Reconvening the MaaS Community of Practice:

Tools to make MaaS Business Models work

Columbia Center on Sustainable Investment • Carbon Trust • July 9, 2026

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Applied research center of Columbia Climate School (since 2006)

Mission: To advance policies and practices that scale and shape investment contributing to sustainable development outcomes.

COLUMBIA CLIMATE SCHOOL
COLUMBIA CENTER ON SUSTAINABLE INVESTMENT

ABOUT CARBON TRUST

Mission Impact consultancy (since 2001)

Mission: To accelerate the move to a decarbonised future. Helping organisations worldwide reduce carbon emissions and achieve greater resource efficiency.

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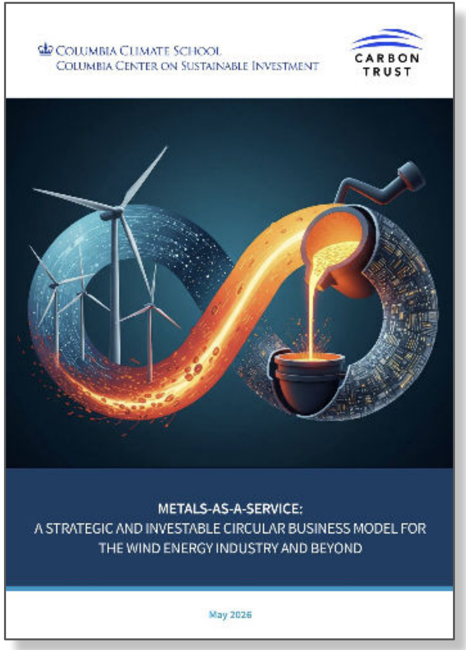
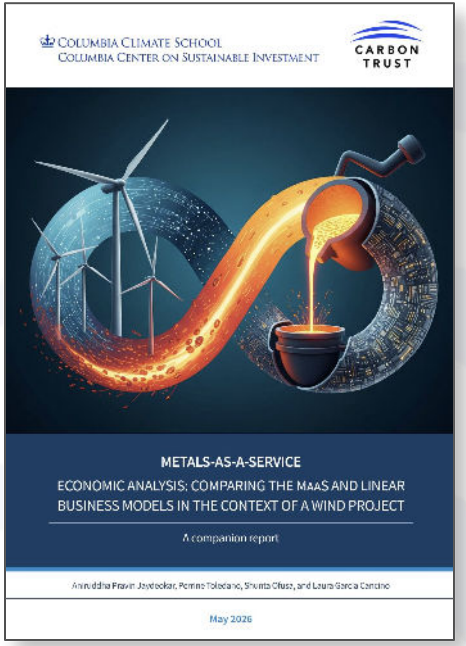
Recent Publications on Metals-as-a-Service

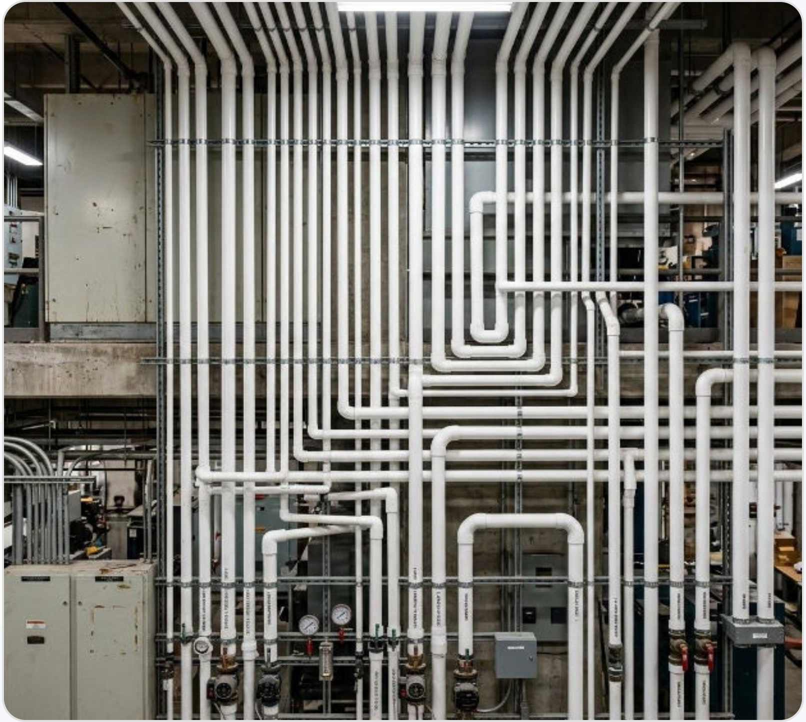


Metals-as-a-service: a strategic and investable circular business model for the wind energy industry and beyond



