI AND EAF

DRI furnaces replace the coking coal traditionally used in the iron ore reduction process with gas or hydrogen to produce directly reduced (liquid) iron. This is then fed into an EAF, along with scrap steel, at a ratio of at least 50% scrap. This combination is melted to form liquid steel. It is then cast and rolled to transform the steel into coils or plates.

Emissions are considerably reduced, particularly if green feedstock (such as green hydrogen) replaces coking coal and the electricity used within the EAF is from renewable sources. However, the cost of producing liquid metal will increase without access to cheap, decarbonized energy to power these processes.

Demonstrating the potential of this green steel, steel producer SSAB, iron ore miner LKAB, and energy company Vattenfall collaborated to create HYBRIT (Hydrogen Breakthrough Ironmaking Technology), a fossil-free iron and steelmaking technology. In June 2021, the three companies showcased the world’s first hydrogen-reduced sponge iron, which was then used to produce steel provided to Volvo. Volume production by SSAB is scheduled to begin in 2026.

THE CHALLENGES TO THE PRODUCTION OF GREEN STEEL

Five challenges face the steel industry as it aims to transition from old-style blast furnaces to cleaner DRI-EAF steel production: technological maturity, growing CAPEX/OPEX investment, securing green energy, securing sufficient scrap, and the need for new skills/capabilities.

1. TECHNOLOGY MATURITY

EAF technology is fully mature and already makes up a substantial proportion of global steel production volumes. It is currently being extended to make new steel types. However, it requires a combination of scrap and primary steel from DRI plants, replacing inputs from blast furnaces. Yet, DRI technology is currently at the developmental stage, with many existing installations relying on natural gas rather than green fuels such as hydrogen. While significant investments have been announced in DRI (over €10 billion in Europe alone), no DRI facilities of 2.5 Mt that consume hydrogen have yet been built. Therefore, scaling green DRI pilots into mature installations is critical to reducing emissions and ensuring a green future for steel.

2. GROWING CAPEX AND OPEX INVESTMENT

In mature markets, many previous investments focused on process improvements or increasing capacity/quality. Business cases were, therefore, relatively simple to calculate based on projected market demand. Securing investment in green steel projects is much more complex, as it requires assumptions on CO2 prices, energy costs, and planned regulations/carbon taxes. According to Eurofer, meeting the EU's 2030 targets requires producers to invest an estimated €85 billion — €31 billion in CAPEX and €54 billion in OPEX — of which €15-17 billion has been announced. This is leading to heavy reliance on state subsidies to fund new plants around the world, including:

- €850 million from France to ArcelorMittal
- €2 billion from the German state to ThyssenKrupp
- £500 million from the UK government to Tata Steel
- US $500 million each from the US Department of Energy to steelmakers Cleveland-Cliffs and SSAB for green steel plants

3. SECURING GREEN ENERGY

Producers must source a continuous green energy supply for DRI and EAF facilities. Consequently, replacing blast furnaces with DRI-EAF means energy will make up a much higher percentage of running costs than iron ore based on current market conditions. Securing these energy supplies at competitive prices is vital for success:

- **Green and blue hydrogen for DRI:** Competition is growing for (currently limited) green and blue hydrogen supplies, which require renewable energy for production and carbon capture technology, respectively. A significant reduction in the price of hydrogen is necessary to make DRI cost competitive.
- **Green electricity for EAF:** Given the need for constant electricity availability to power EAFs, hydroelectric and nuclear power are the most appropriate sources, rather than intermittent solar or wind. However, the availability of such sources varies considerably by country and region, again pushing up costs and handing advantages to producers located near such energy sources.

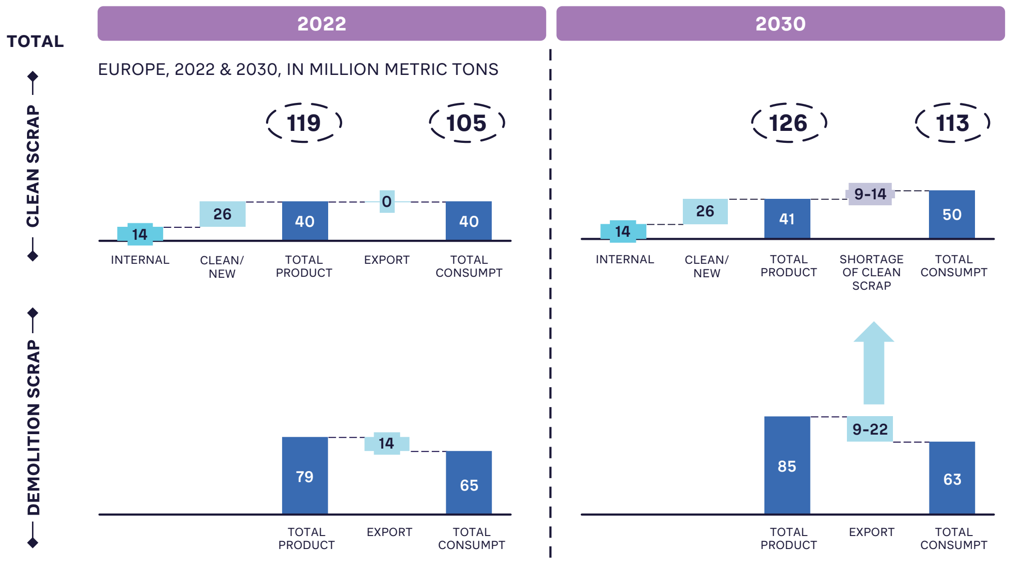
Recently announced European DRI and EAF projects are estimated to require 60 gigawatt hours (GWh) of green energy annually, covering both the direct supply of green electricity and the green energy required to produce hydrogen through electrolysis.

Investments are also being made in new sites that benefit from access to renewable energy and green hydrogen. Vulcan Green Steel (VGS) has begun construction of a greenfield steel complex in Duqm, Oman. When production begins in 2027, it will run on 100% renewable wind and solar energy and incorporate green hydrogen once it becomes available.

4. SECURING SUFFICIENT SCRAP

Scrap steel is essential for EAFs, in which it is melted alongside liquid iron from DRI. It comes from three main sources (see Figure 1):

1. **Internal "clean" steel mill scrap** that is traditionally consumed by the producer
2. **Clean scrap** from downstream players that transform steel into products (e.g., construction and automotive). For example, 30-50% of steel in automotive is currently wasted
3. **"Dirty" demolition scrap** coming from end-of-life (EOL) goods, such as buildings, cars, and domestic appliances



