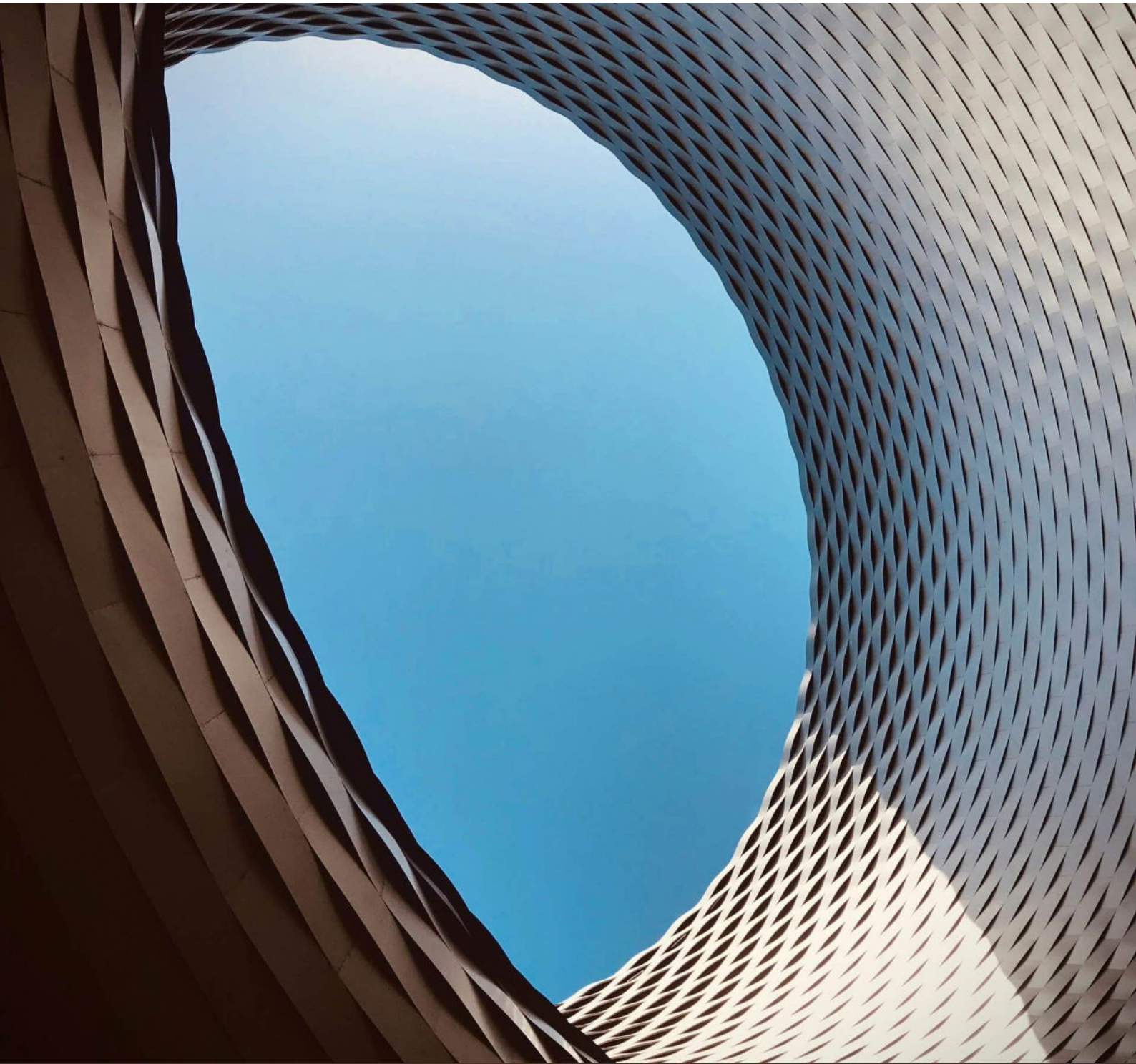




THE FEEDBACK LOOP BETWEEN M_{AAS}, STOCK-AND-FLOW MODELS, AND PERFORMANCE PRICING

Aniruddha Pravin Jaydeokar, Perrine Toledano, Laura Garcia Cancino, and Shunta Ofusa

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Authors

Aniruddha Pravin Jaydeokar, Perrine Toledano, Laura Garcia Cancino, and Shunta Ofusa.

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Executive Summary

Metals-as-a-Service (MaaS) rents metal instead of selling it. The owner retains title to the metal, the user pays for its use or performance over a set period, and the metal comes back at the end for another cycle of use. The recurring question is, how do you actually build and price such a business? This report answers it by considering first what the conventional model cannot do; when metal ownership passes at the point of sale, no single actor maintains visibility over the full lifecycle, and no actor is required or incentivized to report where it is or what condition it is in.

That constraint shows up in two places. Estimating how much metal exists and when it will come back (through stock-and-flow (S&F) models) has to proceed without direct observation, so it relies on assumed lifetimes, failure rates, and recycling efficiencies. Pricing proceeds without that observation too, and settles on what can be easily and cheaply verified when title changes hands, which is volume. Weight is a sound unit for a sale, where the buyer takes on all later condition risk. However, it is an incomplete one for a lease, where the owner takes the metal back and is exposed to a condition that weight does not describe.

Retaining ownership addresses both issues because the same tracking that grounds those estimates with observed quantities supplies the contract with observed conditions. First, metal that stays in one owner's hands can be counted, which puts observed quantities where assumptions used to be. And because those same estimates are what show where recoverable metal is worth pursuing to begin with, the improvement circles back, creating a feedback loop: the estimates point to MaaS, and MaaS tracking sharpens the estimates. Second, metal that returns to its owner can also be inspected, which raises a possibility a one-time sale never had, namely charging for what the metal delivered rather than for what it weighed. This one depends on the tracking the loop provides, and it works only where that measurement can be afforded. **The practical implication is that most of the analytical backbone a MaaS business needs to answer the question of how to advance and price the model already exists through different tools and frameworks used in analogous sectors, and should be adapted rather than built from scratch.**

The report follows this idea in five interrelated steps, adapting existing tools to answer our recurring question. The first two establish the loop by considering what the S&F models can currently estimate, what they cannot, and how firm-level analysis and retained ownership change that. The last three follow what the loop makes possible, moving from financeable structure to unit cost to price. All five are illustrated with the steel-to-wind value chain, chosen not because it holds the most metal (construction does) but because installation cohorts are observable and turbine lifetimes are comparatively well bounded, which makes wind the most predictable place to prove the model.

Stock-and-flow models: turning material data into a business case

A stock-and-flow model, operationalized through Dynamic Material Flow Analysis, is an accounting method for materials. It tracks how much metal is sitting inside the economy (the “urban mine” of buildings, infrastructure, and wind turbines) and how fast it moves in and out through production, wear, and recycling. Because nothing vanishes, what goes in must either accumulate or come back out.

For a MaaS business, this answers the practical questions that make or break a deal:

- How much recoverable metal is out there, when it will return, and from where.
- How large to size the “metal bank” (the pool of metal the business owns and brings back to the loop for multiple cycles).
- Whether the metal returns in good enough condition to rent again, which is what residual value, and therefore the pricing, rests on.

The same accounting tracks how scrap composition changes over time, including the accumulation of tramp elements such as copper and tin that progressively narrow the uses secondary steel can serve. In a simplified form, it could serve as a live inventory model of the metal bank itself.

However, it is important to take into account that because in-use stocks cannot be measured directly at scale, current models substitute assumptions for observation. Material intensity coefficients are typically based on engineering averages, fabrication yields and allocation matrices are built through dozens of separate calculation steps, failure rates are often extrapolated from a single national dataset, recycling efficiencies are averaged across sectors and assumed to remain constant over time, and post-consumer scrap is estimated as a residual rather than measured directly. As a result, the binding constraint is a lack of empirical ground truth, not the model architecture itself.

Finding the stock the models miss: a bottom-up, firm-level screen

The data gap in S&F models is also a big opportunity. Standard accounting depreciates plant, property, and equipment to a book value of zero at the end of its useful life, but the metal is still physically present and still has a residual value. This report proposes flipping the accounting lens from top-down to bottom-up and treating that gap as a screening opportunity. The most promising targets are business-to-business firms with leasable assets, a high share of illiquid assets (the acid test ratio is the single most critical parameter), revenue models that accumulate rather than pass through metal, capital expenditure histories that signal metal-intensive stock, and distressed or junk-rated balance sheets where acquiring recourse debt offers a path to the underlying metal. [Annex I](#) maps public datasets on closed refineries, inactive factories, abandoned and decommissioned power plants, retired pipelines, closed seaports, scrapped ships, and abandoned LNG and hydrogen assets as starting points for that screen.

By screening company balance sheets, a MaaS business model can identify and acquire this overlooked metal cheaply, as a ready-made urban mine. S&F data helps spot where that embedded value sits, and a live MaaS model, where the recovered metal is held by an AO across the full lifecycle, realigns incentives toward recovery and requires systematic tracking. That tracking restores the missing observation and converts rough, assumption-based estimates into contractually defined and verifiable quantities.

Turning material data into financeable structure

S&F variables move through three layers before they reach a balance sheet. The physical layer describes stocks, inflows, in-use accumulation, and end-of-life outflows. The economic layer converts these into residual value, timing of the loop, location of stock, fungibility, entry point, and exposure to the metal spot price. The financial layer turns those into service-fee valuation, cash-flow timing, collateral quantification, recovery certainty, asset-backed structuring, and benchmarks that make MaaS legible to lenders. The three layers trace how observed material data becomes an economic variable and then a financeable structure.

The same logic can upgrade servitization models already operating in the market. Platinum group metal catalyst leasing, EV battery-as-a-service, lighting-as-a-service, telecom copper decommissioning, and refrigerant cylinder leasing all currently rely on static estimates or basic condition tracking, and each has an identifiable point where dynamic S&F modeling would improve retrieval timing, inventory sizing, or pricing.

Testing the unit economics: The Levelized Cost of MaaS (LCoM)

Borrowing from the energy sector's levelized cost of energy (LCOE), the Levelized Cost of MaaS (LCoM) is the net present value of the total lifecycle cost of providing the metal divided by the total

service delivered over the same period. This companion metric lets a company check whether the model beats the linear one, and shows the levers to pull: keep less metal idle, redeploy it faster, sequence high-grade metal to the uses that need it, and build a track record that lowers financing costs over time. The LCoM metric is computed from data provided by the stock-and-flow models, and enhanced with modern tools such as digital twins and AI-based tracking, among others.

The LCoM metric also connects this report to our [earlier work](#). Variable Yield measures the asset (stock of one metal type) level cash flow deficit between selling and leasing the same volume of metal, while the LCoM defines the transaction-level unit economics that close that deficit. What the LCoM does not settle is what the lessee is buying. Under a volume-based contract, the lessee is still buying tons, which leaves the owner's exposure to the condition of the returned metal outside the price.

A pricing ladder: from selling volume to selling performance

This report takes up that gap by introducing performance-based pricing. The bigger shift is charging for what the metal does rather than how much it weighs, moving from dollars-per-ton to performance-based pricing. S&F models, combined with sensors, digital twins, and simple tracking, make performance measurable, which makes it billable. For instance, copper transmits electricity better than aluminum, so instead of selling the copper, a business can charge for that superior performance over time. The same logic already runs the aviation industry, where engine makers sell “power by the hour,” where the airline pays for thrust, efficiency, and reliability, not for the engine itself. MaaS applies that proven idea to the metal inside the asset.

The report sets out four architectures, ordered by how much degradation risk sits with the owner and by market maturity:

- **Standalone performance-based contract:** the lessee pays purely for the service delivered, and if performance drops, payments drop with it. The owner bears all degradation risk and prices it into the base rate. Best for mature, well-monitored MaaS markets.
- **Volume renting plus a performance swap:** a familiar per-ton rental with an “insurance” layer on top: the lessee pays a periodic premium, and the owner guarantees a baseline performance (quality floor), stepping in to recover and replace the metal if it falls below the floor of agreed performance. A bridge for markets still used to volume-based contracts.
- **Volume renting plus a performance swap plus a swaption:** an extra layer that offers protection against future price hikes, like a cap on the rent when a lease renews. Adds the right, not the obligation, to enter a future swap at a pre-agreed premium, protecting the lessee against premium increases in subsequent cycles if conditions worsen. Useful where the environment is volatile, and deployments are long-term.
- **Volume renting plus a degradation-linked note:** a structured fixed-income instrument in which the metal acts as principal and the lessee's interest payments fall continuously as quality degrades. Because cash flows run one way, it is the most securitizable of the four, and it removes the owner's incentive to let quality sit just above a contractual floor.

Performance pricing also changes what the business owns. Continuous condition data is a proprietary asset in its own right as it improves future design decisions, raises the cost of entry for competitors, and is typically associated with the valuation multiples of technology-enabled businesses rather than commodity ones. An operator that prices on performance accumulates that asset as a by-product of billing.

Two limits apply to all four architectures. They are theoretical, do not currently exist in the market, and have not been modeled for commercial or operational viability. And MaaS is not suited to metal

deeply integrated into a lessee's product; it targets uses where the metal is the sole functional unit and retains a homogeneous form, such as standardized steel casings, uninsulated copper busbars, and catalytic powders. Where performance cannot be measured at acceptable cost, volume remains the appropriate unit.

The loop

S&F models can identify where material stocks, future recoveries, and value pools may emerge, defining the opportunity space for MaaS. However, their reliance on aggregated assumptions makes firm-level analysis essential to assess commercial viability. Retaining ownership is what closes that gap. By embedding traceability across the asset lifecycle, MaaS can generate the granular data needed to improve S&F models because it gives the model quantities it can observe in place of assumptions it must substitute, and it makes the returned condition of the metal observable, which is the precondition for pricing it. In turn, traceability-enhanced S&F models can support performance-based pricing and contracting, creating a feedback loop between system-level analysis and business model innovation, where better data supports better pricing, and priced performance generates better data.