Economic Analysis: Comparing the MaaS and Linear Business Models in the Context of a Wind Project

Agenda



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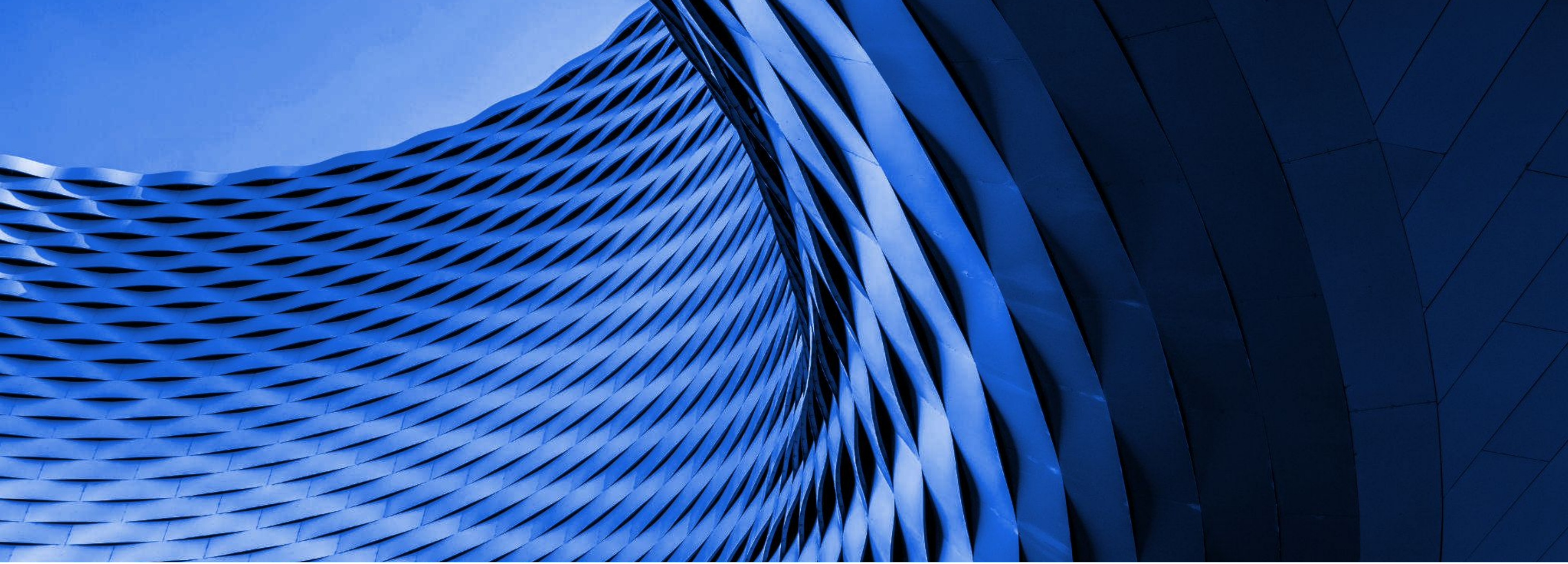

Reminder: What is Metals-as-a-Service?

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Metals-as-a-Service: Turning Circularity into Capital

The Goal

Make MaaS operationally sound and commercially investable

The Motivation

Primary extraction is limited, circular models based solely on recycling don't close the loop → The Result: we don't meet the metal needs of the energy transition

The Loop Will Close Because

- The asset owner has an **incentive to recover** the metal → value chain around design and logistic for recoverability
- Financing is structured to **compete with the linear model**

The Immediate Benefits to Metal Users

- Reduced upfront CAPEX and predictable OPEX
- Supply security
- Access to higher ore grade in the urban stock
- Lifecycle circularity