Source: Arthur D. Little, Eurofer

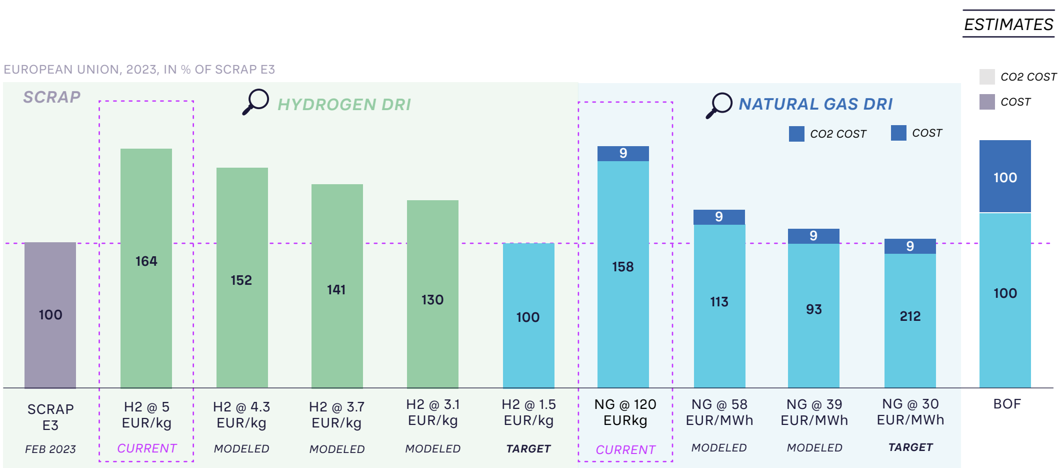
FIGURE 1: SCRAP MARKET AVAILABILITY AND DEMAND BALANCE

Rates of scrap collection and usage are already high in regions with significant EAF penetration, such as Turkey (where it makes up 86% of production volumes), the US (79%), and the EU (43%). These figures are expected to increase with growth in EAF capacity from its current 14% of global steel production volumes (538 Mt annually of crude steel in 2022).

THE ECONOMIC ADVANTAGES OF SCRAP

As Figure 2 shows, using scrap is a highly competitive, efficient option for steel production compared to alternatives such as DRI powered by hydrogen or natural gas.

Taking the indexed cost of processing scrap steel at a baseline of 100, the costs for hydrogen DRI range from €130 to €164; for natural gas DRI, costs range from €93 to €158, depending on current and target-price scenarios. These figures demonstrate the economic feasibility of harnessing scrap steel, especially given that rising environmental regulations are expected to increase the cost of CO2 further.



Source: Arthur D. Little

FIGURE 2: COST COMPARISON OF SCRAP VERSUS ALTERNATIVE DRI PROCESSES

GROWING GLOBAL DEMAND FOR SCRAP

The highest demand is for clean, new scrap. Arthur D. Little's (ADL's) model shows an annual shortage of 9 Mt in Europe by 2030, which will most likely push up prices. This means securing and improving "dirty" demolition scrap is crucial to plug the gap cost-effectively. This means that global competition for scrap is increasing, driving government and industry action across the world:

- **Europe:** Around 50 low-carbon steel projects are expected to be in place by 2030, requiring over 14 Mt of scrap in Europe alone and dramatically increasing competition for supplies. For example, to secure scrap supplies, ArcelorMittal has recently bought scrap metal recycling businesses in Poland, Germany, and the Netherlands. Since European players are currently consuming the majority of clean scrap produced in the region, they need to look further afield for additional supplies. At the same time, the European Parliament has approved a report that may create restrictions on scrap steel exports.

- **US:** American players are modernizing, with many new DRIs planned and M&A activities underway to secure scrap supply. For example, Sims Metal purchased Baltimore Scrap Corporation for US $177 million to better address the demand for scrap for green steel, adding 600 kilotons of capacity.

- **China:** China is currently structuring its scrap supply chain and seeing rapid growth in scrap use, which increased from 90 Mt in 2016 to 220 Mt in 2020. It is expected to reach ~400 Mt by 2030, driven by increasing green steel production investments. While currently behind other regions in scrap use because of low EAF penetration (under 15% of production), China is increasingly benefiting from access to growing volumes of EOL/demolition scrap.

- **India:** The Indian steel sector already has a scrap value chain, with imports growing by 63% between 2021 and 2022. It is expected to grow further to meet the needs of its developing steel producers, increasing by 50% by 2047.

- **Africa:** While considerable untapped scrap reserves exist in Africa, the scrap is difficult to collect and relies heavily on informal supply chains. Nevertheless, 1.8 Mt were exported in 2022, up from 1.1 Mt in 2020, showing the continent's potential.

The necessary equipment for processing larger volumes of scrap steel is already in place, with many facilities currently possessing sufficient capacity. However, expanding scrap-processing operations requires significant capital investment in large storage facilities to accommodate higher volumes. These storage facilities should ideally be located closer to ports to enhance logistical efficiency and reduce transport costs. As a result, the industry faces substantial CAPEX requirements to build and maintain these expanded infrastructures, underscoring the financial challenges associated with scaling up scrap-processing capabilities.

5. DRIVING A NEED FOR NEW SKILLS AND CAPABILITIES

Over the past two decades, players in mature markets such as Europe have focused on extending the life and capacity of existing steelmaking plants through incremental investments. Green steel requires new skills — companies will need the capabilities to manage the construction, ramp-up, and operation of large-scale CAPEX projects built around new technologies. At the same time, they will need strategic and partnering skills to successfully manage energy sourcing and pricing (e.g., hydrogen versus gas for DRIs) across multiple time horizons. Global operators that have already implemented EAF/DRI plants will be at an advantage if they can transfer these skills to other regions, such as Europe.

LESSONS FROM OTHER SECTORS

As they seek to build circular economies around scrap steel, companies can learn from the experiences of other sectors, notably aluminum, glass, and urban mining.

Aluminum

Aluminum recycling saves up to 95% of the energy required for primary production, making it a cornerstone of the industry's strategy to reduce carbon emissions. Companies such as Novelis, Constellium, and Arconic are leading the charge by investing heavily in advanced collection and recycling facilities that turn scrap aluminum into high-quality products.

Glass

By using cullet (recycled glass) in the production process, glass manufacturers reduce raw material consumption, lower energy use, and decrease CO2 emissions. For instance, using 1,000 kilograms (kg) of cullet saves approximately 580 kg of CO2 emissions compared to producing the same amount of glass from virgin materials.

Urban mining

Urban mining, the process of reclaiming raw materials from spent products, buildings, and waste, was pioneered in the electronics industry, where precious metals such as gold, silver, and copper are extracted from e-waste. It is now being extended to other areas, such as lithium-ion batteries. (See our article, "Opening the Urban Mine — Building a Profitable Circular Economy Based on a Lithium Battery Recycling Example" in this issue of *Prism.)* Urban mining alleviates the environmental degradation associated with traditional mining and reduces the strain on finite natural resources.

STRATEGIES FOR SUCCESSFULLY "MINING" SCRAP

Alongside access to green energy, green steel production relies on access to sufficient supplies of scrap steel. Increasing demand and limited supply means traditional, informal methods of collection are no longer enough. Instead, steel producers operating EAFs should look at a combination of these five methods to shape their scrap steel strategy:

1. Acquiring a demolition/recycling company that collects and processes steel from EOL products
2. Improving and optimizing current processing methods for pre-production clean scrap by focusing on processes such as better sorting
3. Ensuring production grades of steel can absorb a greater percentage of demolition scrap, including developing cleaning processes for dirty scrap grades
4. Ensuring melting processes can manage greater volumes of demolition scrap by developing secondary metallurgy processes
5. Building a more circular economy, supporting downstream customers, and helping with their scrap sorting to secure and maximize volumes

INSIGHTS FOR THE EXECUTIVE

Decarbonization is driving transformation in the steel industry, with the focus — especially in mature markets such as the EU and the US — shifting from optimizing existing production to large-scale CAPEX investments in new technologies such as DRI and EAF. For all those involved with steel as a producer or manufacturer of products, or in its recycling, the green transition and greater need for scrap bring opportunities. To ensure success, players should focus on three areas:

1. **Building ecosystems and fully circular economies** to secure scrap supplies through partnerships and acquisitions across the supply chain.