Introduction

A stock-and-flow (S&F) model, most commonly operationalized using Dynamic Material Flow Analysis (DMFA),¹ is a mass-balance accounting framework that tracks how a material moves through an industrial or societal system over time. It distinguishes between stocks (the total mass of material residing within a system at a given moment, e.g., steel embedded in buildings, infrastructure, or wind turbines) and flows (the rates of material movement, e.g., annual production, import, use-phase entry, end-of-life (EoL) waste generation, recycling, and landfill). The governing principle is simple mass conservation: what enters a system must either accumulate or leave it.

In practice, applying this mass-balance logic requires accurate estimates, but because in-use stocks (e.g., steel embedded in buildings, infrastructure, or wind assets) cannot be directly measured at scale, every S&F model must substitute assumptions for empirical observation across multiple structural dimensions. The reviewed literature on S&F features very diverse extrapolation methods, but the basic principle is the same: the calculation of outflows from the in-use stock is based on inflow or stock data and a lifetime distribution function.²

Viewed through a [Metals-as-a-Service \(MaaS\)](#) lens, the value of stock-and-flow modeling is that it converts data relevant for circularity assessment into data that can underpin the construction of a viable business model: the size of the “recoverable” urban (above-ground) stock, the expected timing of end-of-life returns, the geography of those returns, and the residual value of the material in stocks. For MaaS, this is also a performance question in which service value depends not only on whether metal returns, but also on whether it can return, under the MaaS contractual arrangements, in conditions and specifications that remain fit for its next use cycle. These outputs directly inform MaaS feasibility and pricing, including inventory sizing for a metal bank, recovery-rate assumptions, reverse-logistics planning, and the credibility of residual-value cash flows.

These outputs are shaped by one structural constraint: because ownership of metal transfers at the point of sale, no single actor maintains visibility over the full lifecycle, and both the modeling of material flows and the pricing of the material itself proceed without that observation. This report follows both of these consequences and argues that retaining ownership is what restores the missing information, sharpening the models on one side and—where performance can be measured at acceptable cost—changing what the contract prices on the other.

This report is structured in five sections. Section I provides an overview of S&F and DMFA models in the steel-to-wind value chain, including their typical assumptions, practical applications, and current limitations. Section II argues for the need to complement top-down S&F approaches with a bottom-up, firm-level perspective capable of identifying embedded and potentially monetizable metal stocks within real assets and balance sheets. Section III examines how these models can support the development of MaaS business models by translating physical material stocks and flows into economic and financial structures. Section IV delves into how enhanced S&F models can help deliver a synthetic metric, called the Levelized Cost of MaaS, to help assess at a transaction level if MaaS is a competitive business model. Section V further explains how S&F models, accompanied by traceability and AI-enabled systems, can monetize the service delivered by the model, further shifting incentives along the value chains. The report concludes by discussing the mutually reinforcing relationship between MaaS implementation and improved material flow visibility, arguing that MaaS itself may help generate the data infrastructure needed to strengthen future stock-and-flow modeling.

This report gives practitioners five practical takeaways:

- 1. Identify the system-level opportunity space for MaaS:** After understanding what they are, demonstrate how S&F models can estimate where metal stocks accumulate, when they are likely to become available, and where future recoverable value pools may support MaaS business models.
- 2. Develop a framework for assessing MaaS feasibility at the firm level:** Show why top-down S&F analysis must be complemented by bottom-up analysis of ownership structures, embedded metal stocks, and misleading accounting treatment to find new opportunities for a metal bank.
- 3. Position MaaS as both a circular business model and a data infrastructure:** Argue that MaaS can address the structural information failures that limit current S&F modeling by retaining ownership, which in turn enables tracking assets throughout their lifecycle, and generating observable, contract-based data on material use, degradation, recovery, and residual value.
- 4. Demonstrate how stock-and-flow models can underpin MaaS financial architecture:** Show how enhanced S&F analysis can support lifecycle costing and optimization through a unique metric called Levelized Cost of MaaS (LCoM), residual value estimation, collateral valuation, derivative pricing, lender confidence, and other financial mechanisms required to scale MaaS.
- 5. Introduce a pathway toward performance-based pricing for metals:** Propose how traceability, DMFA, and S&F models can shift MaaS from volume-based charging to pricing based on delivered material performance, while outlining theoretical contract architectures—including performance contracts, performance-linked derivatives, and a performance-linked debt instrument—that allocate degradation risk and align incentives for longer asset life and higher material efficiency.

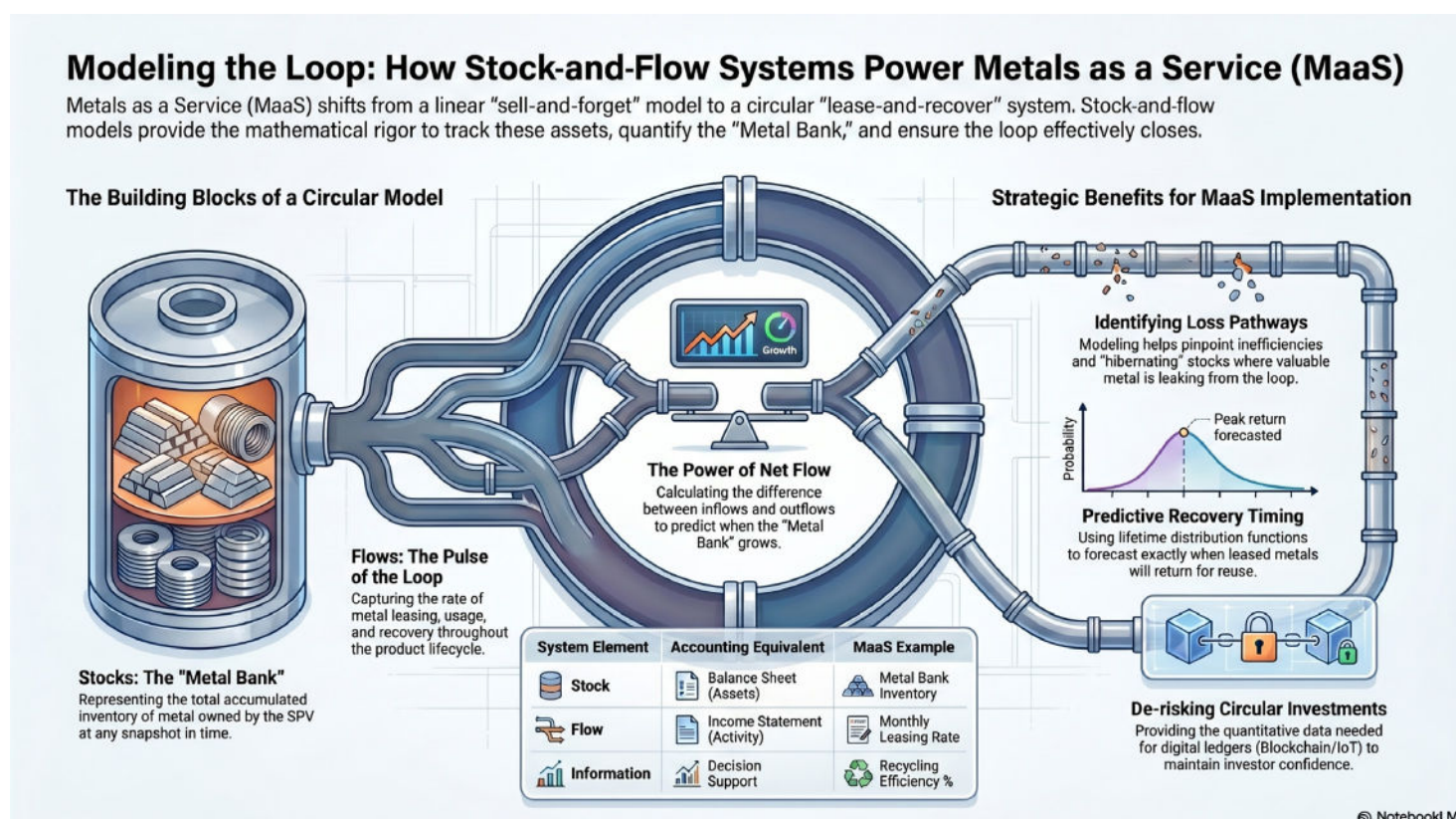


Figure 1. Modeling the Loop: How Stock-and-flow Systems Power MaaS.

Source: Charts based on the cited sources.³

I. Stock-and-flow overview in the steel-to-wind value chain

This section reviews the literature on S&F models used in the steel-to-wind value chain, outlining their core assumptions, main applications, and key limitations.

a. Typical assumptions and outputs

1. Material Intensity Coefficients

Steel content per unit of output (e.g., tonnes per MW of wind turbine capacity, kg per vehicle, kg/m² of floor space) is the foundational input to any S&F model.

2. Yield Rates by Process and Product

Because the steel industry does not report flows beyond intermediate products, there is a need to construct a fabrication yield matrix Y that specifies the fraction of each intermediate product (cold rolled coil, reinforcing bar, sections, etc.) that survives into the final end-use good, meaning that the rest becomes fabrication scrap. These yields are not directly measured at the global level. They are estimated from a combination of sources and vary substantially by product. For instance, cold rolled coil used in construction has a yield of 90%, cold rolled coil used in car body panels has yield of only 60% (complex shaped panels with cut-out holes), or reinforcing bars used in buildings have a yield of 95% (based on data from a single UK steel fabricator), making the overall fabrication average 85% as the assumption of the yield rates.⁴

Additionally, a forming scrap, generated during hot and cold rolling, is not reported in industry statistics because it is recycled internally and excluded from standard recycling data. In one study, it is calculated as 98 Mt from the steelmaking mass balance, plus 40 Mt recycled internally in steel casting and 35 Mt in iron foundry casting.⁵ These figures emerge from forcing the mass balance to close, meaning they are imputed rather than measured.

3. The Allocation Matrix: Which Intermediate Products Go to Which End-Uses

The same study⁶ describes an allocation matrix A that maps 19 intermediate product types to 10 end-use product categories. Without a global dataset for this mapping, each cell is estimated through one of two approaches:

- Where published breakdowns exist for a specific intermediate product, those are used, e.g., “53% of reinforcing steel is used in buildings, based on an analysis of UK, US, and Turkish data.” This is a geographic extrapolation that assumes the UK/US/Turkey share is representative of the global average.
- Where only end-use composition data is available, a back-calculation is performed, where the steel content of the final good is divided by the fabrication yield to infer the intermediate product input. For example, the calculation that 61% of the steel in a car is sheet metal (54 Mt globally) is derived from a “breakdown of materials for a typical car,” itself a representative average, not a global survey.
- The resulting allocation relies on 28 separate calculation steps using data from 20 different sources, each step introducing its own assumption.

4. Post-Consumer Scrap as a Residual Balance

Post-consumer scrap, which is steel recovered from consumer goods at the end of life, remains absent from direct global statistics and is still derived as a residual: total scrap consumed in steelmaking minus upstream fabrication scrap. A study⁷ provides a more recent basis for this calculation, estimating total scrap inputs to steelmaking at 606 Mt in 2019, derived from mass-balance-constrained equations applied to World Steel Association and USGS production data. Balancing flows are introduced only where data violations occur, and production figures are always prioritized, reducing, though not eliminating, the compounding uncertainty of the residual approach.

5. Initial Stock Value (Stock Initialization)

Every S&F model must define a starting stock. Where historical data is thin, as for pre-1990 wind capacity, or for developing countries with limited steel statistics, models either assume a zero initial stock at a chosen baseline year (a “burn-in” simplification) or import a bottom-up estimate from a separate study.

The retrospective top-down approach, the most frequently chosen in the S&F literature, analyzes past stocks and flows based on time series of historical inflow data such as trade, import, or consumption statistics. It is assumed that old scrap supply equals apparent old scrap demand, assuming a balanced scrap market, a homogeneous stock, and a perfectly closed steel cycle.

b. Practical uses of S&F models

The value of S&F models lies in their ability to translate in-use stock structures into forward-looking information on flow timing, spatial distribution, and material quality constraints. By linking cohort-based accumulation to end-of-life outflows, S&F models provide a structured basis for assessing secondary material availability, infrastructure requirements, and transition dynamics in industrial systems.

1. Flow forecasting for supply chains and infrastructure planning: S&F models are used to estimate future scrap generation by linking known installation dates and in-use stock dynamics to prospective end-of-life outflows. In the steel sector, sectoral stock models (e.g., Fraunhofer ISI European steel system models) disaggregate obsolescence-driven scrap generation across applications, providing scenario-based guidance for investments in electric arc furnace (EAF) capacity and scrap-dependent production systems.⁸

At the global level, cohort-based steel stock models consistently indicate that future steel demand and scrap availability can be derived from in-use stock dynamics under the principle that accumulated stocks determine subsequent flow generation (“stocks drive flows”).⁹ Applications of this framework across countries are useful to understand how long-term scrap supply trajectories can be structurally constrained by historical stock accumulation patterns (see Box 1).

2. Decommissioning waves and emerging material surpluses: Because infrastructure cohorts have known installation dates and relatively bounded lifetime distributions, S&F models can be used to anticipate large-scale decommissioning waves before they materialize. In the EU wind sector, model-based projections suggest that end-of-life (EoL) material flows may increase substantially over the coming decades, rising from approximately 133 kt in 2021 to around 1,200 kt by 2030.¹⁰ The same analysis estimates that this EoL material could cover 17–34% of EU demand for aluminum, 18–39% for copper, 22–45% for steel, and 41–124% for neodymium in the wind energy sector. These flow forecasts are therefore actionable for recycling infrastructure planning and secondary material allocation.

3. Scrap quality constraints and metallurgical system transition: Beyond volume dynamics, S&F models capture the evolution of scrap composition over time, including the gradual accumulation of tramp elements¹¹ such as copper and tin. This is important information because as secondary steel production expands, these impurities increasingly constrain recycling pathways by affecting ductility and limiting suitability for high-specification applications.