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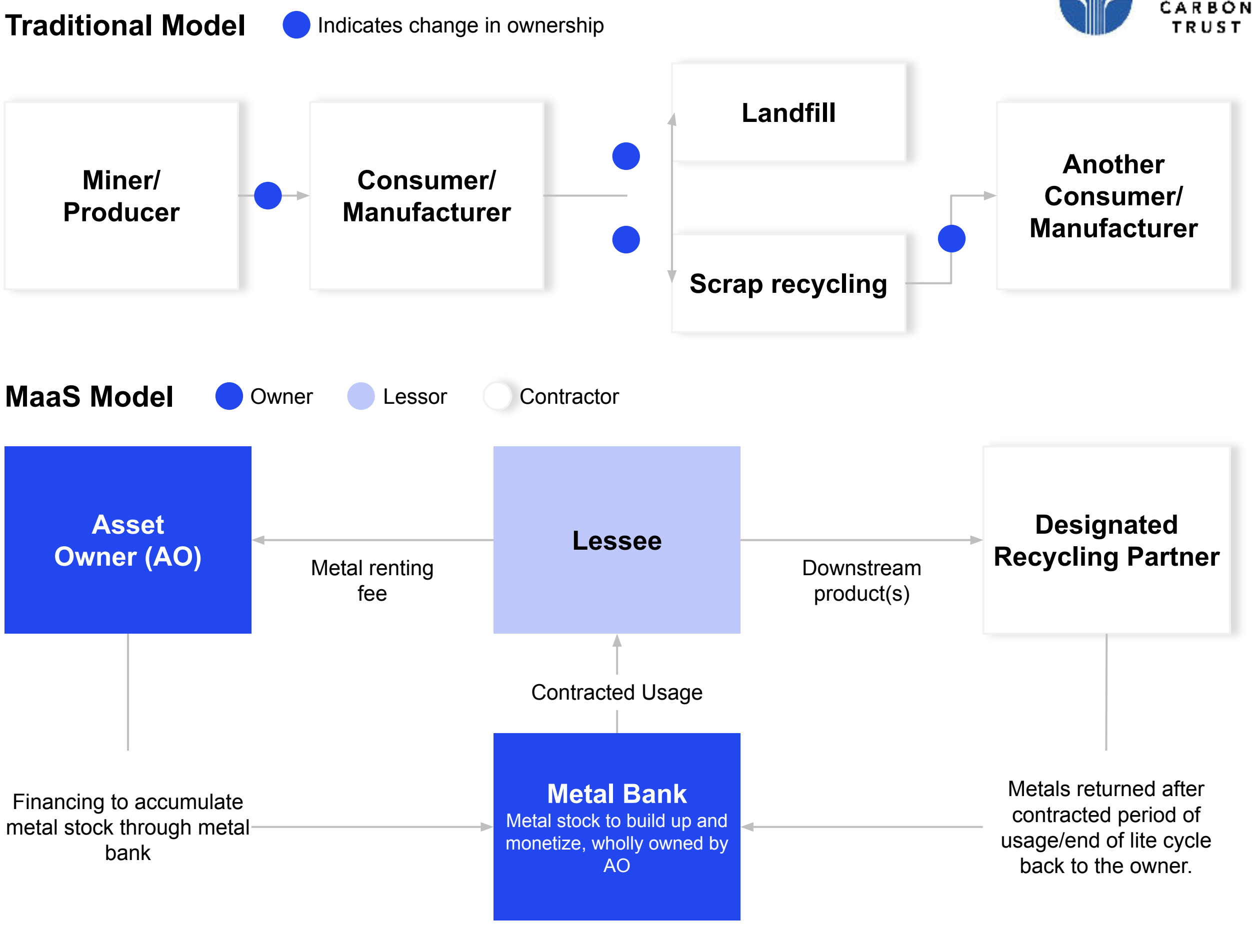
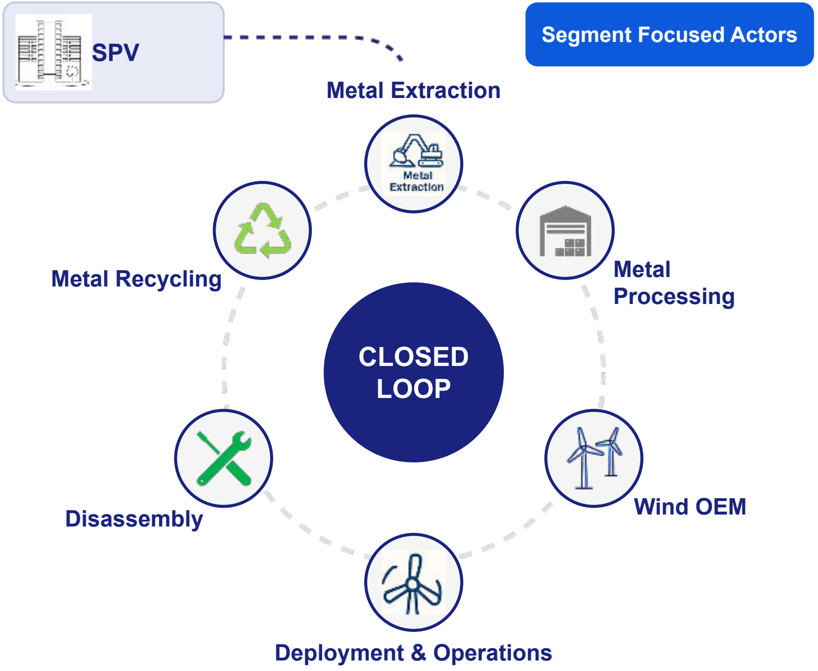
Reminder: What is MaaS?