2. In constrained markets, **looking globally for new, more cost-effective scrap sources**, such as Africa and Latin America, and **building new capabilities and partnerships** to secure supplies.

3. **Developing new skills and capabilities** to meet transforming market needs. This creates a greater need for competencies around managing complex supply chains to secure scrap supply, improving metallurgy and customer acceptance to absorb more scrap, building large-scale CAPEX projects from scratch to production, forecasting regulatory changes and impacts, and securing green energy supplies, as well as introducing new technologies — all while safeguarding quality and optimizing performance.

These lessons can be adapted for other circular economy–focused industries that are transforming to become more sustainable.

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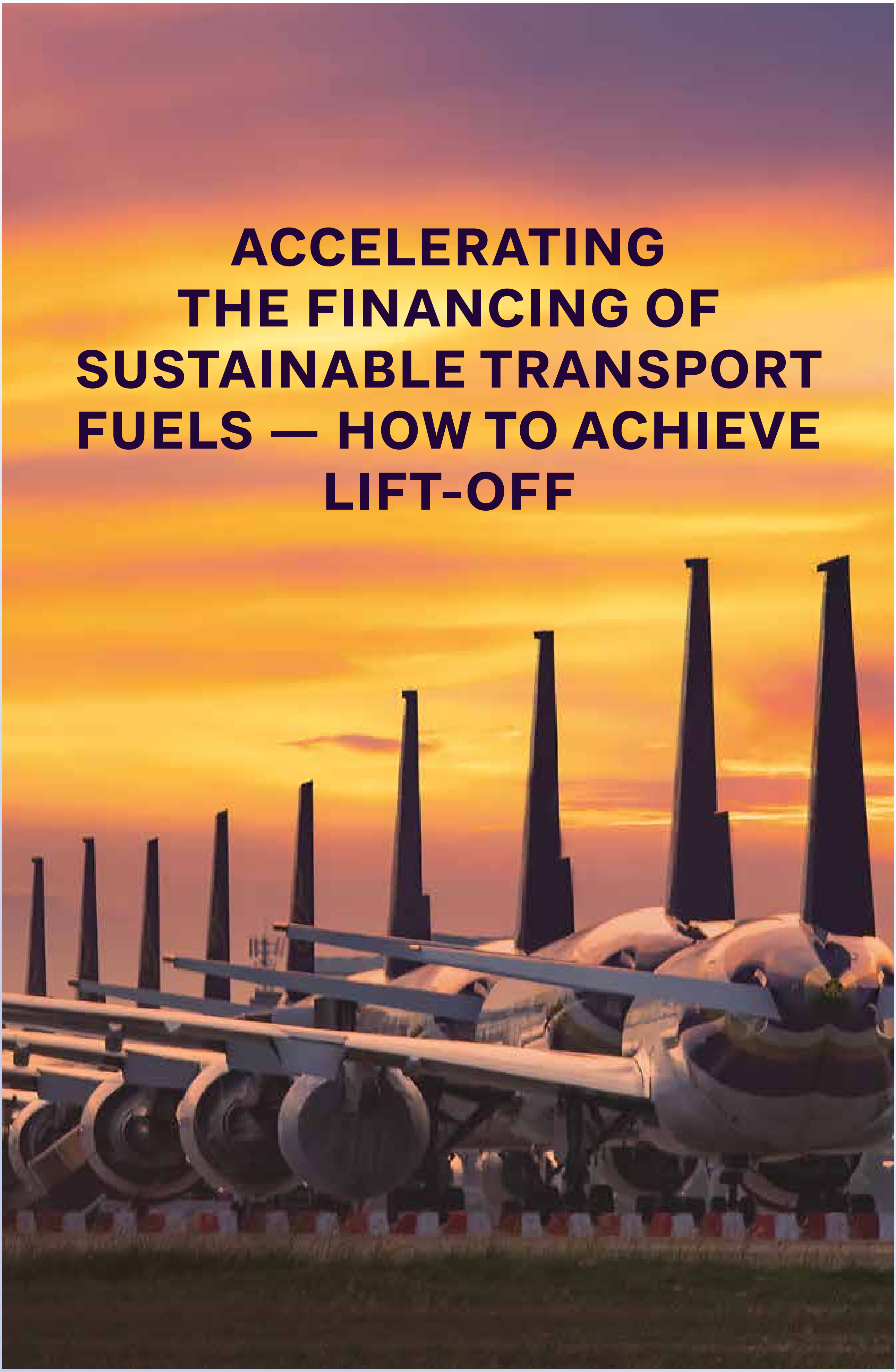
ACCELERATING THE FINANCING OF SUSTAINABLE TRANSPORT FUELS — HOW TO ACHIEVE LIFT-OFF



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Transport was responsible for 14% of global greenhouse gas (GHG) emissions in 2023. While electrification is the most efficient way to decarbonize road transport, inland/nearshore shipping, and even short-haul flights, it does not cover every use case. That means different approaches will be needed for areas such as long-haul flights (2% of GHG emissions) and shipping (1% of GHG emissions).

Sustainable, low-carbon fuels are the only way to fully decarbonize long-haul flights and shipping. The potential within each market is enormous. For aviation alone, rising numbers of flights mean a cumulative 11,600 million tons of fossil jet kerosene will have to be decarbonized, and 9,500 million tons of fossil fuel will have to be replaced for maritime, both by 2050. These sectors are growing and face regulatory imperatives to shift away from fossil fuels.

This should mean sustainable fuels present a great investment opportunity for private capital. Institutional and infrastructure investors have abundant capital available, the latter of which can deploy approximately $50 billion of fresh investment every year.

Despite this, demand-supply scenarios for sustainable fuel by 2030 show an enormous, worrying imbalance. For example, the International Civil Aviation Organization (ICAO) predicts a gap of over 15,000 kilotons between available supply and demand by 2030, based on projects announced before the end of 2023. A large-scale shortage of sustainable fuels will hamper efforts to decarbonize, even though the aviation and maritime industries are keen to invest in moving to net zero. The problem is critical and likely to worsen — demand for sustainable fuels will rise even faster post-2035, driven by 2050 CO2 net zero ambitions, as opposed to the seven years required to get a new production facility up and running.