Steel scrap system models suggest that the historical practice of directing mixed scrap primarily to construction steel (where tolerance for residual elements is higher) may become increasingly constrained as scrap availability grows.¹² This information should equip steel industry planners with the understanding that there is a gradual need for broader sectoral absorption of secondary steel, alongside increased requirements for sorting, refining, and process control.

Similarly, S&F model-based scenarios indicate a gradual shift from primary (blast furnace–basic oxygen furnace) to secondary (electric arc furnace-based) steel production over the course of the century.¹³ Global steel stock modeling suggests that primary steel production may plateau and potentially peak within the first half of the century, while secondary production increases in relative importance.¹⁴

This transition has implications for capital allocation in the steel industry.

4. Regional divergence in scrap availability and trade structures: Regional models indicate a growing divergence between mature and developing economies. In regions with high in-use stock saturation¹⁵ (such as China, Western Europe, and the former Soviet Union), end-of-life scrap generation is projected by mid-century to approach or exceed domestic steel demand, enabling partially closed-loop steel cycles. By contrast, rapidly industrializing regions, including India, Latin America, and parts of developing Asia, are expected to remain more dependent on primary steel production or scrap imports.¹⁶ These spatial asymmetries have implications for scrap trade patterns, recycling infrastructure development, and the geographic distribution of secondary steelmaking capacity.

5. Monetizing metal performance: While S&F models are currently primarily used to forecast volumes and timing of end-of-life flows, their logic can be extended to describe how material quality evolves over time, and support contracts that value metals by functional performance rather than volume. This report develops that performance-based pricing application in Section V, as an extension of the current uses of S&F models found in place.

6. Live Inventory model for a metal bank for Maas: A simplified version of an S&F model could serve as a live inventory model for a metal bank, effectively creating a metal inventory stock wholly owned by an Asset Owner, which can be monetized over time through the Metals-as-a-Service¹⁷ business model (see section III). Changes in metal inflows as a result of procurement, whether from the acquisition of existing stocks (see section II), or through open market transactions, as well as metal outflows to lessees can be analyzed, tracked, and optimized for a metal bank's operations to run efficiently and profitably.

7. Source of data to train Agentic AI to scale practical uses listed above: Data from DMFA models can be fed into a Large Language Model (LLM) to fit specific practical uses of the DMFA listed above, such as continuously optimizing a Metal Bank's live inventory, predicting imminent decommissioning waves to secure high-grade scrap¹⁸ proactively, and autonomously determining the optimal scrap-DRI blending ratios for specific electric arc furnaces.¹⁹

Box 1: Long-term structural evolution of steel stocks in wind turbines

This box summarizes the structural stock dynamics that explain why wind assets are a comparatively tractable starting point for S&F analysis and circular business model design.

Long-term S&F scenarios suggest that global in-use steel stock will continue to expand over the coming decades, with signs of saturation already emerging in industrialized economies at per capita levels of roughly 11–16 tons.²⁰ As stock growth slows in these regions, end-of-life outflows increasingly converge with inflows, reshaping the global scrap supply structure.

Because a large share of steel stock is embedded in long-lived construction assets, future scrap generation is structurally delayed by infrastructure lifetimes on the order of several decades. Within this broader trajectory, wind energy infrastructure represents a distinct and increasingly important cohort that represents a relatively well-identified empirical case for S&F: installation cohorts are observable and lifetime distributions are comparatively constrained, making projections of decommissioning flows less parameter-uncertain than in more heterogeneous steel end-use sectors.²¹

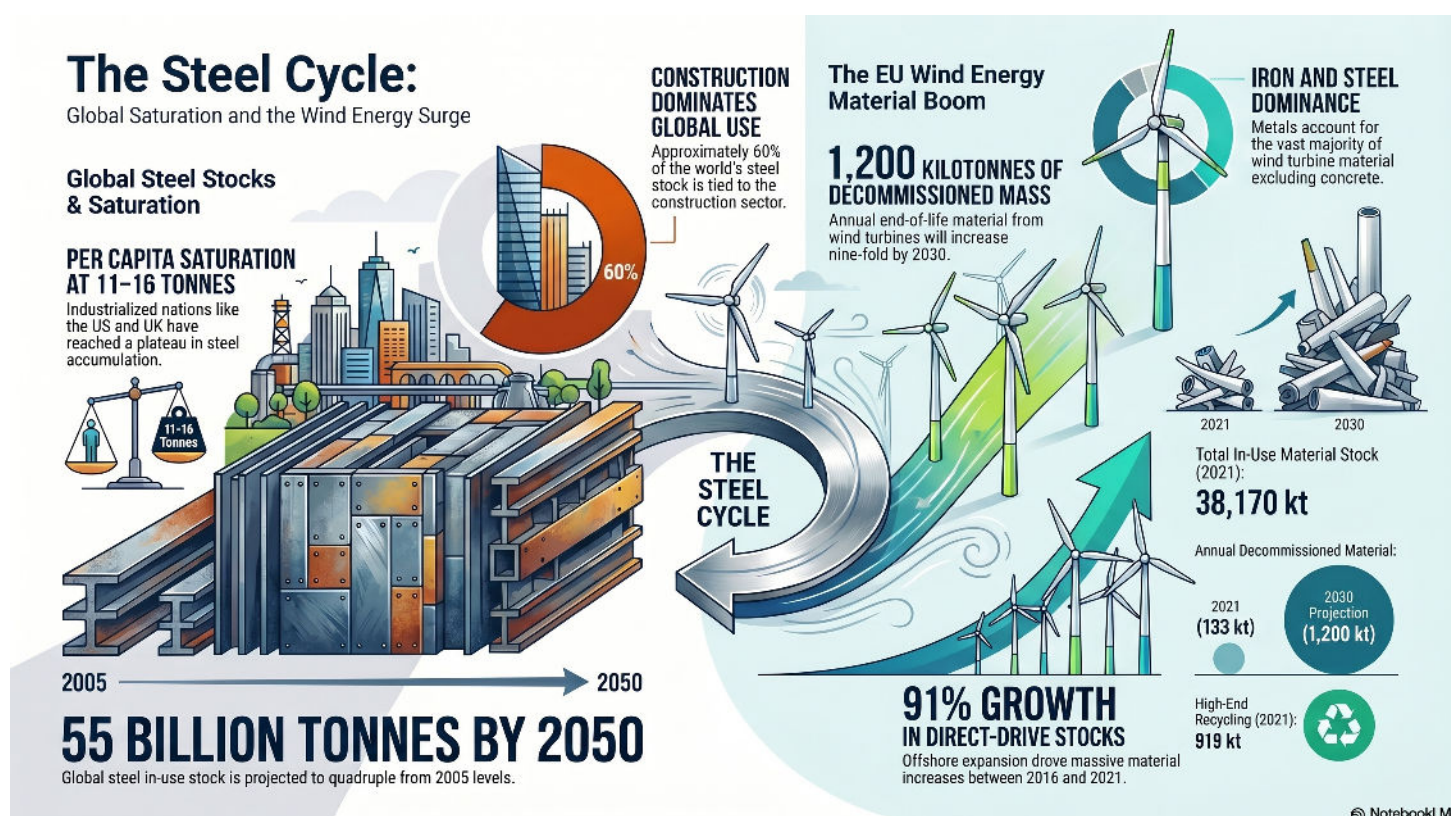


Figure 2. The Steel Cycle: Global Saturation and the Wind Energy Surge

Source: Hatayama (2010)²² and EU study (2025)²³

c. Limitations of stock-and-flow models

Despite their value, S&F models carry inherent limitations, most of which stem from **data scarcity and the use of proxy values**, as discussed in the potential assumptions within the S&F model. These limitations are not merely academic, and they are precisely the bottlenecks that prevent circularity from being accurately planned and financed.

- 1. Material intensity uncertainty:** Intensity coefficients are typically derived from engineering averages across a technology class or era. For wind turbines, the steel-to-power ratio changes with turbine size, with larger rotor diameters and taller towers altering the relationship, yet many models apply static values or smooth temporal trends, potentially misrepresenting any given installation year.²⁴
- 2. Component failure rates as geographic proxies:** The failure rate parameters can be used for one country and applied to one region. For instance, in the EU-level modeling effort mentioned above, these rates are typically drawn from a single national dataset, e.g., German wind farms, post-2001 in the study. Failure rates are highly sensitive to technology type, operational environment, and wind loading conditions, meaning that a German-derived dataset may systematically over- or under-represent failure frequencies for offshore UK or onshore southern Spain installations.²⁵
- 3. Recycling efficiency generalization:** Recycling efficiency values are often sector-averaged rather than application-specific, such as wind-turbine-specific. Steel scrap from a turbine tower enters the same secondary market as construction demolition scrap. The model therefore cannot distinguish collection efficiency specific to wind assets because of current practices where diverse scrap streams from multiple sources are aggregated.²⁶ This homogenization precludes the extraction of granular, category-specific data, thereby limiting the utility of stock-and-flow models. Furthermore, the same efficiencies can be applied across time, ignoring any improvement in industrial recycling practice over this period.²⁷

The above limitations suggest that the key data gaps are not primarily in model architecture but in empirical ground truth that real-asset monitoring of decommissioned turbines, broader geographic coverage of failure databases, and recycler-level data on actual recovery rates per product category are needed. The recycling sector specifically is poorly covered, with recovery efficiencies for specialty metals (neodymium, dysprosium) at near-zero levels in current S&F models because the industrial infrastructure to recover them at scale simply does not yet exist. Improving model accuracy thus depends on **simultaneously improving real-world recycling infrastructure and the data systems that document it.**

These gaps are not primarily defects of method. Each stands in for an observation that no actor in a linear value chain is positioned to make, because ownership of the metal does not survive the point of sale. Section II takes up that structural cause and what follows from reversing it.

II. The need for a bottom-up approach: Creating a feedback loop between MaaS and S&F models

Metals are produced, embedded in assets, and dispersed across firms and geographies with only partial recovery at end of life. This fragmentation is driven by a core feature of the system: ownership of metal is transferred at the point of sale. As a result, no single actor maintains visibility over the full lifecycle, and actors are neither required nor incentivized to report material stocks and flows. This creates a condition of structural opacity and information asymmetry across the value chain.

The result is that S&F models, which aim to map this system, must rely on **proxy assumptions within a top-down approach** (e.g., lifetimes, failure rates, recycling efficiencies). These assumptions are symptoms of the underlying linear ownership structure that fragments information.

For instance, if one were to look at the Chinese Copper Cycle²⁸ and observe where potential metal cycle inefficiencies could be solved by a MaaS model, the findings presented in the paper rely on simplifying assumptions that fail to capture the inherent complexities of the Chinese copper cycle. Consequently, this simplified framework makes it difficult to accurately ascertain the precise location, quantity, and material quality of the copper stocks within the system.

A bottom-up approach complements this by shifting the unit of analysis to the firm level, where metals are physically embodied in assets. The underlying hypothesis for a bottom-up approach is that “Plant Property and Equipment (PP&E)” on a company’s balance sheet is a **stock**²⁹ for metals, and depending on the industry³⁰, this stock may over time be substantially valuable to justify its (eventual) monetization under a MaaS model (Table 1). Companies that are operating in industries where their growth in revenue is tied to production capacity (which is tied to non-movable high CAPEX) are likely to have built up metal stock in their Plant Property Equipment (PPE).

Standard linear accounting rules force companies to use “straight-line” or “accelerated” depreciation. They mathematically model the PP&E’s value as a smooth, continuous line drifting downwards until it hits zero at the end of its “useful life.” At that point, the financial model declares the asset dead, worthless, and invisible to the balance sheet.

But physics disagrees. The metal may not have completely degraded. It may not have vanished. Therefore, a massive structural break occurs between the *financial model* (which says the value is 0) and the *physical reality* (which says 100 kilograms of metal is sitting right there). This gap is where opportunity exists, and within it, overlooked, unaccounted, residual value.

What appears as a lack of data for the S&F model because of fragmented value chains also suggests that metal stocks are not fully internalized or monetized, pointing to a latent economic opportunity for MaaS. This aligns with the fundamentals of efficient price formation, which depends on the circulation of information in the market. Where information is fragmented or absent, prices are unlikely to fully reflect the underlying value of embedded metal stocks.

The parameters laid out in the Table below could serve as a starting point to scope out potential MaaS opportunities using a data-driven bottom-up approach.

Table 1. Parameters for MaaS Implementation using a bottom-up approach.

Parameter	Notes	Note on the ideal candidate for MaaS
B2B ³¹ vs D2C ³²	B2B companies often have existing contracts (e.g., leased equipment) that can be monetized under a MaaS model. D2C companies rarely offer this advantage.	Prefer B2B with leasable assets
Public vs Private	Public companies are easier to screen. Private companies require more effort, but non-public information is where the real alpha lies, if sourced efficiently.	Either: private means higher effort, higher reward
Illiquid assets (PPE) ★	What percentage of assets are illiquid (plant, property, equipment) vs liquid? Use the acid test ratio (measures a company's ability to pay its short-term liabilities using its most liquid assets) to measure this.	If it fails the acid test, it means that most value is locked in illiquid assets.
Revenue sources	Do revenue sources lead to flows? What ratio of metal stock from suppliers ultimately flows to customers? What ratio of metal stock is retained? Map supply chains via Bloomberg <SPLC> (Supply Chain function).	Natural accumulation of metal stock due to the nature of the company's business (e.g.: telecom, utilities, construction/demolition, primary metal producers, scrap recycling). Lower outbound metal flows are preferred, signaling stock accumulation. If revenue sources are linked to metal flows, stock accumulation may not occur.
Historical CAPEX	Look for anomalies in reported data. AI and Machine Learning analysis of historical 10-K filings can estimate metal stock embedded in CAPEX and PPE.	CAPEX fluctuations may signal shifts in metal-intensive capital stock, but accounting depreciation may misstate it due to changing tax rules affecting write-downs.
Credit ratings	Distressed/junk-rated companies with depreciated PPE-heavy balance sheets are prime targets. Buying their recourse debt offers a path to acquiring underlying metal stock at pennies on the dollar if default occurs.	Junk-rated + depreciated PPE = high-conviction entry

★ = most critical screening parameter

The MaaS business model responds directly to the structural opacity of current metal value chains, where limited visibility not only constrains analysis but also signals the presence of unmonetized and weakly internalized metal stocks. MaaS retains metal ownership within a Special Purpose Vehicle (SPV) across the full lifecycle, helping realign incentives toward recovery while requiring systematic tracking and monitoring of material use. In doing so, it generates the currently missing data infrastructure, transforming metal flows from probabilistic, assumption-based estimates into contractually defined and verifiable quantities. This reconfiguration closes the loop between top-down and bottom-up perspectives: while S&F models identify system-level opportunity and firm-level analysis reveals embedded value, MaaS bridges the two by reshaping ownership and information flows, enabling a transition from proxy-based modeling toward empirically grounded, observable systems. This feedback loop between S&F models and MaaS is developed in the following sections.