A model where metal ownership does not change. Only the right to use metal is transferred along with a contractual duty to ensure recoverability. Metal is leased and returned back in its original form at the end of a contract



Reminder: MaaS needs a backbone that is operationally and financially efficient

A ‘value chain business model’ focused on retaining metal value along its length



Circular Value Chain Enablers

- **Business Leadership:** Drives circularity systematically within wind value chains.
- **De-risking Mechanisms:** Technologies, tools, and standardized contracts de-risk closed-loop metal use.
- **Metal Bank:** Secures reliable, long-term Access to essential transition materials.
- **Financial Benefits:** Promotes revenue generation and balance sheet strengthening.

To This End: Core Operational Structure

- **Single SPV Entity:** Operationalizes the metal renting model and structures critical financial liquidity.
- **Entity-Owned Metals:** Retained by the provider, rented transparently to lessees, and systematically recovered for reuse.

Core enabling conditions of MaaS

Circularity & technical feasibility

- Recoverability, recyclability, material degradation
- Design for disassembly, logistics systems

Business model & contracting

- Ownership structure (SPV backbone)
- Leasing logic / service-based payment
- Risk allocation

Economic viability

- Competitive vs linear model
- Stable long-term cashflows
- Sensitivity to price volatility

Technology & data

- Traceability systems
- Digital monitoring to support recovery and financing

Ecosystem conditions

- Policy and regulatory support
- Value chain coordination
- Stakeholder alignment

The Feedback Loop Between MaaS Business Models and Stock-and-Flow Models

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S&F Modeling enables Converting Circularity Data into Business Value

The value of S&F modelling

- Tracks material movement through industrial systems using Dynamic Material Flow Analysis (DMFA).
- Distinguishes between **stocks** (total mass in use) and **flows** (movement rates like EoL waste and recycling).
- Applies the governing principle of **mass conservation** to ensure data integrity.
- Identifies the **size, timing, and geography** of recoverable "urban mines".
- Supports reverse-logistics planning and residual-value cash flow credibility.

Stock and Flow Overview: The Steel-to-Wind Value Chain

Core Modeling Assumptions in Leading Steel Studies

- **Material Intensity:** Foundation input based on steel content per MW of wind capacity.
- **Fabrication Yields:** Average 85% yield rate assumed; car panels (60%) vs. rebar (95%).
- **Allocation Matrix:** Maps 19 intermediate products to 10 end-uses via 28 calculation steps.
- **Post-Consumer Scrap:** Derived as a residual balance constrained by mass-balance equations.

Practical Applications of Dynamic Material Flow Analysis (DMFA)