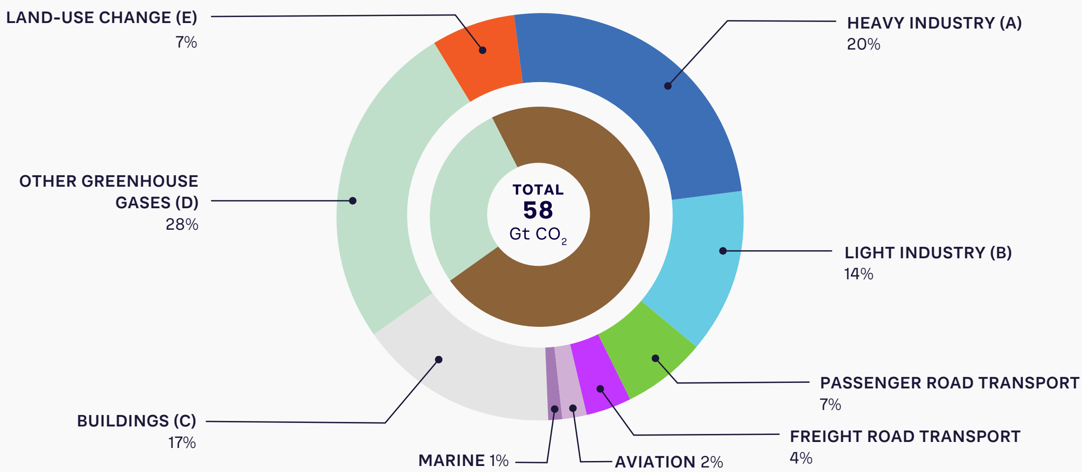
> ***SUSTAINABLE, LOW-CARBON FUELS ARE THE ONLY WAY TO FULLY DECARBONIZE LONG-HAUL FLIGHTS AND SHIPPING.***

To address this mismatch between supply and demand, this article looks at how the growth of the sustainable fuels market can be accelerated to drive decarbonization and reduce emissions.

THE NEED FOR SUSTAINABLE FUELS

MEETING PRESSURES TO DECARBONIZE TRANSPORT

As a major GHG emitter, the transport sector is under regulatory, financial, and consumer pressure to decarbonize. Passenger and freight road transport account for the lion's share of current emissions (see Figure 1). However, electrification of road transport via battery-electric vehicles is progressing.



(A) INCLUDES EMISSIONS FROM INDUSTRIAL PROCESSES, 18% OF THIS CATEGORY
(B) INCLUDES RAIL, 3.5% OF THIS CATEGORY
(C) EMISSIONS FOR OPERATION OF BUILDINGS — NOT CONSTRUCTION (WHICH IS IN INDUSTRY SECTORS)
(D) 70% METHANE FROM AGRICULTURE AND FOSSIL FUEL PRODUCTION AND USE; 23% NITROUS OXIDE; 7% OTHERS
(E) LAND USE, LAND-USE CHANGE EMISSIONS, AND FORESTRY (LULUCF)

SOURCE: SHELL ANALYSIS AND IEA'S EXTENDED ENERGY BALANCES (2023)

FIGURE 1: GLOBAL GHG EMISSIONS 2023

By contrast, electrification is not a viable option for the maritime and air transport sectors because of journey distance and weight constraints. Both of these hard-to-decarbonize sectors are seeing significant growth, meaning emissions will only rise further if left unchecked. Together, they are expected to hit annual emissions of approximately 1.8 billion metric tons of CO2 equivalent by 2030.

Given the size of the issue, regulators, customers, and maritime/air transport companies themselves are looking to take action.

- An increasing number of governments and regulatory bodies have set deadlines for decarbonization. For example, the International Maritime Organization (IMO) has set targets for the maritime industry to decrease its GHG emissions by at least 50% before 2050 and lower the carbon intensity of operations by 40% by 2030 and a further 70% by 2050. The EU has set out mandated targets for using sustainable fuels in aviation through the Refuel EU regulation.
- Customers are demanding decarbonization, particularly in the maritime sector. The coZEV initiative, which includes major shipping users such as Target, Philips, Amazon, and Electrolux, has set a target of 2040 for its freight to be carried by vessels powered by zero-carbon fuels.
- Shipping and aviation companies have committed to reaching net zero. For example, Maersk aims to do so by 2040.

This need can only be met through sustainable fuels. These are drop-in replacements for existing fossil fuels, with oil and gas replaced as feedstock by available biological substitutes (such as biomass or alcohol) or hydrogen/carbon dioxide (so-called e-fuels).

THE CHALLENGES TO FUNDING THE CHANGE

A clear market need for sustainable fuels has emerged, which requires production to scale up. Therefore, project-finance investments from banks and infrastructure funds, among others, will be crucial.

However, despite the fact that many clean fuel production technology pathways, particularly around sustainable aviation fuel (SAF), are mature and technically ready for large-scale production, a number of risks currently hamper clean fuel growth, making some off-takers (customers) reluctant to sign up to binding long-term agreements. This is a vicious circle, with investors unwilling to commit to funding new facilities without customer contracts in place to demonstrate demand and future revenues.

A CLEAR MARKET NEED FOR SUSTAINABLE FUELS HAS EMERGED, WHICH REQUIRES PRODUCTION TO SCALE UP.

On top of this, inflationary pressures and high interest rates make investment in high-CAPEX projects, such as SAF, particularly challenging, as it will take time for such projects to earn revenues and start to repay funding costs. The challenges to unlocking funding fall into four key areas:

1. TECHNOLOGY READINESS

Multiple maturing technology pathways lead to the production of clean fuels, with around 20 currently being pursued. Regarding SAF, oil-to-jet fuel conversion (HEFA) is technically ready for commercialization, with a technology-readiness level (TRL) of 9. Demonstrating this, US producer World Energy and others, such as TotalEnergies, already produce SAF by converting used cooking oil and waste animal fat into a fully usable aviation fuel. Among other flights powered by SAF, a Virgin Atlantic Boeing 787 has successfully flown from London to New York on 100% SAF.

Many technology pathways will have TRLs of over 7–8 by 2030, among which are alcohol-to-jet, power-to-liquid (e-SAF), and methanol-to-jet. Lanza Jet, one of the market leaders, recently commissioned the first large-scale pilot plant in Georgia, US, to explore alcohol-to-jet. e-SAF, although not yet proven on a pilot scale, is being actively developed and will be crucial to full decarbonization of the aviation sector. Consequently, investors should understand that technology immaturity risks are reducing year-on-year.

2. ECONOMIC RISKS — HIGH UNCERTAINTY AROUND PRODUCTION COSTS

Many green technologies are still immature — or require large-scale change from customers to incorporate them into their operations. This is less of an issue with many of the technology pathways to produce clean fuels, which have already reached high maturity levels.

While technology pathways are generally proven, concerns remain around the availability of sufficient feedstock. For example, SAF is created from used cooking oil and animal fats, and collecting significant volumes can be expensive for producers. At the same time, bio-based feedstock faces challenges in three main areas:

1. **"Fuel versus food":** Worries that prime agricultural land is being used to produce feedstock for clean fuels at the expense of feeding local people have led many governments to regulate in this area, such as banning the use of crops for feedstock and reducing supply.

2. **Adverse environmental effects:** Booming demand for biofuel feedstock (such as palm oil) has created concerns around deforestation and consequent environmental (and reputational) damage, hence the need to regulate and foster "Gen 2" biofuel feedstock.

3. **Bio-based sustainable fuel plants:** These require large volumes of feedstock, but to be economically viable, this has to come from a relatively small collection area, typically within a radius of 150–300 km. It increases the bargaining power of feedstock producers, pushing up prices.