III. Identifying MaaS opportunities through S&F models

S&F models provide a structured basis for analysing MaaS business models by linking in-use metal stocks to system dynamics over time, highlighting the addressable market. The sections that follow first observe how S&F models contribute to MaaS across three analytical layers: physical system representation, economic translation, and financial structuring. These layers trace how stock-flow variables translate from material dynamics into business model design, before showcasing practical cases in existing uses of metal servitization where they can improve unit economics for their implementers.

These three layers trace how observed material data becomes an economic variable and then a financeable structure. Each converts what the previous one records into a form the next can use, ending in structures that a lender or an investor can underwrite.

a. S&F Models vs MaaS at every layer of the business model

LAYER 1 — Physical System Representation

(Material reality: stocks and flows of metals in the economy)

Table 2: Physical system representation

Component	Definition	Wind + steel example	Function
Material stock	Total metals embedded in long-lived assets	Steel in turbines, towers, foundations, grids	Represents accumulated industrial “metal reservoir”
Inflow flows	Extraction + production entering system	Mining → steel production → turbine manufacturing	Creates new embedded stock
In-use stock accumulation	Metals locked into operational assets	Active wind farms globally	Long-duration storage of material value
Outflow flows	End-of-life decommissioning + recycling	Dismantled turbines → scrap steel	Releases embedded metals back into system
System logic	Economy as dynamic accumulation system	Growing renewable fleet = growing steel stock	Enables long-term material forecasting

LAYER 2 — Economic Translation Layer

(Turning physical stock–flow into structured economic variables)

Table 3: Economic translation layer

Dimension	What stock–flow enables	MaaS implication
Residual value of stock ³³	Future recoverable metal embedded in assets	Becomes monetizable end-of-life value stream
Timing of loop	Predictable lifespan + decommissioning cycles	Enables lifecycle revenue structuring
Location of stock	Geographic mapping of embedded metals	Enables reverse logistics + regional circular planning
Fungibility of stock	Substitutability across scrap/ material pools	Determines scalability and arbitrage potential
Entry point identification	Where intervention occurs in the lifecycle	Defines MaaS operational insertion point (design, finance, operation, end-of-life)
Metal spot price	Enables meaningful metal stock valuation	Helps shape the economic viability of MaaS; lower metal prices = higher stock accumulation

LAYER 3 — Financial Structuring Layer

(Where material economics becomes financeable architecture)

A. Pricing Architecture

Table 4: Pricing architecture

Element	Stock–flow role	Financial outcome
Service fee valuation	Embedded stock + usage duration	Converts metal into annuity-like payments
Timing of cash flows	Lifecycle + decommissioning curves	Enables structured repayment profiles
Residual value pricing	Scrap recovery probability + timing	Forms back-end cash flow component
MaaS contract valuation	Changes in stock-and-flow directly influence supply and demand dynamics, ³⁴ which has an impact on MaaS contract valuation by the market ³⁵	Provides the data infrastructure for trade, enabling liquidity in MaaS contracts

B. Collateral and Asset Valuation

Table 5. Collateral and asset valuation

Element	Stock–flow role	Financial outcome
Collateral valuation	Embedded metal stock quantification	Enables balance sheet recognition of assets
Recovery value certainty	Predictable scrap flows	Supports credit enhancement
Asset-backed structure	Traceable metal lifecycle	Enables securitization of embedded material

C. Lender Reassurance (Credit Architecture)

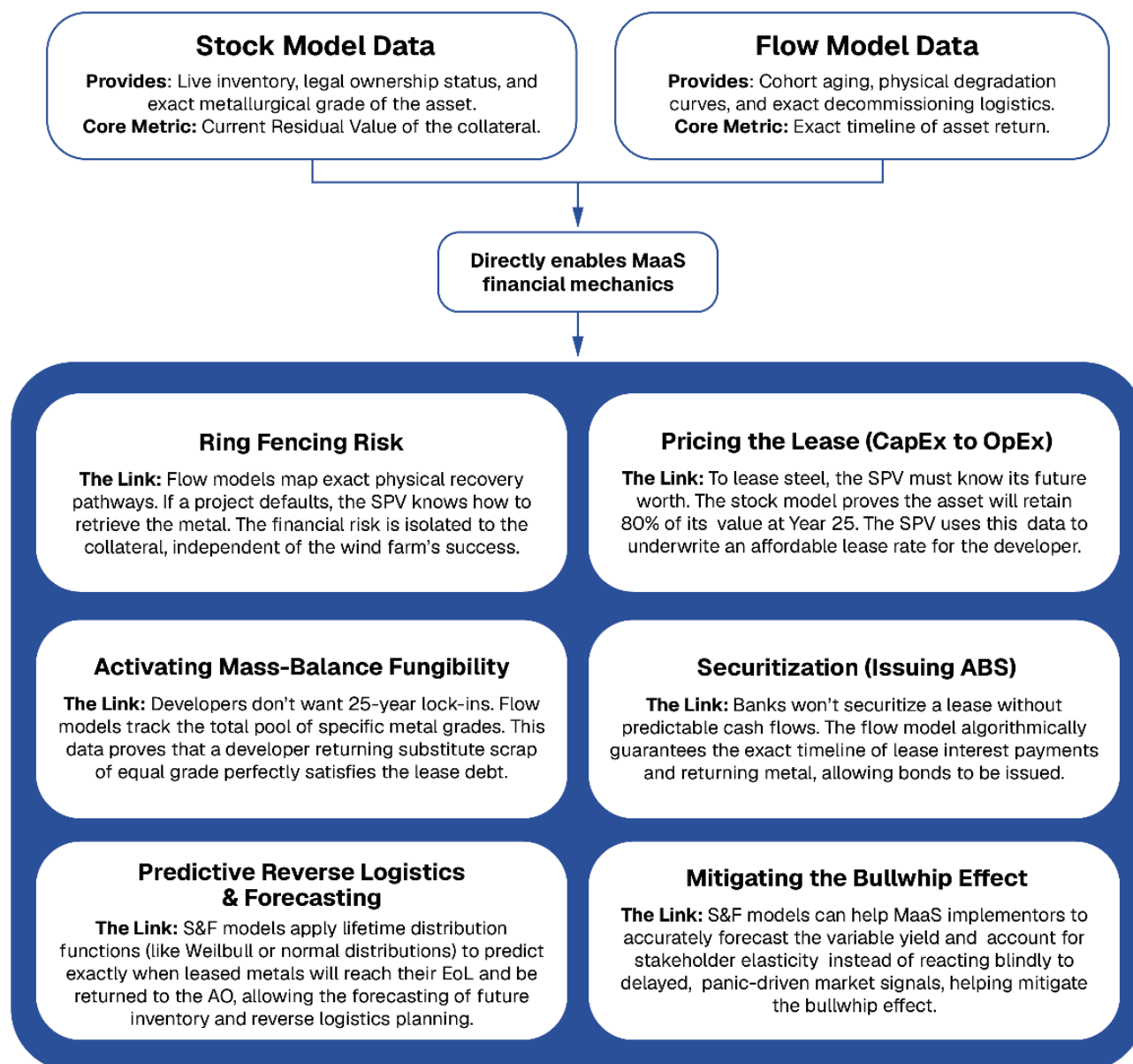
Table 6: Lender reassurance

Element	Stock–flow role	Financial outcome
Benchmark value	Comparison to commodity + infrastructure cash flows	Makes MaaS legible to lenders
Benchmark timing of returns	Lifecycle distribution of recovery	Aligns with infrastructure-style amortization
Risk visibility	Traceable stock-and-flow evolution	Reduces information asymmetry

Figure 3 summarizes how stock model data and flow model data enables MaaS financial structuring.

The Direct Link - Stock & Flow Data and MaaS

How material tracking explicitly enables the financial architecture of Metals-as-a-Service



¹ The Weibull distribution defines the probability that an item leaves the stock at a certain age.

² The Bullwhip effect is a pattern in supply chains where small changes in customer demand at the retail level cause increasingly large fluctuations in orders and inventory as you move upstream.

Figure 3: The direct link between stock-and-flow data and MaaS

b. Opportunities to use S&F models in other servitization models

Beyond theoretical applications, introducing dynamic S&F modeling provides a clear mathematical mechanism to upgrade and optimize established servitization models across the broader industrial economy.

Table 7: Opportunities to use S&F models in existing servitized metal businesses

Existing Use-Case & Metal	Current Servitization Model (Status Quo)	Proposed S&F Model Integration (The Upgrade)	Optimized Outcomes & Strategic Impact
PGM Catalyst Leasing (Pt, Pd, Rh, Ru, Ir) ³⁶	Suppliers retain ownership using pool accounts. Basic tracking calculates post-use recovery yields to manage volatility.	Predictive Degradation Mapping: Implement S&F models to track continuous thermodynamic wear. Optimize the exact moment of retrieval before irreversible metallurgical loss occurs.	Maximizes recovered material volume; shortens the time to close the Variable Yield gap; enables dynamic pricing premiums based on operating heat stress.
EV Battery-as-a-Service (Ni, Co, Li) ³⁷	Customers pay subscriptions. Operators track basic State of Health (SOH) to schedule secondary-life recycling.	Fleet-Level Inventory & Cascade Modeling: Use S&F to forecast stochastic battery degradation across geographic fleets. Model secondary flows (e.g., transitioning EVs to stationary grid storage) based on capacity thresholds.	Smooths capital expenditure for fleet operators; prevents premature recycling; mathematically optimizes the pricing of second-life utility contracts.
Lighting-as-a-Service (Aluminum, Steel) ³⁸	Outcome-based service (lux-hours) with end-of-life fixture take-back. Lowers TCO but requires heavy upfront Day 1 capital.	Lifecycle Optimization & Component Arbitrage: Track the physical stock of metal housings across multiple commercial real estate lifecycles. Model the financial timing of refurbishing vs. melting down components based on scrap market curves.	Drives down the Levelized Cost of MaaS (LCoM) by extending structural asset life; minimizes redundant manufacturing of new alloy housings.
Telecom Decommissioning (Copper) ³⁹	Static take-back programs using estimated historical stock data to plan large-scale reclamation when prices rise.	Dynamic Spatial & Market Tracking: Transition from static estimates to continuous S&F modeling. Overlay the physical degradation of underground cables with stochastic price simulations to identify optimal extraction windows.	Eliminates “blind” extraction timing; maximizes the arbitrage spread between recovery costs and the residual value of the deployed copper stock.
Refrigerant Leasing (Alloys in High-Pressure Cylinders) ⁴⁰	Electronic tracking systems monitor cylinder location to prevent lost assets and reduce supply chain emissions.	Structural Fatigue Forecasting: Use S&F to track cumulative pressure-cycling and wear on the metal alloy cylinders over thousands of refill loops.	Prevents catastrophic failure through predictive maintenance; optimizes the total fleet size required to maintain unbroken service utility.

These upgrades both emphasize that better material data shows up in unit economics rather than only in reporting. Section IV makes that shared premise measurable.

IV. The Levelized Cost of MaaS (LCoM)

As a direct continuation from the discussion above, this section explains how S&F models can help create a synthesized metric that will not only help implement MaaS but also make it economically viable by highlighting areas for optimization.

Akin to the energy sector's LCOE metric, this metric can be coined the "Levelized Cost of MaaS" (LCoM). This metric represents the net present value of the total lifecycle cost of providing the metal divided by the total service provided (e.g., tons of metal leased or months of functional utility) over that same period.

$$LCoM = \frac{\sum_{t=1}^n \frac{I_t + O_t + M_t + R_t}{(1+r)^t}}{\sum_{t=1}^n \frac{S_t}{(1+r)^t}}$$

Where I_t = the initial cost of acquiring the metal, O_t = operating costs (including sales, general, and administrative), M_t = Maintenance/refurbishment costs, R_t = recovery costs⁴¹, S_t = value of the service utility delivered by the metal, n = lifespan of the MaaS contract, and r = discount rate/cost of capital.

The service utility S_t represents the value of the service utility delivered by the metal during the period t . It is strictly a measure of functional performance, not physical volume (tonnes). The exact measurement of this utility depends on the metal, its quality, and its specific end-use. Examples of S in other servitization models are detailed in Section III.b.

Data from S&F models can help analyze how the LCoM for a metal can get lower than the levelized cost of linear metal procurement, which in turn could contribute to the accelerated adoption of MaaS models (see Table 8).

Table 8: Interaction between S&F models and LCoM and MaaS implications.