Flow Forecasting

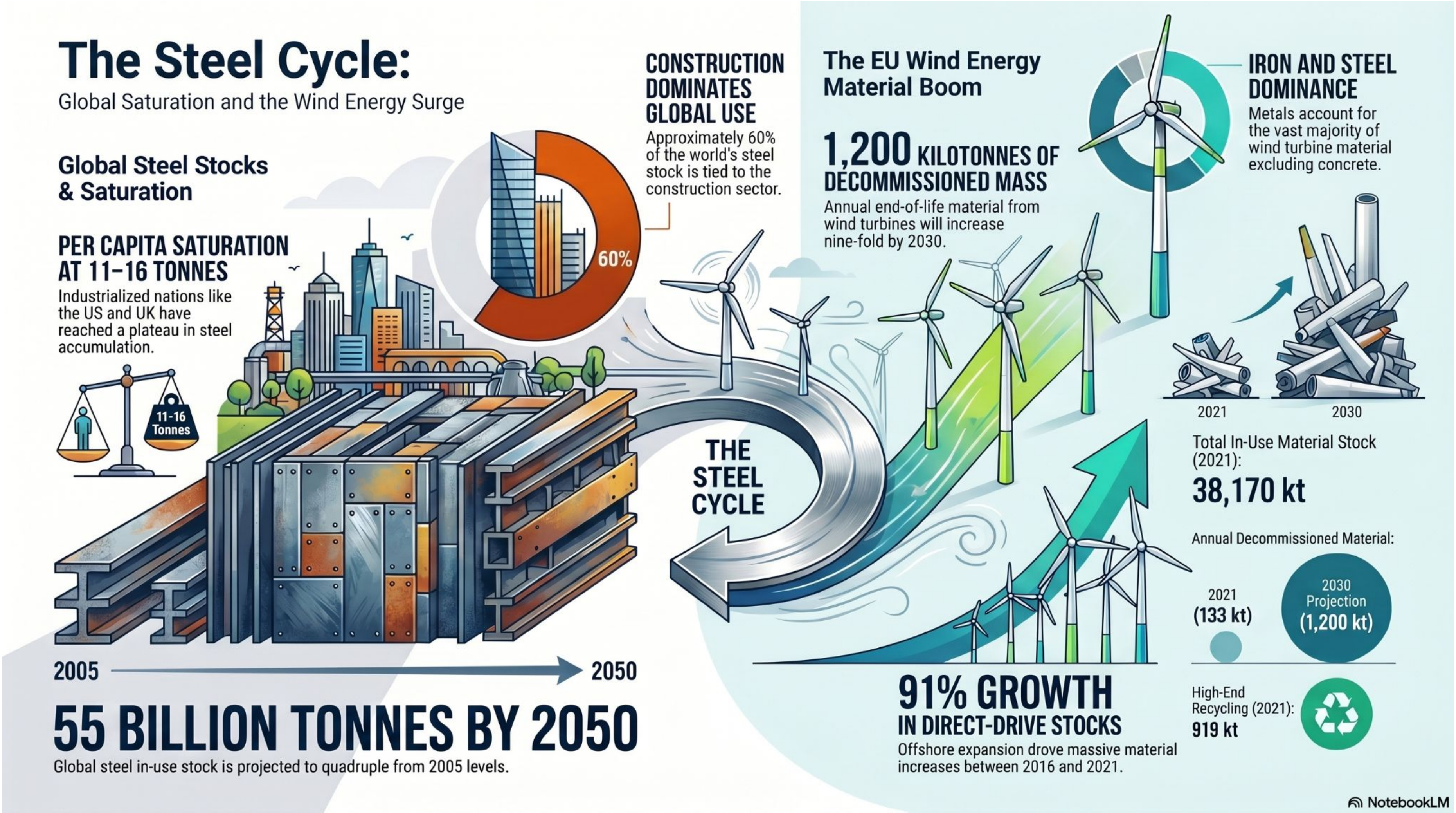
Links installation dates to EoL outflows for infrastructure planning.

Decommissioning Waves

Anticipates surpluses; EU wind EoL flows to hit 1,200 kt by 2030.

System Transition

Informs shift from primary (BF-BOF) to secondary (EAF) production.


The Steel Cycle:
Global Saturation and the Wind Energy Surge
Global Steel Stocks & Saturation
PER CAPITA SATURATION AT 11–16 TONNES
Industrialized nations like the US and UK have reached a plateau in steel accumulation.
11-16 Tonnes
CONSTRUCTION DOMINATES GLOBAL USE
Approximately 60% of the world's steel stock is tied to the construction sector.
60%
THE STEEL CYCLE
2005
2050
55 BILLION TONNES BY 2050
Global steel in-use stock is projected to quadruple from 2005 levels.
The EU Wind Energy Material Boom
1,200 KILOTONNES OF DECOMMISSIONED MASS
Annual end-of-life material from wind turbines will increase nine-fold by 2030.
IRON AND STEEL DOMINANCE
Metals account for the vast majority of wind turbine material excluding concrete.
2021
2030
Total In-Use Material Stock (2021):
38,170 kt
Annual Decommissioned Material:
2021 (133 kt)
2030 Projection (1,200 kt)
91% GROWTH IN DIRECT-DRIVE STOCKS
Offshore expansion drove massive material increases between 2016 and 2021.
High-End Recycling (2021):
919 kt
NotebookLM

Limitations of S&F Models

Material Intensity Uncertainty

Coefficients derived from engineering averages often miss technological shifts. In wind, steel-to-power ratios change with turbine size, yet models apply static or smoothed values.