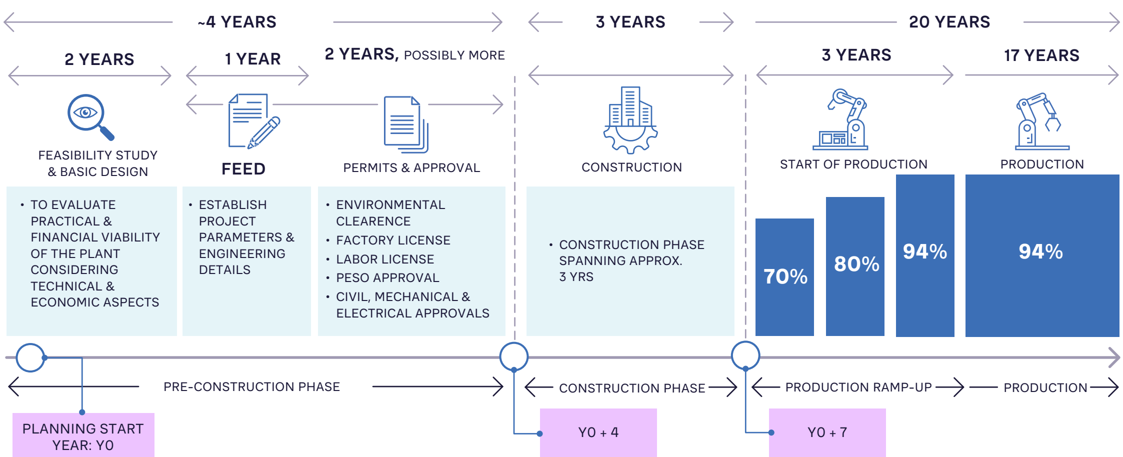
Considering the high (and rising) demand for bio-based feedstock, suppliers are not ready to commit to long-term contracts, which leads to price volatility. The market is not yet sufficiently developed to have any transparent price mechanisms in place.

E-sustainable fuels/e-biofuels rely on green hydrogen, which makes up 70% of the fuel's total production costs. In turn, this hydrogen requires green electricity for electrolysis, which makes up around 70% of green hydrogen production costs. Added together, this means green electricity is around 50% of the total production cost for e-fuels. Given current demands on renewable energy sources and their inherent intermittent nature, green electricity prices are extremely volatile, making securing sufficient supplies at reasonable, known prices difficult. This creates uncertainty around sustainable fuel investment cases.

3. EXECUTION RISK: THE NEED TO SHORTEN DEPLOYMENT TIMES

In many countries, from Europe to India, it takes up to seven years from the inception of a sustainable fuel production facility to the first drop. This covers feasibility studies, front-end engineering design (FEED), and permitting (four years total), as well as construction itself (a further three years). This elongated time frame means execution risks are large, while CAPEX costs can also increase considerably because of external economic factors over this period (see Figure 2).

Alongside planning and constructing production facilities, producers need to create supply chains to guarantee feedstock availability. Production/collection ecosystems must be built from scratch, with producers competing with other users who may offer higher prices if the feedstock has other, more lucrative uses.



Source: Arthur D. Little

FIGURE 2: TIMESCALE FOR ROLLING OUT A SUSTAINABLE FUEL PLANT

4. CLIENTS ARE WILLING TO BUY BUT REGULATION IS UNCERTAIN

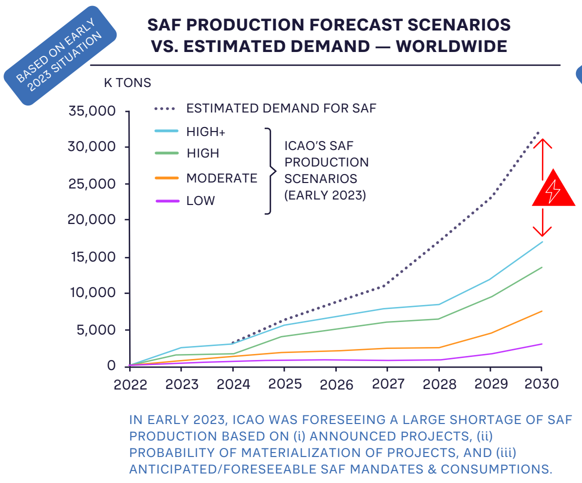
Policies and regulations to support the adoption of sustainable fuels are growing around the world, lowering investment risks every day. For example:

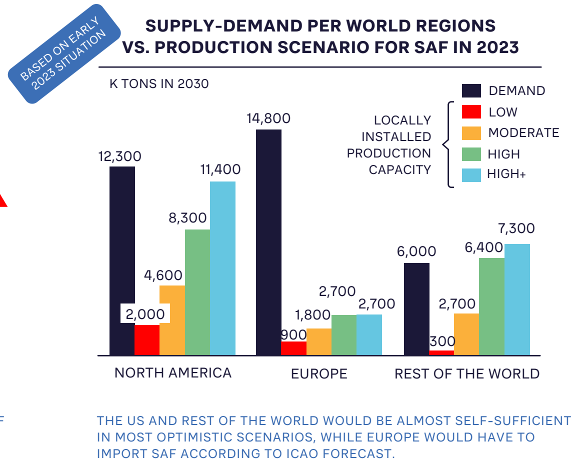
- The EU and the UK have introduced fuel-blending mandates with sub-mandates for bioSAF and e-SAF.
- Japan has mandated that fuels used on international flights to and from the country contain 10% SAF by 2030, while Singapore aims for 5% by the same date.
- The US and Qatar have not yet introduced any blending mandates but have stated ambitions to reach 10% adaptation by 2030 via voluntary blending of SAF, while aiming for full carbon neutrality by 2050.

However, policies and supporting incentives are not set in stone, leading to uncertainty, particularly if governments change. For example, in the United States, SAF blending was supposed to be supported by federal and state-level incentives, which would have significantly reduced the SAF premium over the price of conventional jet fuels, making it attractive for off-takers. Uncertainty about the duration of federal tax credits (part of the Inflation Reduction Act) and volatility of federal and state certificates (such as RIN prices and the California Low Carbon Fuel system) make it difficult to incorporate this revenue into bankable business cases with 100% certainty.

> ***INVESTORS UNDERSTAND THAT END-CLIENT OFF-TAKERS (AIRLINES AND MARITIME SHIPPING LINES) ARE COMMITTED TO DECARBONIZING THEIR OPERATIONS.***

Despite this regulatory uncertainty, investors understand that end-client off-takers (airlines and maritime shipping lines) are committed to decarbonizing their operations, under pressure from both public opinion and their B2C and B2B clients, creating large-scale pull demand, as shown in Figure 3.





Source: Arthur D. Little

FIGURE 3: ESTIMATED DEMAND AND PRODUCTION FORECASTS FOR SAF TO 2030

5. THE NEED TO EDUCATE AND LOWER THE COST OF CAPITAL

Based on market conversations, the largest investors do not seem fully familiar with the risk/reward profile of investing in sustainable fuels. The market is still educating itself and just starting to assess this investment opportunity.

Consequently, the cost of equity to fund sustainable fuels remains in the high teens, meaning only transformation or impact funds are set to invest in what are seen as riskier projects. Given the market demand and technology maturity, sustainable fuel projects have a much lower risk profile and should instead be compared to other infrastructure-like investments (such as battery storage or solar farms) when making investment decisions. Sustainable fuels should then benefit from a lower-teen/high-single-digit cost of equity and also higher debt leverage.

BASED ON MARKET CONVERSATIONS, THE LARGEST INVESTORS DO NOT SEEM FULLY FAMILIAR WITH THE RISK/REWARD PROFILE OF INVESTING IN SUSTAINABLE FUELS.