Framework Layer	Contribution of the S&F role to the LCoM formula	Financial Outcome / MaaS Implication
Layer 2: Economic Translation	Enables the synthesis of holding times, degradation rates, and recovery probability contributing to the Levelized Cost baseline of the metric.	Serves as the primary indicator of whether a specific metal or use case is economically viable for a service model versus a linear sale.
Layer 3A: Pricing Architecture	Enables aggregation of extraction, maintenance, and reverse logistics costs over the total lifecycle iterations to create the Levelized Cost baseline of the metric.	Establishes the absolute pricing floor (minimum viable service fee) required to achieve the target hurdle rate and, in turn, helps analyze which variable of the LCoM needs to be optimized.
Layer 3C: Lender Reassurance	Enables the comparison of MaaS lifecycle costs to traditional linear commodity procurement (only based on flows).	Makes MaaS legible to lenders by providing a familiar, standardized, energy infrastructure-style metric (ie: LCOE) for evaluating cost competitiveness.

BOX 2: Variable Yield vs LCoM.

Our previous MaaS analysis⁴² had put forth a key metric to assess the threshold at which the MaaS model can surpass the linear model in terms of cash flow generation. We called this metric the Variable Yield, which represents the gap between upfront sale proceeds and leasing returns, depending on the sensitivity of the asset owner to external market factors.

The fundamental financial viability of a Metals Bank relies on the mathematical relationship between the LCoM and the Variable Yield (V). While V quantifies the asset-level cash flow deficit between the linear model and the MaaS model for a certain volume of the same metal (e.g.: 100 tons of copper), LCoM defines the transaction/contract level unit economics to optimize and help close that deficit. This is where the S&F feedback loop acts as the critical optimizer. Through the utilization of traceability data to maximize a metal's total delivered service utility (S_t) while minimizing premature maintenance (M_t) and recovery (R_t) costs, the S&F provides the necessary information to drive down the LCoM. Minimizing this levelized cost expands the Asset Owner's leasing returns, enabling the closing of the Variable Yield gap through the metal bank and making the MaaS model competitive with the traditional linear model.

The LCoM establishes whether metal can be provided as a service at competitive cost. It does not settle what the lessee is buying. Under a volume-based contract, the lessee is still buying tonnes, which leaves the owner's exposure to the condition of the returned metal outside the price. Section V takes up that gap.

V. Use of S&F models to evolve towards performance-based pricing

This section sits downstream of everything before it. The feedback loop described in previous sections restores grounded observation to the modeling of material flows. What follows here depends on that tracking already being in place and uses it for a different purpose, bringing monitoring of the function of the metal inside the contract. Because performance-based pricing is highly complex, this evolution represents an “adoption ladder” where standard volume-based leasing must be established first to build trust and operational infrastructure. Consequently, it is a possibility that the loop opens, growing and reinforcing itself, only where the measurement of advanced, functional materials can be afforded, rather than being applied to commodity-grade metals.

While S&F models are currently used primarily to forecast the volumes and timing of end-of-life material flows, they can also be extended to capture changes in material quality over time, providing a basis for MaaS contracts that value metals according to their functional performance rather than their volume.

Within the MaaS business model transformation, the question of performance-based pricing is key. Not only can it help capture higher value, but it can also support superior circular economy outcomes by promoting material efficiency. Instead of fees tied to throughput (e.g., \$/ton), revenues are linked to end-use performance, shifting incentives away from volume sold toward efficiency and delivered performance. Pricing per structure or performance unit aligns incentives across the value chain, encouraging precision manufacturing, digital design optimization, and longer product lifecycles, thereby reducing waste and total system costs while improving value delivery.⁴³

Importantly, performance-based models enable the accumulation of proprietary data through the development of traceability mechanisms (to track end-use performance linked to metal degradation, for instance). Using digital monitoring (e.g., IoT-enabled assets) and iterative feedback loops, firms can build analytics and “digital twin” capabilities that improve future product design and operational performance. This data layer becomes a strategic asset, creating barriers to entry and enabling continuous innovation beyond the initial sale.⁴⁴ From a financial perspective, differentiation and embedded data are typically associated with higher valuation multiples, often closer to those seen in technology-enabled or service-oriented sectors rather than traditional commodity industries.⁴⁵

By digitizing the metal’s lifecycle, traceability and DMFA models provide the operational foundation for a MaaS performance-based pricing. In this context, DMFA coupled with traceability enables asset-level monitoring, generating condition data, and stock & flow accounting structures how that data is translated into asset-level forecasts and contract parameters.

Traceability systems utilize unique identifiers and sensor data to log every transformation and environmental exposure the metal undergoes during the lease. This continuous data stream populates DMFA models that track the inventory level of “quality units” rather than just bulk mass. By tracking this degradation continuously, the model transforms physical wear into a transparent ledger. This visibility allows both parties to remotely verify the asset’s condition, ensuring the terminal quality measurement (Q_T) is an objective, undisputed data point for calculating the financial payoff. The implementation relies on a basic conservation of quality equation where the final state equals the initial state minus the accumulated flow of wear. This can be modeled as:

$$D_T = \sum_{t=0}^T (\alpha \times U_T + \beta \times E_T)$$

Where U_t represents usage intensity and E_t represents environmental stress factors at time t . The coefficients α and β translate these stressors into physical quality loss. This total accumulated wear D_T , determines the terminal quality Q_T through the relationship $Q_T = Q_0 - D_T$ where Q_0 is the initial quality at the start of the lease.

A pricing ladder: from selling volume to selling performance

Depending on the market maturity and the specific metal, AOs can structure a MaaS contract under one of four distinct pricing architectures, all enabled using S&F models. These range from a standalone performance contract, to layered volume-plus-derivative contracts, and a structured fixed-income architecture. These four MaaS pricing architectures are purely theoretical and do not currently exist in the market. At the time of writing, we have not developed any models to assess their commercial or operational viability.

The core difference between the four options lies in how the underlying risk of the materials degradation is monetized.

The viability of the four pricing architectures outlined below hinges on the ability of S&F models to accurately translate real-time traceability data into financial pricing. Because the standalone performance contract is entirely reliant on this mechanism, it is inherently challenging to deploy without an established proof of concept. To facilitate the industry's transition toward pure performance-based pricing, we introduce transitional architectures. These structures take traditional volume-based metal contracts⁴⁶ and layer them with financial derivatives or structured fixed income mechanics, effectively isolating and hedging the risk of asset degradation to prevent mispriced capital allocation.

Option 1. Standalone Performance-based Contract

The lessee pays exclusively for continuous performance (e.g., thermal resistance uptime, catalytic throughput, or MWh transmitted).

The lessee's contract is priced dynamically as the cumulated service delivered over time:

$$P_{total} = \sum_{i=1}^n R \times C_i \times \Delta t_i$$

Where P_{total} is the total contract cost to the lessee, n is the total number of billing periods, R is the rate charged per unit of service delivered (for instance, \$/MWh transmitted for copper), C_i is the material performance coefficient⁴⁷, the average measured performance metric tracked by traceability tech during period i , and Δt_i is the duration of that specific period.

Under a performance-based MaaS contract, the lessee never pays a degradation premium. They buy guaranteed performance, paying a flat operational expense for the service delivered, and if the performance drops (as a result of metal loss or metal quality degradation), their payments automatically drop with it (until the AO initiates recovery and replaces the asset).

In other words, the owner carries all the degradation risk, prices in the expected cost of eventual recovery and refurbishment, and folds it into a flat base rate that automatically scales down if performance drops.

Because the AO bears 100% of the degradation risk, the expected financial impact (or downside exposure) is calculated using the risk pricing formula:

$$P = E (N \times \max(Q_{min} - Q_T, 0))$$

Where:

P is the expected shortfall cost, the expected actuarial (probabilistic) cost of reverse logistics and refurbishment.

E represents the expected value operator,

N is the notional principal (asset value),

Q_{min} is the minimum acceptable performance threshold, and

Q_T is the actual measured terminal quality at the end of the period.

This expected P cost is then amortized and baked directly into the base rate (R), charged to the lessee.

Option 2. A Volume-based contract + Performance Swap

Option 1, while representing the true servitization of metals solely based on their performance, rather than their volume, may be premature. To help introduce the market to a new solution, a double-layered contract structure may be suitable. Volume-based contracts are already well-established, and a performance swap as an added layer may serve as a transitional tool to induce performance-linked MaaS.

Under a volume-based MaaS contract, the lessee pays a fixed rental fee based on metal volume, but is liable for the metal degrading below optimal performance levels during the lease (through the payment of a contractually agreed penalty).

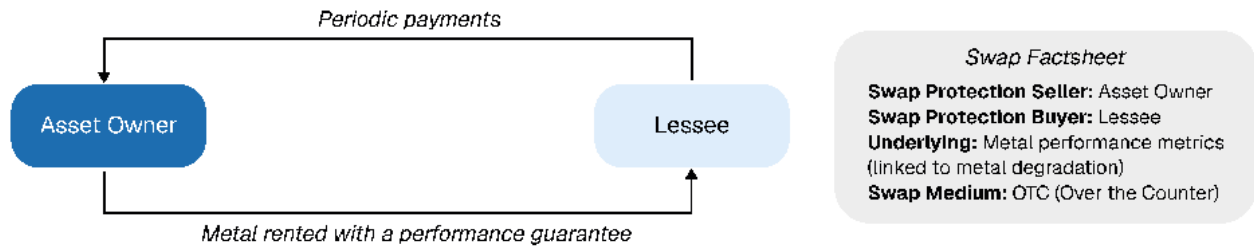
To hedge against this risk, the lessee purchases a separate performance swap from the AO. This mechanism is separate from alternatives available on the market such as traditional property and casualty insurance or warranties in the way that the latter strictly insures against metal loss and not against degradation impacting the metal's performance.

The premium paid by the lessee under this swap is meant to address the uncertainty associated with metal degradation-related recovery costs. Predictable reverse logistic costs remain outside the swap arrangement. DMFA models can offer a robust framework for managing operational uncertainty in performance-linked MaaS by providing the vital asset-level forecasts of material degradation needed to price future swap contracts. In cases where the quantification of uncertainty of future degradation rates is required, DMFA's probabilistic extension (DPMFA) can propagate parameter uncertainty through Monte Carlo simulation⁴⁸, producing the distributional forecasts necessary to underwrite financial derivatives.

Figure 4 below describes this financial instrument.

MaaS Performance Swap

An Over The Counter financial instrument to make performance-linked MaaS bankable, enabled by stock and flow models



How It Works

1. The Asset Owner (AO) enters into a contractual agreement with a lessee, renting metal with a performance guarantee.
2. When the minimum performance threshold is hit, periodic payments stop and the AO initiates recovery.
3. When the AO replaces the recovered metal with new metal, a new swap cycle starts.
4. If the AO does not replace the metal, the AO is liable to pay the lessee for the marginal decrease in performance.

Role of Stock & Flow Models

1. Stock & Flow Models help calculate the range where the performance threshold will the product's / metal's lifecycle (determined using probabilistic extensions of Dynamic Material Flow Analysis, where performance is linked to metal degradation).
2. These models further optimize for the AO's own inflows and outflows of metal to multiple lessees, helping to improve the Levelized Cost of MaaS for that Metal.
3. Continuous optimization leads to a point where the LCoM is lower than primary procurement, creating further incentives to initiate new MaaS Performance Swaps.

Figure 4: Structure of a MaaS Performance Swap, how it works, and the role of stock-and-flow models.

The swap payments function like a (European) put option where the lessee pays the expected value of the shortfall (the premium P) to cap their downside risk at (Q_{min}) periodically at time T , as specified by the swap contract.

$$P = E [N \times \max(Q_{min} - Q_T, 0)]$$

Where:

P : The Swap Premium. This is the fair price or "fair value" of the contract that the lessee (or protection buyer) pays to the AO (or protection seller) at time T .

E : The Expected Value operator. It indicates that the premium is calculated based on the probability-weighted average of all possible outcomes for the metal's condition at the end of the lease. DMFA enables the AO to anticipate outcomes.

N : The Notional Principal. This is the dollar value assigned to the metal asset, such as its total replacement cost, its initial purchase price, or a pre-agreed insured value.

Q_{min} : The Quality Floor or Threshold. This is the minimum acceptable quality level (e.g., a specific percentage of tensile strength or purity) agreed upon in the contract.

Q_T : The Terminal Quality. Measured continuously in real-time by embedded sensors, representing the actual, tracked condition of the metal through the contract's evaluation at time T : This represents the actual, measured quality of the metal when the lease ends at time T , derived directly from the DMFA's wear calculation.

P is calculated and charged as a dynamic periodic premium at each time step T . The lessee pays this premium over time, strictly on the condition that the real-time material quality (Q_T) remains above the minimum threshold (Q_{min}). Because this payment is calculated continuously rather than amortized from a static upfront cost, it allows the lessee to fund risk mitigation strictly as an ongoing operating expense. The swap payments, paid by the AO to the lessee and as per the payoff function, are only triggered when $Q_{min} > Q_T$. This allows the AO to engineer longer operating cycles to maintain their continuous premium revenue stream.

Table 9: The Payoff Functions:

The Payoff Function for the AO $\max(Q_T - Q_{min}, 0)$	The Payoff Function for the Lessee $\max(Q_{min} - Q_T, 0)$
As long as the continuously measured quality (Q_T) remains above the threshold, the AO collects the premium (like an insurer would do). In the event of a reversal where the payoff condition becomes true, i.e., when $Q_{min} > Q_T$, the premium payments stop immediately while the AO retrieves the metal.	A payout to the lessee is triggered if the final monitored quality (Q_T) at the end of the swap cycle is lower than the threshold. In this situation, the swap payments payable to the lessee are proportional to the amplitude of that degradation. The AO naturally is incentivized to recover the metal and restart a new performance swap with the lessee to avoid losses from swap payments to the lessee and the opportunity cost of not having a new performance swap in place.

After the metal is recovered by the AO and is replaced with a new batch, the existing swap expires, and a new swap cycle begins. This is because every swap's payoff is tied to the quality of each batch of metal, and any changes to the metal's grade introduced by the AO (at the request of the lessee, for instance) can cause changes to the rate at which Q_T declines. That said, the swap cycle might not be aligned with the contract cycle based on volumes. This is up to the design of the transaction between the AO and the lessee.