Geographic Proxy Failure Rates

Failure parameters are often borrowed from one region (e.g., German wind farms) and applied globally, ignoring local operational environments and wind loading conditions.

Recycling Efficiency Generalization

Values are sector-averaged rather than asset-specific. Recovery for specialty metals (e.g., neodymium) is often modeled near zero as infrastructure does not yet exist at scale.

The Bottom-Up Imperative: Capturing Hidden Value in PP&E

The Financial-Physical Gap

Standard linear accounting creates a structural break between balance sheets and reality:

- **Financial Model:** Depreciation drives Book Value to $0 at the end of "useful life".
- **Physical Reality:** Physics disagrees—the metal remains embedded in the asset, retaining its intrinsic value.
- **The MaaS Opportunity:** Monetizing this "invisible" residual value trapped in depreciated PP&E.

Screening for MaaS Opportunities

Key parameters to identify firm-level metal stocks:

- **Asset Liquidity:** High illiquid-asset share (PP&E vs Liquid) signaled by "Acid Test" failure.
- **Revenue Dynamics:** Low outbound metal flows relative to CAPEX indicates stock accumulation.
- **Credit Distress:** Junk-rated firms with heavy PP&E provide high-conviction entry points.

Closing the Loop: From Proxy Assumptions to Empirical Truth

Structural Opacity

Ownership transfer at point-of-sale fragments data, forcing Top-Down models to rely on proxies.

Firm-Level Insight

Bottom-up analysis identifies where value is embedded in specific assets and balance sheets.

MaaS as Infrastructure

MaaS generates the missing traceability data, turning estimates into verifiable quantities.

Identifying MaaS Opportunities Through S&F Models

Analytical Framework

Three Key Layers make up the analytical framework:

- **Physical Layer:** Tracks stocks (reservoirs) and flows (production/EoL) in the economy.
- **Economic Layer:** Translates physical data into residual value and timing metrics.
- **Financial Layer:** Structures collateral, pricing, and credit architecture.

Performance-Based Pricing

Shifts fees from volume-based ($/ton) to functional utility through:

- **Traceability:** IoT sensors log transformation and stress.
- **Digital Twins:** Monitor real-time quality degradation (QT).
- **Quality - Based Formulas :** Track physical wear as a depletable stock.
- **Agentic AI:** Optimize all data flows for use

Strategic Economic Translation: From Physical to Financial Structures

Residual Value
Converts in-use stock into monetizable end-of-life value streams for MaaS.

Predictive Reverse Logistics
Predicts when asset stocks convert into material flows, providing the basis for cash-flow forecasting.

Risk Visibility
Traceable flow evolution reduces information asymmetry for lenders.

Modeling the Loop: How Stock and Flow Systems Power Metals as a Service (MaaS)

Metals as a Service (MaaS) shifts from a linear "sell-and-forget" model to a circular "lease-and-recover" system. Stock and flow models provide the mathematical rigor to track these assets, quantify the "Metal Bank," and ensure the loop effectively closes.

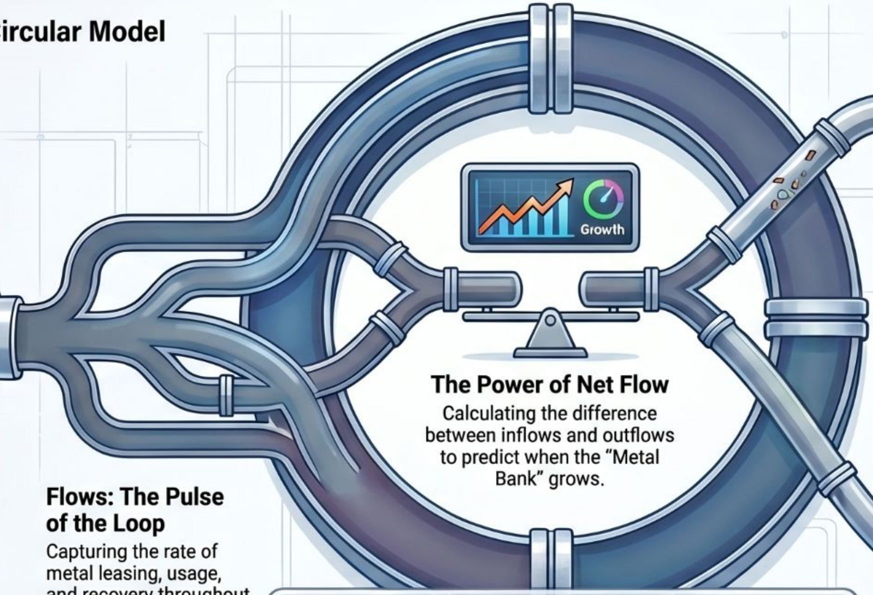
The Building Blocks of a Circular Model

Stocks: The "Metal Bank"

Representing the total accumulated inventory of metal owned by the SPV at any snapshot in time.