Additionally, a persistent belief holds that SAF costs will come down massively in the next decade. This leads to reluctance from off-takers and investors to step in now and make the necessary long-term commitments, as they feel waiting will deliver a better deal. While analysis shows that this belief is incorrect, it still impacts market sentiment and decision-making, deterring first movers from scaling projects significantly.

BREAKING THE VICIOUS CIRCLE AND MAKING SUSTAINABLE FUEL PRODUCTION A CLEAR INVESTMENT OPPORTUNITY

Looking at the challenges above, action clearly needs to be taken now to prevent avoidable shortages of sustainable fuels in the near future, with the negative impacts on decarbonization that such supply chain issues would bring. Breaking this vicious circle requires action from both governments and the private sector.

THE NEED FOR GOVERNMENT SUPPORT

Governments hold many of the necessary keys to unlock market growth — and often, these keys are not about subsidies or financial support, although the latter will be crucial. At a country and regional level, governments should look to:

- Introduce clear blending mandates, with set timelines for the percentage of sustainable fuels to be included within existing fossil fuels, increasing this over time. This powerful solution provides visibility to all stakeholders around the market direction and delivers security around future demand.
- Overcome uncertain economics for sustainable fuel production by:
    - Implementing harsher CO2 taxes that would reduce the price gap in favor of sustainable fuels. For instance, in aviation, the EU's ETS CO2 system will likely reduce the price gap between SAF and existing fossil-based fuels by 20%. This would also bring in additional tax revenues that can potentially be reinvested in other sustainability initiatives.
    - Capping or at least regulating the price for bio-feedstock, particularly agricultural and forestry residues used for bioSAF. This reduces the challenge of local monopoly providers charging extortionate prices.
- Mitigate execution risks by simplifying and shortening the permitting phase for sustainable production projects.
- Provide government financing to lower the cost of capital or at least encourage the creation of large venture capital funds via incentives or lowering some regulatory risk management constraints for investors. This is a powerful lever to boost the IRR of sustainable fuel production projects and lower the final price for clean fuels, thus accelerating their adoption.

THE NEED FOR PRIVATE SECTOR ACTION

Producers, investors, and customers should also change their investment strategies around sustainable fuel production to drive market growth and secure first-mover opportunities:

Producers:

- Mitigate risk and balance portfolios by exploring and investing in different technology pathways, such as by looking beyond SAF-HEFA in aviation. They should invest in multiple projects across various regions and technology pathways. This maximizes the chances of success and limits the risk of failure.
- Consider vertical upstream integration into the sustainable fuel production value chain, or at least secure consistent OPEX via long-term power purchase agreements. Controlling the sources of production inputs (bio-based feedstock, green hydrogen, renewable power, and CO2) is a powerful lever to secure their availability and fix costs reasonably.

Investors:

- Educate themselves about the market opportunity, particularly around rising demand and the consequent lowering of risk around investments.
- Follow a balanced approach to investing, looking at a range of technologies, projects, and regions.

Customers (transport companies):

- Understand the market need and reputational benefits of switching to sustainable fuels early and sign contracts to guarantee sufficient supplies.
- Communicate plans to demonstrate commitment to sustainable fuel to end customers (passengers, users of shipping), regulators, and investors, helping drive the sector forward.

INSIGHTS FOR THE EXECUTIVE

Sustainable fuels represent a very attractive investment class: market and technology risk is decreasing every year, while economic returns are comparable to or higher than those of other infrastructure investments.

Sustainable fuels provide an opportunity for transport players to invest in the sector and diversify or re-insource some key operating costs.

Investors in sustainable fuels should ensure that they can secure sufficient volumes of feedstock and lower the cost of capital. They could potentially co-invest to reach the very high bar of required CAPEX while sharing risks.

Finally, all key private stakeholders within the sustainable fuel ecosystem (feedstock suppliers, producers, off-takers, and investors) should create a compelling "equity story" for governments, helping them design the right incentives and locate financing for the industry.

Coordinated efforts between agriculture, green electricity generators, H2- and CO2-producers, and transportation off-takers would demonstrate the market's full potential and, therefore, unleash wider financing of sustainable fuel projects.

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BACK TO THE FUTURE –
WHAT MIRRORS IN SPACE CAN TEACH US ABOUT INNOVATION FOR SUSTAINABILITY

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Most would agree that technological innovation is an essential part of our response to the existential threats of climate change. Indeed, only through innovation will it be possible to achieve net zero emissions and adapt to new climate conditions while maintaining — and hopefully further improving — economic and social well-being. Yet one of the main obstacles for new and emerging climate change technologies is often their unattractiveness in terms of ROI due to factors such as risk and uncertainty, difficulty in monetizing environmental benefits, high capital outlays, and long payback periods.

Energy from space is a great example. The idea of harnessing an uninterrupted, virtually limitless source of solar energy from a device in orbit has captured the imagination since the mid-20th century, when space travel became a reality. Back in 1968, one of Arthur D. Little's (ADL's) leading space technology experts, Peter Glaser, first published his concept for harnessing solar energy from space, which involved deploying satellites to beam solar energy to Earth using microwaves.[1] Despite the considerable interest at the time, the technical challenges were concluded to be too high, and there were safety concerns about the microwave-based energy transmission technology. In fact, Peter (who later became known as the "father of the solar-power satellite") continued to work as a VP of ADL on multiple groundbreaking innovation projects, including project manager for the Apollo 11 lunar Laser Ranging Retroreflector array installed on the Moon's surface in July 1969 and two other arrays installed during follow-on Apollo landing missions. All this hardware still functions on the Moon today.

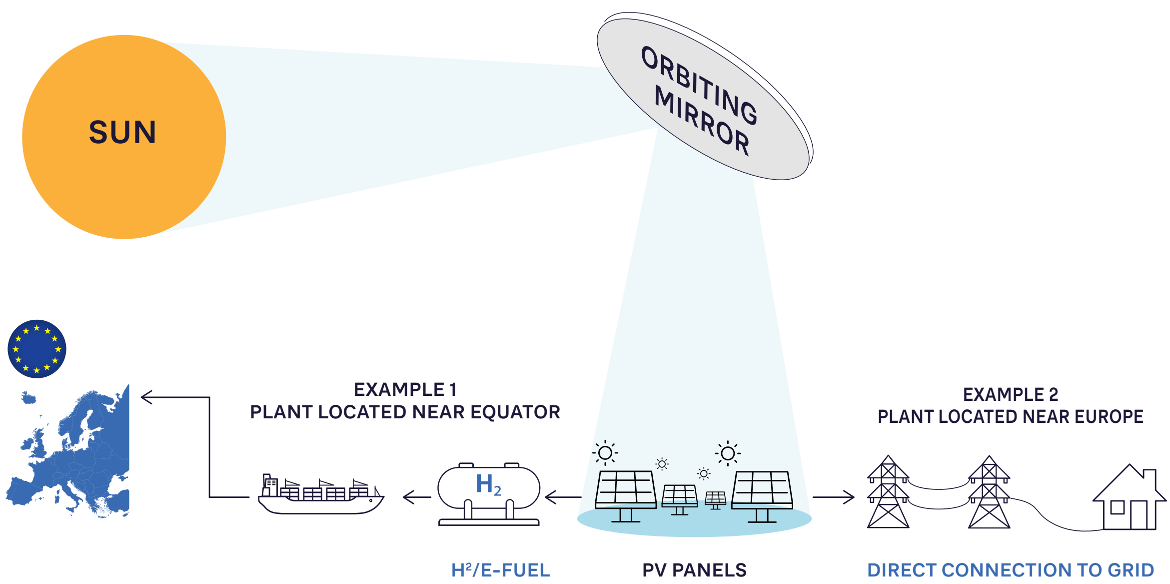
1. Glaser, Peter E. "Power from the Sun: Its Future." *Science*, Vol. 162, No, 3856, November 1968.