In short, in a MaaS Performance Swap, the AO guarantees the lessee access to a metal's functional utility rather than its physical volume.

The AO's revenue is substantially contingent on maintaining agreed performance thresholds like electrical conductivity or catalytic uptime. Unlike volume-based contracts where degradation risk is entirely borne by the lessee, a performance swap helps transfer degradation risk back to the AO while metal-specific recovery process costs incurred by the AO get amortized across the asset lifecycle and folded into the premium the end-user pays.

Embedded traceability sensors monitor asset condition continuously and trigger material retrieval once degradation approaches a defined threshold, with the goal of recovering the asset before irreversible loss of metallurgical quality or embodied value occurs. True real-time economic optimization of take-back timing remains a tangible target with the advent of wide deployment of AI (see Section I, practical uses, point 7), and condition-based retrieval is a meaningful improvement over conventional scheduled maintenance.

A structural challenge in performance swaps can occur when the leased material is heavily integrated into a final product owned by the lessee. While the AO may have rights to the final product to ensure the effectiveness of the collateral, they cannot unilaterally extract the degraded metal without disrupting the lessee's operations. To resolve this "boundary problem," MaaS contracts separate financial remedies from physical interventions. If a material breaches its performance threshold, it immediately triggers a financial adjustment, suspending the lessee's premium payments to compensate for the lost

utility (however, the physical extraction is contractually deferred until a mutually aligned maintenance window). In any case, MaaS is not suitable for complex integration and is targeting applications where the metal is the sole functional unit and retains its homogenous form factor, such as raw catalytic powders in heavy industry⁴⁹, standardized steel casings, or un-insulated copper busbars, ensuring the AO can retrieve and reprocess the exact raw material they deployed.

Option 2B. A Volume-based contract + Performance Swap + Swaption⁵⁰

For lessees with exposure to high environmental uncertainty, a sudden increase in metal degradation could result in the AO being liable to initiate an earlier recovery of metal (than initially projected or expected). This may lead to the AO charging a higher premium when a new performance swap is created between the AO and the lessee, anticipating a shorter cycle from faster degradation (causing fewer premium payments being made by the lessee and higher recovery costs for the AO). A higher premium can be a drag on the lessee's cash flows. Option 3 utilizes advanced derivative structuring by adding a third layer, a Swaption, on top of the volume-based contract and performance swap (referred to in Option 2 above), to defer this cost.

The use of a Swaption gives the lessee the right, but not the obligation, to enter into a future MaaS performance swap at a fixed, pre-agreed premium.

This results in the lessee achieving highly asymmetric risk protection. If environmental conditions remain benign, the swaption expires unexercised, and the lessee saves capital by never paying a higher swap premium in future performance swap cycles. If uncontrollable environmental factors aggressively degrade the metal, the lessee exercises the swaption, forcing the AO to enter into a new Performance Swap at a mutually fixed premium.

Swaptions for Performance-Linked Metal Swaps - An Introduction

Significant operational uncertainty can exist for Performance-linked Metal Swaps. Asset Owners (AO) may not know the degree of degradation that the leased metal will face, which may expose them to the risk of early metal recovery. Embedding a “Swaption” on top of the Performance-Linked Metal Swap can help mitigate this risk, as explained below.



The Base - A Degradation-linked Metal Performance Swap

Suppose a lessee uses a specialized metal component/system: the AO guarantees usable performance, which degrades over time. The swap economically transfers degradation risk to the AO. Example metrics: conductivity, catalytic efficiency, tensile strength, purity, thermal efficiency, corrosion resistance.

Swap Trigger Condition

Recovery/replacement occurs once degradation reaches a set minimum degradation threshold (D_t) at time (t).

At this point, the current performance swap terminates, the metal is recovered/reprocessed/replaced, and a new performance cycle begins.

Mechanics: The lessee pays an upfront Swap Premium. A payoff is only triggered if degradation exceeds the threshold.



The Hedge - A Swaption on top of the Swap

The swaption gives the lessee the right, but not the obligation, to enter into the next performance swap under pre-negotiated reset mechanics.

Importantly, the option is tied to degradation-state economics, not metal market prices.

Exercising the swaption yields guaranteed future lease terms, not a cash payout

Without the Swaption

Once degradation hits the minimum threshold, the AO may have pricing power on the next cycle*. AO also faces operational uncertainty due to environmental factors outside of their control. As a result, the lessee may also be exposed to unhedged risk of operational disruptions caused by early degradation.

With the Swaption

The lessee **locks in reset terms today**, protecting against steeper degradation baselines and worsening future lease terms. Probabilistic extensions of the DMFA model help map and size the exposure to environmental degradation (based on traceability data), helping price the Swaption.

Legend: ■ Performance Swap Layer ■ Swaption Layer embedded on top of the underlying Performance Swap layer

*If the metal degraded faster than expected during the first cycle due to harsh environmental factors, the AO realizes the lessee's operation carries higher degradation risk. Consequently, the AO will demand a higher periodic payment for the next cycle to cover the cost of more frequent replacements. The Swaption protects the lessee from this sudden price hike.

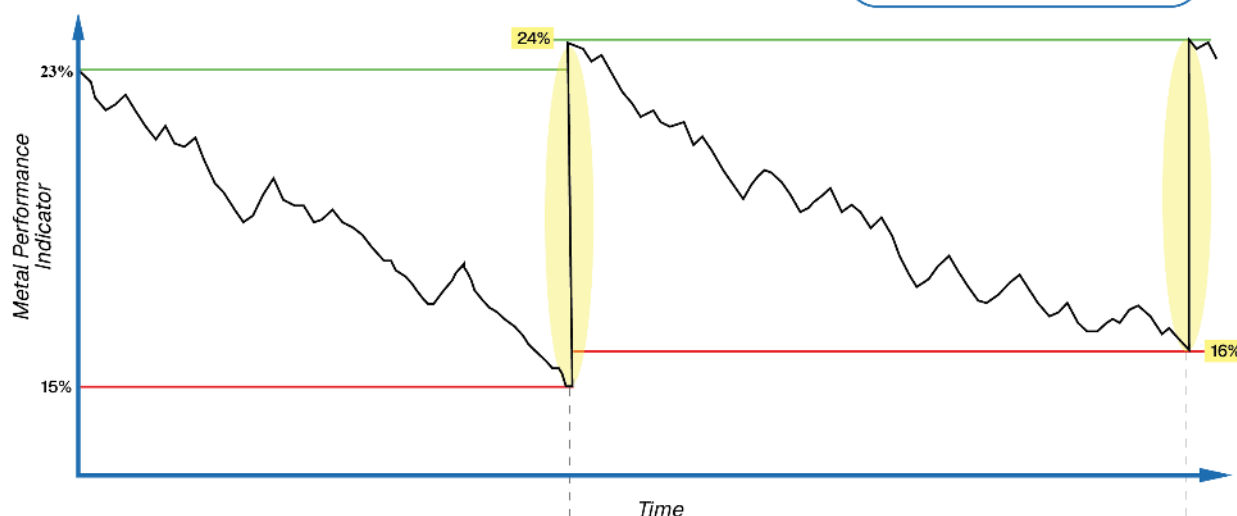
Figure 5. Swaptions for Performance Linked MaaS Swaps - An Introduction

Demonstrating the operational utility of a MaaS Performance Swaption

When higher metal degradation is expected in a Performance-linked MaaS Swap, a Swaption can be employed, which allows the asset owner to protect their income stream if the metal degrades faster than expected and allows the lessee to lock in a fixed protection premium should the metal actually degrade faster due to increase in environmental stressors.

Legend:

- Beginning Quality (Q_0)
- Quality Threshold (Q_{min})
- Metal Performance Indicator
- Metal Recovery and Replacement once Quality Threshold is hit.



First Contract

The Blue Swaption

1st Swaption created between the AO and Lessee on top of the MaaS Performance Swap.

Second Contract

The Black Swaption

Second Swaption created after the Blue Swaption is exercised, calling for a 100 bps higher performance range.

Swaption exercise trigger is determined by the minimum performance threshold in the underlying performance swap, which can be calculated using probabilistic DMFA methods (Bornhöft et.al 2021)

A Tale of Two Swaptions: What is happening in each case?

The Blue Swaption

Metal performance is guaranteed between the range of 23% and 15% with the latter being the minimum performance threshold that would trigger the obligation of replacement and recovery of metal stock for the AO.

The data generated from traceability technologies is fed to build a DMFA model, which helps inform the next price of the swap premium.

This data helps inform the lessee to expect higher metal degradation in the next cycle, which leads them to negotiate a higher starting threshold for metal performance.

The Black Swaption

As seen in the Blue Swaption, the lessee anticipated higher metal degradation and therefore exercised the Blue Swaption.

The new starting metal performance threshold is set at 24% instead of 23% and the minimum performance threshold is set at 16% instead of 15%.

Prior traceability data that was fed into the DMFA model helps identify sinks and places where the lessee can optimize to further extend the utility of the metal, which leads to a longer metal cycle.

As a result, the Black Swaption lasts longer, and the AO overall gets to earn higher swaption premiums in comparison to the Blue Swaption, all while optimizing performance-linked MaaS Swaps that are operationally resilient in the face of uncertain environmental factors.

Assumptions Used

- Degradation of metal is linked to metal performance. As metal degrades, traceability data shows decline in metal performance, which is monitored as close to real-time as possible, whenever possible.
- The metal performance indicator does not measure metal degradation rates explicitly; rather it is an embedded quality that is inferred as a function of metal degradation and will vary by metal and its associated usage.
- Numbers (in %) used are hypothetical and are only used to show the lifecycle of a single metal where a swaption was exercised.
- In the scenario, the lessee expected higher degradation in the future, which is why the swaption was exercised to lock in a higher starting performance guarantee.
- The performance guarantee may not necessarily mean modification to the existing metal to increase its quality or physical nature. The metal may already be of a quality that can exceed the upper limit performance range stated.
- In the "Second Contract" historical traceability data, experience in metal performance management and the integration of DMFA's probability-based extension methods helped improve the metal's in-service time, leading to slower degradation.
- Slower degradation leads to more periodic payments to the AO as the minimum performance threshold is hit later in the second contract than in the first contract.
- At times, performance of metals may not necessarily decrease continuously, and may improve depending on environmental factors.
- Recovery cost is borne by the AO by working with a designated recycling partner.
- An extensive study into the financial viability of a swap and a swaption in this context has not been explored beyond the details mentioned in the text.

Figure 6. Demonstrating the operational utility of a MaaS Performance Swaption

Limitations of Swaptions in Performance Linked Metal Swaps: Despite its advantages, embedding swaptions may present certain risks and corresponding limitations for its implementors:

1. Counterparty risk - Since the proposed structure of a swaption in the context of metal performance is a novel concept, it may only be initiated over the counter (OTC), which typically bears higher counterparty risk. The use of an independent intermediary such as a Central Counterparty (CCP) may help, though could be subject to higher transaction costs.
2. Liquidity risk - OTC Swaptions may be illiquid due to the specificity of their underlying performance-linked contracts. Securitizing the underlying may help pass on this risk to external investors.
3. Hedging risk - Miscalculating future environmental exposure could lead to mispricing the swaption, which could make it economically unviable. With more swaptions being implemented and knowledge sharing across different stakeholders, this risk may decrease over time.
4. Limited standardization - Each Swaption may be unique depending on its underlying metal's performance swap (which in turn may be tied to different performance metrics forked from different end-uses).
5. Transaction costs - Swaption proceeds present an additional cost to the lessee. This added cost may increase the LCoM by increasing the operational costs per unit of service delivered, which in turn may make their implementation obsolete.

Swaps and Swaptions are most suitable for high-value corporate deals between two giant counterparties (e.g., a major mining conglomerate leasing specialized Platinum Group Metals to a global chemical manufacturer). The introduction of bi-directional cash flows, as the nature of Swaps, helps deliver a penalty that would ensure a higher likelihood of metal recovery by the AO rather than writing it off as a stranded asset.⁵¹

Option 3: A Volume-based Contract + Degradation-linked Note

While the Performance Swap effectively caps downside risk, it can create a situation where the AO continues to collect premium as long as the asset's quality (Q_r) sits just barely above the Q_{min} . This incentivizes the AO to let the metal degrade exactly to the edge of the threshold before intervening.

To eliminate this dynamic, AOs and lessees can shift from a derivative framework into a structured fixed-income framework by executing a "Degradation-linked Note (DLN)," a concept coined here to function like a fixed-income instrument already available in the market called Inverse Floater.⁵² In this model, the physical volume of the metal acts as the principal of the loan, and the AO issues a fixed-income instrument bought by the lessee where the continuous interest rate paid by the lessee moves in the *opposite* direction of a physical benchmark tied to metal quality degradation⁵³ (Q_{loss}).

$$P_t = R_{base} - (L \times Q_{loss})$$

Where:

P_t is the dynamic interest rate paid at the specific time period (monthly, quarterly, semi-annually, perpetual, etc).

R_{base} is the fixed maximum lease rate (what the lessee pays if the metal is at $Q_r = 100\%$)

Q_{loss} is the real-time degradation measured by sensors ($100 - Q_r$)

L is the leverage multiplier that dictates how aggressively the AO is penalized for degradation.

Because the penalty for quality degradation is continuous, the AO loses fractional revenue for every single drop in quality. This establishes perfect synergy with continuous IoT sensor data and mathematically forces the AO to retrieve and replace the metal at the earliest signs of degradation to protect their yield generation, while being incentivized to engineer longer cycles and slower rates of metal degradation over time.

A DLN layered on top of a volume-based contract works as a better transitional bridge towards true servitization discussed in Option 1 than the use of derivative layers (discussed in Options 2a and 2b). This is fundamentally because a DLN is a structured fixed-income instrument rather than an OTC derivative, which makes it significantly easier to scale through securitization⁵⁴ under an SPV.