Flows: The Pulse of the Loop

Capturing the rate of metal leasing, usage, and recovery throughout the product lifecycle.



The Power of Net Flow

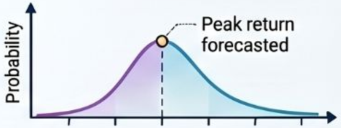
Calculating the difference between inflows and outflows to predict when the "Metal Bank" grows.

System Element	Accounting Equivalent	MaaS Example
Stock	Balance Sheet (Assets)	Metal Bank Inventory
Flow	Income Statement (Activity)	Monthly Leasing Rate
Information	Decision Support	Recycling Efficiency %

Strategic Benefits for MaaS Implementation

Identifying Loss Pathways

Modeling helps pinpoint inefficiencies and "hibernating" stocks where valuable metal is leaking from the loop.



Predictive Recovery Timing

Using lifetime distribution functions to forecast exactly when leased metals will return for reuse.

De-risking Circular Investments

Providing the quantitative data needed for digital ledgers (Blockchain/IoT) to maintain investor confidence.

Levelized Cost of MaaS (LCoM): A metric to make MaaS economically viable

The LCoM Equation

$$LCoM = (\sum [(I_t + O_t + M_t + R_t) / (1+r)^t]) / (\sum [S_t / (1+r)^t])$$

Variable Definitions

- **I_t:** Initial metal acquisition cost
- **O_t:** Operations & monitoring
- **M_t:** Maintenance & refurbishment
- **R_t:** Recovery & logistics
- **S_t:** Service utility delivered
- **r:** Discount rate / cost of capital

Optimization Levers via Stock & Flow

1. Minimize Idle Stock

Flow models enable just-in-time logistics, reducing excess buffer inventory and acquisition costs (I_t).

2. Asset Velocity

Predictive retrieval increases the velocity (S_t) of redeployment, diluting initial capital costs.

3. Managed Degradation

Sequencing high-grade to low-grade applications reduces Smelting/Refining costs (M_t).

4. De-risking Capital

Predictable recovery schedules reduce investor risk, lowering the discount rate (r).

Three Performance-Based Pricing Architectures for MaaS

1. Standalone Performance

Pure Service Level Agreement

Lessee pays exclusively for continuous functional utility (e.g., $/MWh transmitted or catalytic throughput).

Risk Logic:

AO bears 100% of degradation risk. Costs are internalized and baked into the base service rate (R)*.

Key Formula*:

$$P_{\square o \square a \square} = \Sigma\,(R \cdot C_i \cdot \Delta t_i)$$

Best for: Mature markets with high-fidelity asset monitoring.

2. Double Layered (Swap)

Volume Lease + Performance Swap

Transitional model combining standard volume-based rental with a financial hedge against degradation.

Risk Logic:

Lessee pays a premium (P) to transfer degradation risk to the AO, behaving like a European put option.

Swap Premium (P)**:

$$P = E\,[\,N \cdot \max(Q_{\square i \square} - Q_{\square},\, 0)\,]$$

Best for: Inducing MaaS in markets accustomed to volume contracts.

3. Triple Layered (Swaption)

Volume + Swap + Swaption

Advanced structuring for high-uncertainty environments (e.g., extreme environmental stress).

Risk Logic:

The Swaption gives the lessee the right to enter a future performance swap at a fixed, pre-agreed premium.

Strategic Outcome:

Asymmetric protection: if conditions are benign, the swaption expires; if harsh, it caps downside costs.

Best for: Managing volatility in long-term material deployments.

*Ptotal is the total contract cost to the lessee, calculated across n billing periods. R represents the rate per unit of service delivered (e.g., $/MWh for copper), Ci is the material performance coefficient (average metric from traceability tech during period i), and Δti is the duration of period i.