However, the energy-from-space concept recently gained new momentum. ADL, working with partners Thales Alenia Space France, Dassault Aviation, Engie, and Air Liquide, has, in a sense, returned "back to the future" of energy from space with a new study[2] for the European Space Agency (ESA) on direct solar reflection (DSR). Rather than generating energy from the Sun in space and using microwaves to transmit it to a fixed base station on Earth, DSR involves deploying a constellation of mirrors in space to reflect sunlight directly onto a range of Earth-based solar farms, acting like an additional sun for them. DSR is still at the concept stage, but initial deployments could happen as early as 2035.

The sudden acceleration of the DSR concept illustrates some key lessons for harnessing innovation to achieve sustainability goals. It's also a fascinating project in its own right.

HOW DSR WORKS

Global installed solar photovoltaic (PV) continues to be one of the fastest-growing green energy technologies, reaching around 2,000 gigawatts (GW) in 2024. However, solar farms only produce energy when the sun is shining and high in the sky. DSR involves deploying large mirrors in space that redirect the sun's energy on the ground toward existing or new PV plants to increase their illumination, especially when there is no (or not enough) sun (see Figure 1).



Source: Arthur D. Little

FIGURE 1: DSR CONCEPT

2. Arthur D. Little. "Pre-Phase A System Study of a Commercial-Scale Space-Based Solar Power (SBSP) System for Terrestrial Needs." Nebula Public Library, European Space Agency (ESA), 2023.

The mirrors can be placed in low Earth orbit, potentially adding up to two extra hours of peak sunlight per day, at dawn and dusk. This leads to a significant increase in energy production from solar farms — as much as 60% annually near the equator — greatly improving their overall efficiency.

The technology concept examined to date involves deploying into space an array of 4,000 mirrors, each approximately 1 km in diameter, at an orbit altitude of 890 km. The orientation of the mirrors is automatically controlled to illuminate a spot on the Earth's surface that is approximately 8 km in diameter. The array is given an orbital path around Earth that enables it to cover many ground-based solar farms. (The concept evaluation considered 30 such farms.) The array covers each solar farm's dawn and dusk hours before moving on to the next one along the orbital path. To prevent the "solar spotlight" from the array from affecting any populated areas, a clear space with a diameter of 15-20 km would be needed around each solar farm. This means that many of the likely solar farm candidates for DSR would be off-grid. Indeed, many of the world's largest solar farms located near the equator, now and in the future, are or will be off-grid. Instead of delivering electricity, they produce green hydrogen, which is shipped by pipeline or boat to commercial or industrial customers. Today, hydrogen is produced from a solar PV farm by using the power to electrolyze water — this is the typical way of transmitting the energy produced when a direct grid connection is not feasible.[3]

THE TECHNOLOGY CONCEPT EXAMINED TO DATE INVOLVES DEPLOYING INTO SPACE AN ARRAY OF 4,000 MIRRORS, EACH APPROXIMATELY 1 KM IN DIAMETER, AT AN ORBIT ALTITUDE OF 890 KM.

DSR is one of two energy-from-space concepts currently being explored. The other one, known as "space-based solar power (SBSP)," involves deploying a 7 km x 5 km solar PV factory into geostationary orbit. The space-based PV array would transmit an uninterrupted energy supply via microwaves to a fixed ground station on Earth. SBSP is best seen as a complement to DSR. They have different objectives: DSR aims to better exploit the huge financial and material investments already being made into solar farms on earth, while SBPS aims to provide a completely new source of baseload power.

THE VALUE PROPOSITION OF DSR

The key question, of course, is whether the economics of DSR are attractive enough. The work done so far on the concept concludes that it could be attractive; however, like some other new energy technologies, it requires a high up-front investment. We can consider the value proposition from the perspectives of environmental benefits, ground-based energy operators, and space operators.

3. Emerging technologies such as solar fuel cells could generate hydrogen directly from solar energy, without the use of electricity in the process, leading to triple the yield rate.

DSR HAS A STRONG, POSITIVE ENVIRONMENTAL IMPACT

DSR infrastructure at full scale is estimated to avoid around **8.8 billion** tons of carbon emissions over a 30-year operational period, compared to what would be emitted by a gas-fired power station to generate the same amount of energy without it. To compare, EU countries currently emit just under 3 billion tons of greenhouse gas per annum.[4] Against this, we need to account for the carbon footprint of DSR operations, which is dominated by the launch phase. Overall, approximately 85 million tons of CO2 are emitted over the project lifetime, yielding a net CO2 benefit of around **8.7 billion** tons. Carbon neutrality would be reached around five years after launch.

DSR has an insignificant energy footprint compared to its energy production capacity. In the reference scenario, around 20,400 terawatt hours (TWh) are produced over the project lifetime versus only around 300 TWh needed for launch, satellite production, and deployment. At full scale, **18 million tons of hydrogen** would be produced annually, more than **10%** of the projected European consumption in 2050.

DSR CAN DELIVER SUBSTANTIAL VALUE TO GROUND ENERGY OPERATORS

Once the original capital outlay has been made, DSR could provide up to 60% of additional energy output from each solar farm it services, without the need for additional CAPEX. If we consider the case of a single PV+electrolyzer station with an installed capacity of 8.8 gigawatt peak (GWp), generating this amount of additional energy would require US $5 billion of capital investment. This $5 billion saving means the operator could decrease its hydrogen production cost (LCOH)[5] by 50%. Even if the DSR provider charges a transfer price for the additional energy, the operator would still have a large net margin.

Further gains could occur if and when solar fuel cell (SFC) technology becomes available. SFC converts solar energy directly to hydrogen without generating electricity as an intermediate step. SFC increases the efficiency of green hydrogen production from 12% to around 40%.

DSR COULD BE PROFITABLE FOR SPACE OPERATORS

For the concept to be feasible, the technology must also be profitable for the space operator managing the DSR constellation. Some 80% of the investment needed is for launch and deployment, the costs for which depend on the array's size and scale. For the 4,000 mirrors needed to reach 1,000W/m2,[6] the investment would be around $60 billion. Reducing the size of the array lowers the cost, but the study calculated that an array of at least 800 mirrors is needed to provide a competitive green hydrogen generation cost. This may be considered, therefore, a minimum viable product (MVP), which would reduce the

4. "Trends and Projections in Europe 2023." European Environment Agency (EEA), 7 July 2023.
5. LCOH is the price per unit of hydrogen that operators need to charge customers in order to break even.
6. 1,000W/m2 is the power provided by the Sun at noon.

investment to $10–$13 billion and the same level of revenue over the period for the space operator.