Table 10: Comparing MaaS Pricing Architectures

Pricing Feature	Option 1: Standalone Performance Contract	Option 2A: Volume Lease + Swap	Option 2B: Volume Lease + Swap + Swaption	Option 3: Volume Lease + Degradation-linked Note
Optimal Deployment Stage	Early-Stage Pilot to Late Stage MaaS. Initial use in equity-funded pilots to build S&F data, scaling later to mature, closed-loop B2B ecosystems where the AO relies on balance-sheet strength, not debt.	Mid-Stage MaaS. Ideal for bilateral conglomerate-to-conglomerate deals requiring custom downside insurance.	Mid-Stage. Ideal for multi-decade infrastructure requiring extreme long-term macroeconomic hedging.	Early-Stage Pilot to Late Stage. Starts as a simple B2B (quality degradation) penalty contract, scaling eventually into standardized contracts that are ideal for SPV securitization and institutional capital markets.
The Base Contract	Pure Service Level Agreement (SLA).	Standard Operating Lease.	Standard Operating Lease.	Standard Operating Lease
Mathematical Base Pricing	$P_{total} = \sum_{i=1}^n R \times Q_i \times \Delta t_i$	Base = V x W x T	Base = V x W x T	Base = V x W x T
Derivative Layer	None. (Risk is fully internalized by the Asset Owner).	The Performance Swap (behaving like a European put option).	Swaption (Option to buy the next Performance Swap at a fixed premium).	Degradation-linked Note (leveraged structural penalty)
Mathematical Risk Pricing	Internal actuarial calculation baked into the rate R.	$P = E [N \times \max(Q_{min} - Q_T, 0)]$	Option pricing model mapping variance (σ) of environmental volatility.	$P_t = R_{base} - (L \times Q_{loss})$
Upfront Capital Required (Day 1)	Zero.	Moderate. Lessee pays standard lease costs + the first periodic Swap Premium (P) upfront.	Moderate/High. Lessee pays lease costs + a periodic Swap Premium + a Swaption Premium upfront.	Low. Lessee pays standard lease + the first continuous floating interest rate.
Ongoing Operating Expense (OPEX)	Variable. Lessee pays a flat base rate, scaled down by real-time degradation (Q_i).	Fixed. Lessee pays the fixed volume lease schedule.	Fixed. Lessee pays the fixed volume lease schedule.	Floating. Lessee pays base lease + interest that continuously declines as metal degrades.
Cost to Lessee Upon Degradation Event	Zero. The invoice automatically drops. AO pays for refurbishment.	Zero. Premium payments pause immediately. The AO absorbs the refurbishment cost.	Contingent. Lessee must exercise the Swaption and pay the fixed strike price (P_{strike}) to trigger refurbishment.	Zero. Interest revenue continuously shrinks. The AO absorbs the refurbishment cost.
Impact on Net Present Value (NPV)	Maximizes NPV. Eliminates upfront capital completely and defers all cash outflows strictly as variable ongoing OPEX.	Lowers NPV. The required Day 1 upfront swap premium creates an immediate cash drag against the project's present value.	Significantly Lowers NPV. The compounded Day 1 cost of both Swap and Swaption premiums creates the heaviest initial cash drag.	Negligible Change in NPV. Avoids upfront derivative capital drag by spreading risk-mitigation costs continuously over time.

Conclusion

An S&F approach can help identify the system-level opportunity space for MaaS by estimating where material stocks are accumulating, when they are likely to return to the economy, and where future value pools may emerge. In that sense, it can provide an initial view of the potential addressable market for MaaS. However, existing S&F models remain constrained by high-level assumptions, proxy data, and limited observability across actual assets, firms, and recovery pathways. This is why a bottom-up, firm-level analysis is necessary. If S&F models reveal where latent material value may exist at the system level, firm-level analysis helps assess whether that value is embedded in identifiable assets, subject to recoverable ownership structures, supported by the right incentives, and capable of being monetized through a MaaS model.

The lack of granular S&F data should not be treated only as a modeling limitation. It may also signal a deeper market failure where embedded metal stocks are often weakly monitored, fragmented across ownership structures, and undervalued or fully written down despite retaining physical and residual economic value. In this sense, MaaS does not merely respond to opportunities identified by S&F analysis. Properly designed, it can help create the very data infrastructure that current models lack.

This continuous data generation allows MaaS to move beyond mere asset tracking and enables a fundamental evolution in monetization, shifting from volume-based charging to performance-based pricing. Digital twins, traceability sensors, and S&F models let MaaS measure exact material degradation and price the functional utility of the metal rather than its physical weight. This transition, whether executed through standalone performance contracts, performance swaps, or DLNs, shifts the financial risk of material degradation away from the user and back to the AO. In doing so, it aligns market incentives with circular outcomes. It rewards asset owners who engineer longer product lifecycles, maximize material efficiency, and retrieve metals precisely before irreversible degradation occurs.

Stated at its simplest, the argument follows one constraint to two consequences: because metal ownership traditionally transfers at the point of sale, pricing is bound to physical volume, and S&F models are forced to rely on assumptions. Retaining ownership across the metal's lifecycle through MaaS breaks this constraint. It creates a reinforcing feedback loop where observable data replaces estimates, improving S&F models so they can better identify future MaaS opportunities. Downstream of that loop, contracts finally gain the ability to price the actual condition of the material, making circular metal ownership both analytically credible and commercially actionable.

ANNEX I: Datasets to explore potential metal stocks around the world.

Potential MaaS opportunities: where stocks have accumulated and can be released: These are the datasets showing plant property equipment that are about to be closed, have already been retired, abandoned, or decommissioned.

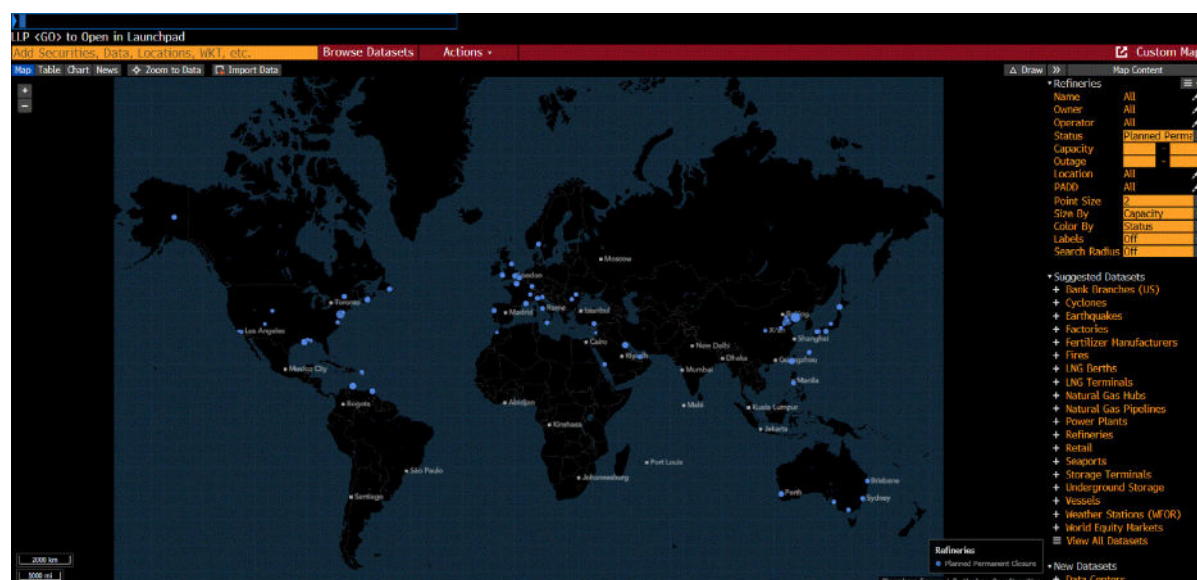


Fig. 7. Refineries with permanent closure planned, Bloomberg LP, 26 April 2026.

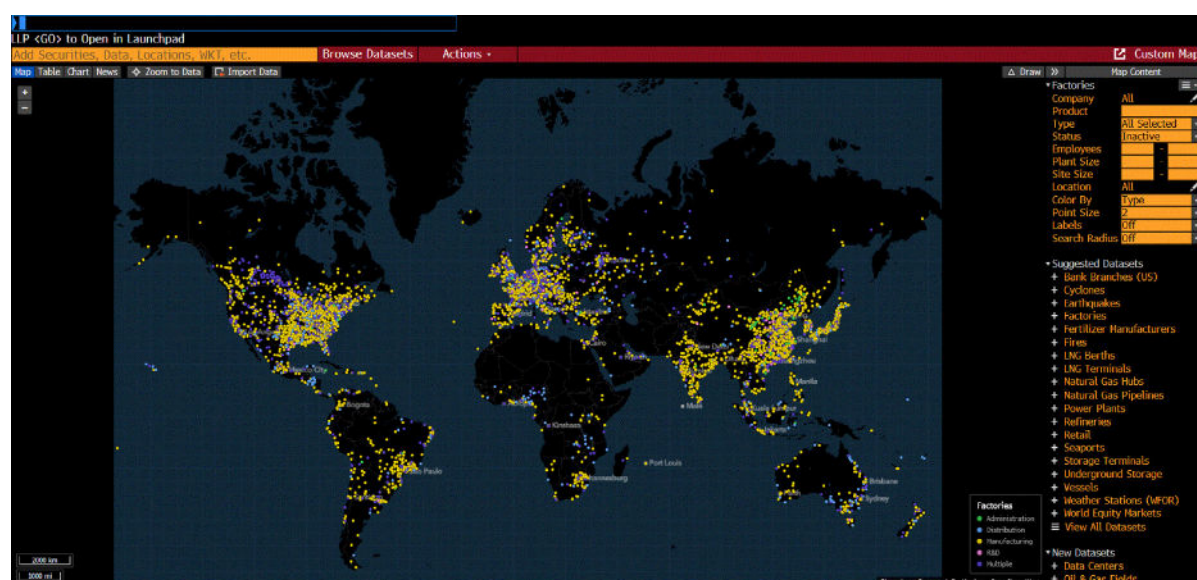


Fig. 8. Inactive factories around the world, Bloomberg LP, 26 April 2026.

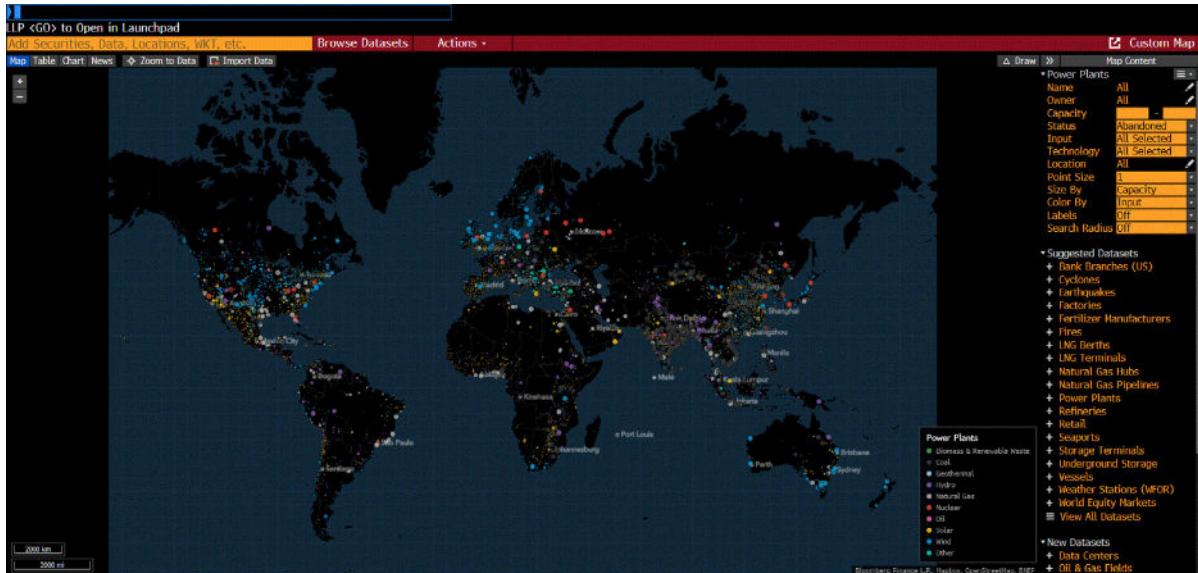


Fig. 9. Abandoned power plants around the world, Bloomberg LP, 26 April 2026.

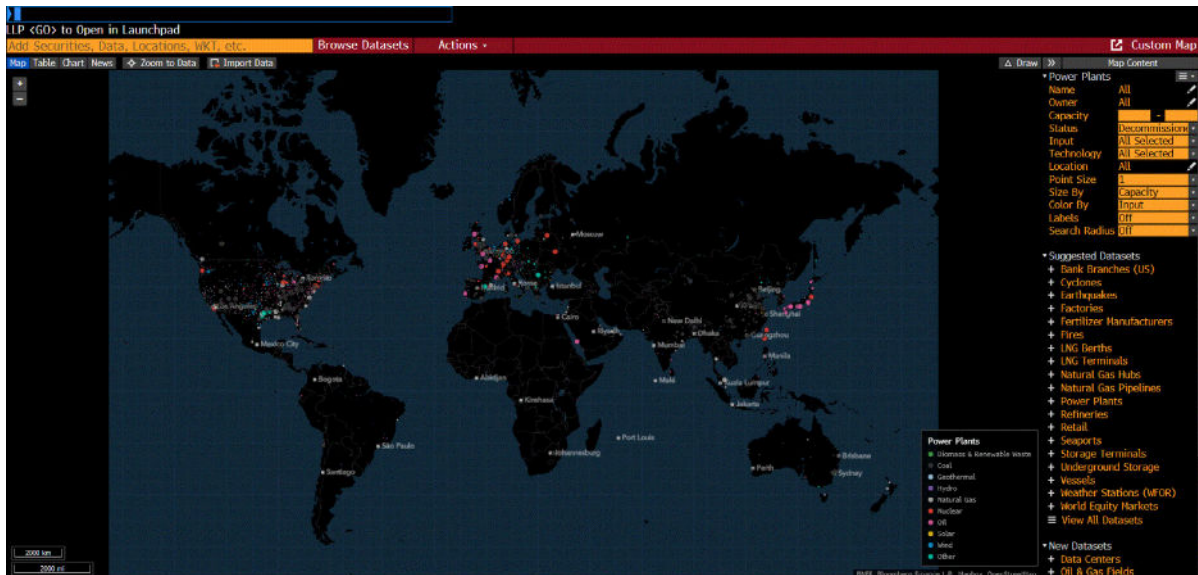


Fig. 10. Decommissioned power plants around the world, Bloomberg LP, 26 April 2026.