SOME KEY CHALLENGES TO BE ADDRESSED

As with any developing technology, there are some challenges to making DSR a reality, but in theory, at least, these seem to be within reach:

- **Technical:** DSR is significantly less complex than SBSP, and most of the technologies it relies on are mature or almost mature. Challenges still to be overcome include mirror deployment, attitude control, mirror production capacity, and development of earth-based solar fuel cells. A further challenge is ensuring safe and sustainable operation. Collision with space debris is an issue for any hardware deployment in space, particularly space infrastructures deployed in low orbits. We could expect to launch the first small-scale mirror into orbit as a demonstrator in less than two years to prove the technical feasibility of deployment and attitude control. The DSR technology is also modular, so it could be further developed in stages to start operating with five mirrors as early as 2035 to prove that these technical issues can be tackled.

- **Financial:** The main challenge here is the initial capital investment to deploy an MVP, which, as we have seen, is at least $10 billion. This would likely require several stakeholders, including space agencies, governments, and private funders. Space agencies are generally strongly motivated to pursue energy-from-space projects as they benefit humans on Earth directly. Governments are often interested in catalyzing the creation of new value chains, as many have tried to do for nuclear projects. Regions such as the Arabian Gulf, India, North Africa, and Australia, with their large, empty, sun-baked spaces, may especially be interested. From a private funding perspective, even if the payback period for a full-scale DSR deployment may not be so attractive per se, investment in the technology bricks that enable it (e.g., mirror and coating technologies, control systems, and remote robotics for assembly and maintenance) have broad applications and could create value in much shorter timescales.

> ***A FURTHER RISK THAT NEEDS TO BE CONTROLLED IS COLLISION WITH SPACE DEBRIS, AN ISSUE FOR ANY HARDWARE DEPLOYMENT IN SPACE, PARTICULARLY FOR SPACE INFRASTRUCTURES DEPLOYED IN LOW ORBITS.***

- **Deployment:** The excessive cost of deployment used to be the main barrier for energy-from-space concepts. However, since the 1980s, the cost per kg for space deployment has plummeted from $60,000 to $2,300 today. The SpaceX roadmap envisages an even more dramatic decrease, with the Starship launcher claiming to reach $100 per kg in the short term. Europe is considering developing a similar launcher. This means deploying 800 mirrors (the MVP case) could be feasible by 2035, with 4,000 mirrors by 2043.

- **Public acceptance:** Current public opinion is concerned about the risks of deploying technology in space, from the point of view of space pollution, accidents, and any unexpected complex adverse effects from what might be seen as "geoengineering." DSR has the benefit of being inherently safe (for example, the radiation from an array is not harmful to humans within the "spotlight") and is localized in its impact, with very low light pollution.[7]

SOME LESSONS ON INNOVATING FOR SUSTAINABILITY

The acceleration of the DSR concept in terms of technical feasibility and attractiveness illustrates the following five important lessons about innovating for sustainability.

1. ASSUMPTIONS ABOUT TECHNOLOGY PERFORMANCE AND RISK NEED TO BE CONSTANTLY REVISITED

Energy from space has been considered a risky, uncertain concept for decades. Some energy operators perceive it at the same level of uncertainty and risk as nuclear fusion. However, individual breakthroughs on the technological bricks needed for energy from space have continued to the point where, collectively, what seemed unfeasible is now becoming feasible — examples include progress made on super-heavy launchers to reduce cost per kilogram, new ultra-thin and low-weight reflector materials, better robotization for deployment, and greater attitude-control accuracy. It is important to continuously challenge preconceptions and assumptions, which can be quickly overturned when stepwise progress reaches a tipping point. This often occurs by leveraging ongoing innovations and new use cases in adjacent, or even completely unconnected, domains.

> ***ENERGY FROM SPACE HAS BEEN CONSIDERED A RISKY, UNCERTAIN CONCEPT FOR DECADES. SOME ENERGY OPERATORS PERCEIVE IT AT THE SAME LEVEL OF UNCERTAINTY AND RISK AS NUCLEAR FUSION.***

7. This would be further confirmed in the early deployment phases of the project.

2. COLLABORATION ACROSS TRADITIONAL BOUNDARIES IS CRITICAL FOR INNOVATION TO ADDRESS SUSTAINABILITY CHALLENGES

Energy-from-space innovations such as DSR are only possible with convergence between two separate value chains: space and energy. Space and energy traditionally operate in completely different worlds, with different technologies, economics, markets, customers, and ways of working. Beyond energy from space, many climate mitigation and adaptation challenges require convergence between diverse sectors and stakeholders, such as space and agriculture for crop monitoring and space and telecoms for maritime communications (to optimize boats' fuel consumption, for instance). Climate change adaptation also depends heavily on finding new ways to collaborate between governments, local communities, businesses, and individuals to combine local, national, and global system-level interests and challenges. A new mindset is needed that is willing to set aside reluctance to expose intentions and constraints in the interests of collaboration.

ENERGY-FROM-SPACE INNOVATIONS SUCH AS DSR ARE ONLY POSSIBLE WITH CONVERGENCE BETWEEN TWO SEPARATE VALUE CHAINS: SPACE AND ENERGY.

3. NEW APPROACHES TO ECOSYSTEM WORKING ARE NEEDED TO DRIVE THIS TYPE OF INNOVATION

For these extended, diverse ecosystems to be established and operate effectively, new approaches are needed. For example, the DSR project involves energy players, space players, public authorities, and investors. Establishing an independent orchestration role can be key to making this work. The orchestrator acts as an unbiased party to encourage open information sharing to help in "translation" for better communication and understanding between diverse players, to be a trusted resource to research the necessary evidence to answer key questions, and to resolve differences of opinion.

4. MULTIPLE PARALLEL TECHNOLOGY APPROACHES NEED TO BE PURSUED TO IMPROVE THE LIKELIHOOD OF SUCCESS IN ADDRESSING SUSTAINABILITY

While the idea of a balanced portfolio of technology development projects is well established within companies' R&D departments, this is less the case on a global scale. For example, there has been a tendency at national levels to compare DSR with SBSP technologies to decide which to fund. In fact, the two concepts deliver completely different outcomes and are wholly complementary to each other.

To tackle challenges on the scale of global sustainability, multiple technologies must be pursued at the level of a global "portfolio." Space technologies can become mature by leveraging short-term use cases on Earth. For example, radio frequency power beaming technology (such as that envisaged for SBSP) could have exciting terrestrial use cases, such as providing energy to planes or drones or connecting electricity grids without cables.

5. FINANCING INNOVATION FOR SUSTAINABILITY NEEDS DIFFERENT STRATEGIES

The initial outlays for sustainability-related projects such as DSR and SBSP are very large, so financing is challenging, even with a positive ROI. The initial investments are beyond the capacity of all but the largest public sources, and the payback periods of 15–20 years are too long for private funders. This means that innovative financing approaches involving public and private funding, such as green bonds, should be considered. A second strategy is to focus first on developing some of the technology bricks rather than the whole system, which can often be done with other more attractive use cases — even if the system integration afterward becomes more complex.

Ultimately, the severity of the sustainability challenge may force new levels of global collaboration, but our aim should be to establish this collaboration before catastrophic events impose it on us. Managing the ecosystem is the last, but certainly not the least, challenge to overcome to make energy from space a reality for the benefit of humanity.

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