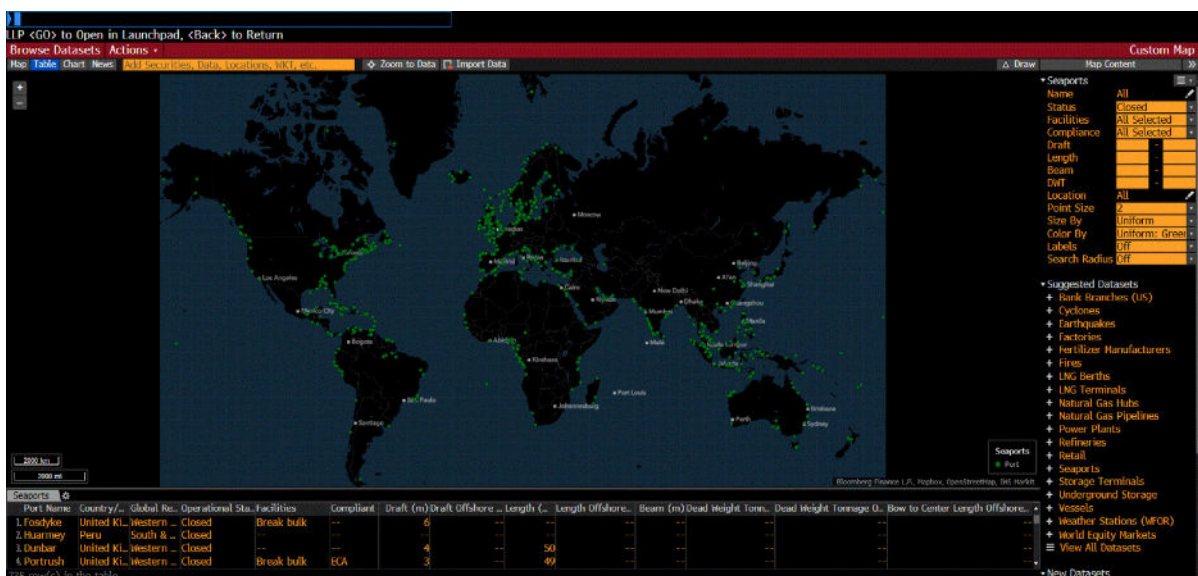


Fig. 11. Permanently Closed Seaports around the world, Bloomberg LP, Jul 28 2026



Fig. 12. Abandoned LNG Terminals around the world, Bloomberg LP, Jul 28 2026



Fig. 13. Retired Natural Gas and Crude Oil Pipelines, Bloomberg LP. Jul 28 2026



Fig. 14. Broken-up, Laid-up, Hulked, Scrapped before completion, To be broken up Ships around the world, Bloomberg LP. Jul 28 2026.



Fig. 15. Abandoned Hydrogen assets around the world, Bloomberg LP. Jul 28 2026.

ANNEX II: Further Notes on MaaS Pricing Architectures

Securitizing Metal Performance using Degradation-Linked Notes

Late-stage MaaS relies on securitization to scale⁵⁵. While a Performance Swap can introduce de-risking measures for both the AO and the lessee along the lifecycle of the contractual agreement, and while S&F models can provide a robust actuarial baseline needed to price metal degradation, pooling Performance Swaps transforms a standard Asset Backed Security into a Synthetic Collateralized Debt Obligation, introducing prohibitive structural hurdles. Unlike Degradation-linked Notes with strictly one-way cash flows, swaps carry bidirectional liability. This means that an environmental shock (even if accurately probabilistically forecasted by S&F models) could simultaneously trigger payouts across the pool, bankrupting the SPV because it lacks the liquidity to cover major reverse cash flows. Furthermore, post 2008 banking regulations impose punitive capital reserve requirements on OTC derivative pools⁵⁶ which could result in higher margin requirements. Consequently, despite the predictive power of S&F models, this compounding legal, regulatory, and liquidity friction renders swap securitization commercially unviable for scaling a metals bank.

Tranching the Degradation Risk

For standardized applications of uni-directional performance pricing using Degradation-linked Notes, S&F models can help slice cash flows into tranches based on projected degradation risks.

- The Senior Tranche (low risk, fixed yield): Institutional Investors receive a highly predictable, fixed coupon. Their payouts are mathematically protected from normal material degradation as forecasted by the S&F models.
- The Mezzanine Tranche (moderate risk, higher yield): These investors absorb the financial hit if an unexpected environmental shock causes real-time degradation (Qloss) to spike above the S&F projections across the pool, dropping the interest revenue coming into the SPV.
- The Equity Tranche (high risk, residual yield): The AO must retain this tranche. If the metal degrades faster than the S&F model predicted, this tranche absorbs the lost revenue first. This legally would force the AO to keep skin in the game and ensure they maintain the physical assets properly.

The main challenge for Degradation-linked Notes to be adopted would lie in the transparency, accuracy, track record, and reliability of the IoT sensors reporting Q_T . Institutional investors are only likely to buy these bonds if the sensor data is cryptographically secure, tamper-proof, and audited by a neutral third party. S&F models can act as a bridge to flag results from IoT sensors that deviate significantly from the forecast, helping cement trust and credibility between the AO and the lessee.

Endnotes

- 1 A stock-and-flow (S&F) model is a broad systems approach used to track the accumulation, use, and retirement of materials over time, whereas Dynamic Material Flow Analysis (DMFA) is a specific methodological application of S&F modeling that quantifies material stocks and flows dynamically across sectors, products, or lifecycles. Given the scope of the report, we will thereafter only refer to S&F models as the broader category.
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- Companies that are operating in industries where their growth in revenue is tied to production capacity (which is tied to high CAPEX) are likely to have built up metal stock in their Plant Property Equipment (PPE). This is often depreciated on balance sheets until no value is being shown, whereas the opposite could only be true. This information asymmetry is where the real alpha lies.
- An AI company that outsources most of their computing capacity to a third party (like using Amazon Web Services for hosting and cloud infrastructure) may not be an ideal candidate in this approach for instance.

- 31 B2B - Stands for Business-to-Business. It describes a model where one business sells products or services to another business rather than directly to individual consumers.
- 32 D2C - Stands for Direct-to-Consumer. It's a business model where a company sells its products directly to customers, without going through middlemen like wholesalers, distributors, or retail stores.
- 33 Residual value in a circular economy is the retained economic and material worth of an asset or product at the end of its useful life cycle (Spijker et. al 2025, Rethinking Value).
- 34 Nathaniel J. Mass, "Stock and Flow Variables and the Dynamics of Supply and Demand," in *Proceedings of the 1976 International Conference of the System Dynamics Society (Massachusetts: System Dynamics Society, Alfred P. Sloan School of Management, Massachusetts Institute of Technology, 1976)*, <https://proceedings.systemdynamics.org/1976/proceed/mass381.pdf>.
- 35 Mass, "Stock and Flow Variables and the Dynamics of Supply and Demand."
- 36 United States Department of Energy (DOE), *Platinum Group Metal Catalysts: Supply Chain Deep Dive Assessment* (DOE, December 2024), [https://www.energy.gov/sites/default/files/2024-12/PGM%2520catalyst%2520supply%2520chain%2520report%2520-%2520final%2520draft%25202.25.22\[1\].pdf](https://www.energy.gov/sites/default/files/2024-12/PGM%2520catalyst%2520supply%2520chain%2520report%2520-%2520final%2520draft%25202.25.22[1].pdf).
- 37 Shantanu Bhattacharya and Lipika Bhattacharya, *NIO: Battling Tesla with Battery as a Service* (Case SMU-21-0033, Singapore: Singapore Management University, December 2021), https://ink.library.smu.edu.sg/cases_coll_all/386.
- 38 "Light as a Service: A Smarter Way to Illuminate," Signify, <https://www.signify.com/global/signify-services/managed-services/light-as-a-service>.
- 39 "Services," TelCycle, <https://telcycle.net/services>.
- 40 "F-Gases as a Service and Service Leasing," EcoScandic, <https://ecoscandic.fi/en/f-gases-as-a-service-and-service-leasing>.
- 41 Maintenance and Recovery Costs may be included or excluded depending on the contractual agreement. In the event that it is excluded, LCoM calculations should not include these variables.
- 42 Toledano et al., *Metals-as-a-Service (MaaS)*.
- 43 Michael Staebe, Joshua Hinkel, Xavier Houot, Tessa Bysong, and Leon Lu, "Machinery and Equipment: The Circular Path to Value," *Bain & Company*, April 3, 2024, <https://www.bain.com/insights/machinery-and-equipment-the-circular-path-to-value-global-machinery-and-equipment-report-2024>.
- 44 Carlotta Boerner, Jonathan Georg, Sita Gleichauf, Fabienne Kim, and Anis Nassar, *Circular Transformation of Industries: Unlocking Economic Value* (Geneva: World Economic Forum (WEF), 2025), https://reports.weforum.org/docs/WEF_Circular_Transformation_of_Industries_2025.pdf.
- 45 See for instance: Jonathan Haskel and Stian Westlake, *Capitalism Without Capital: The Rise of the Intangible Economy* (Princeton, NJ: Princeton University Press, 2018), <https://press.princeton.edu/books/hardcover/9780691175034/capitalism-without-capital>;
Jérôme Hugonnier and Erwan Morellec, "Bank Capital, Liquid Reserves, and Insolvency Risk," *Journal of Financial Economics* 125, no. 2 (August 2017): 266–285, <https://doi.org/10.1016/j.jfineco.2017.05.006>.
- 46 Volume-based metal lease are well established in the market, for instance: "Master Lease Agreement" (Exhibit 10.1), U.S. Securities and Exchange Commission, September 28, 2009, <https://www.sec.gov/Archives/edgar/data/1431824/000119312509234084/dex101.htm>.
- 47 Material Performance Coefficient, or Ci, can be thought of as a real-time health score for the metal. The metric isolates the metal's actual condition from the performance of the broader machine it sits inside of. It acts as a simple percentage, tracking metrics like copper's current conductivity, or steel's yield strength against their original baselines. If sensors show the material has worn down to 92% of its optimal state during a given billing cycle (Δt), Ci drops to 0.92. The lessee's payment for that period will then be adjusted to match the metal's true condition.
- 48 Nikolaus A. Bornhöft, Bernd Nowack, and Lorenz M. Hilty, "Representation, Propagation, and Interpretation of Uncertain Knowledge in Dynamic Probabilistic Material Flow Models," *Environmental Modeling & Assessment* 26 (2021): 709–721, <https://link.springer.com/article/10.1007/s10666-021-09775-5>.
- 49 For catalytic powders used in heavy industry, applications may be limited to processes where reversible deactivation occurs (such as fouling and coking) where the original form of the metal can be restored by burning off the carbon in an oxygen-rich atmosphere (decoking) or through hydrogen reduction: Jibin Zhou, Jianping Zhao, Jinling Zhang, Tao Zhang, Mao Ye, and Zhongmin Liu, "Regeneration of Catalysts Deactivated by Coke Deposition: A Review," *Chinese Journal of Catalysis* 41, no. 7 (July 2020): 1048–1061, <https://dmtoc.dicp.ac.cn/2020-15-14.pdf>.
- 50 A typical swaption is an option that gives its holder the right, but not the obligation, to enter into an interest rate swap at a future date. There are two main types: payer swaptions, which benefit when interest rates rise, and receiver swaptions, which benefit when rates fall. Swaptions can also differ by exercise style, including European, American, and Bermudan structures. They are widely used by banks, insurers, and traders for hedging interest rate exposure or speculating on future rate movements: Cedric Thompson, "Swaptions Primer: Learning Types and Styles for Better Risk Management," *Investopedia*, July 20, 2026, <https://www.investopedia.com/terms/s/swaption.asp>. We are suggesting an adaptation of the concept to performance as the underlying variable to hedge against operational uncertainty driven by external environmental conditions.
- 51 Please refer to "ANNEX II: Further Notes on MaaS Pricing Architectures" for further explanations.

- 52 In traditional financial markets, an inverse floater is a bond where the interest rate moves in the opposite direction of general market interest rates. The behavioral mechanism of an inverse floater has been modified and applied for MaaS, where a decrease in metal performance leads to a decrease in the continuous interest rate.
- 53 In a traditional fixed-income instrument, if the collateral on a loan degrades, the lender penalizes the borrower by raising the interest rate or calling the loan. This model completely inverts this. Because the AO (the lender) is responsible for the quality of the metal, the lender is penalized with a lower interest rate when the metal degrades, aligning physical maintenance with debt servicing.
- 54 Please refer to “ANNEX II: Further Notes on MaaS Pricing Architectures” to learn more.
- 55 Toledano et al., *Metals-as-a-Service (MaaS)*.
- 56 “Over-The-Counter Derivatives,” Federal Reserve Bank of New York, <https://www.newyorkfed.org/financial-services-and-infrastructure/financial-market-infrastructure-and-reform/over-the-counter-derivatives>.

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475 Riverside Drive, Suite 504. New York, NY 10115

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