**P (Swap Premium): The fair value paid by the lessee to the protection seller at time T, E (Expected Value): A probability-weighted average of the asset's condition at lease end, determined by DMFA projections, N (Notional Principal): The assigned dollar value of the metal (e.g., replacement cost or initial price)., Qmin (Quality Floor): The contractually agreed-upon minimum acceptable quality (e.g., purity or strength), and QT (Terminal Quality): The actual, measured quality of the metal at time T, derived from DMFA wear calculations.

Option 1: The Standalone Performance Contract

Pure Service Level Agreement (SLA)

Lessee pays exclusively for **continuous functional utility** (e.g., thermal resistance uptime or catalytic throughput) rather than physical mass.

Pricing Dynamics:

$$P_{\square o \square a \square} = \Sigma \, (R \cdot Q_i \cdot \Delta t_i)$$

- **Zero Degradation Premium:** If performance drops, payments automatically decrease until the asset is replaced.
- **Internalized Risk:** The Asset Owner (AO) bears 100% of the degradation risk.

Best For:

Mature markets with high-fidelity asset monitoring and established traceability.

Actuarial Risk Calculation (Internal)

The AO calculates expected downside exposure to bake it into the base rate (R):

$$P = E \, [\, N * max(Q_{\square i \square} - Q_{\square}, 0) \,]$$

Option 2: Transitional Double-Layered Contract

Volume Lease + Performance Swap

Combining standard volume-based rental with a financial hedge against degradation risk.

1. The Volume Base:

Lessee pays a fixed rental fee based on metal weight (W) and lease duration (T).

$$Base = V * W * T$$

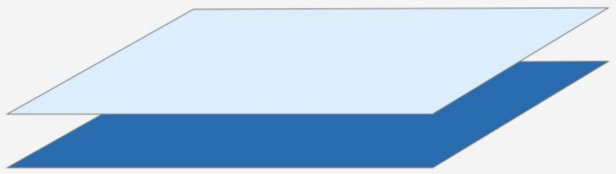
2. The Performance Swap Layer:

A hedge where the lessee pays a premium (P) to transfer degradation risk to the Asset Owner (AO).

- Behaves like an **Insurance Policy,** but on **Metal Performance.**.
- Triggers material retrieval when degradation hits a defined threshold.

Strategic Benefit:

Allows transition for markets accustomed to volume contracts while de-risking capital.



Swap Premium (P) Calculation

The fair value is calculated by integrating expected flows over the contract duration:

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

Qmin: Quality Floor | **QT:** Measured Terminal Quality | **N:** Notional Principal

Option 3: Advanced Triple-Layered Swaption Contract

Volume + Swap + Swaption

Advanced structuring for high-uncertainty environments (e.g., extreme environmental stress) to defer future risk costs.

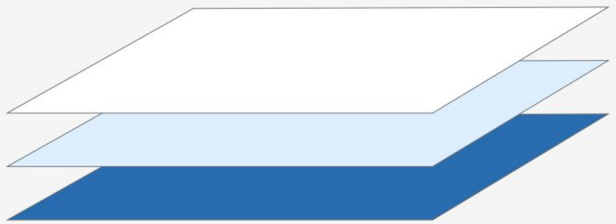
1. The Asset Foundation: Combines the standard volume lease and the performance swap hedge (Option 2).

2. The Swaption Layer:

- Gives the lessee the **right but not the obligation** to enter a future performance swap at a fixed strike premium (P).
- Provides **asymmetric protection**: if conditions are benign, it expires; if harsh, it caps future costs.

Strategic Outcome:

Best for managing volatility in long-term material deployments where future degradation rates are unpredictable.



Swaption Payoff Mechanics

The derivative manages the variance (σ) of environmental volatility, yielding a payoff based on market premiums:

$$Payoff = max(P_{market} - P_{strike}, 0)$$

Strategic Hedge: If environmental stressors degrade metal faster than expected, the swaption protects the lessee's cash flow by locking in the lower strike premium.

Q&A

METALS-AS-A-SERVICE

Market discovery Framework

Identifying where a circular service-based metals model may be commercially viable

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From broad interest in MaaS to a structured way of asking the right questions early

Exploring a MaaS Market Discovery Framework

Exploring if there is value in developing a light-touch MaaS Market Discovery Framework to identify potential opportunities

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The problem:

- Interest in MaaS is growing
- Value chain conditions vary enormously
- Stakeholders lack a structured way to identify MaaS opportunities
- Risk of pursuing MaaS in the wrong contexts or missing where it could work

What the framework does:

- A high-level, criteria-based framework
- Supports early-stage identification, screening and prioritisation
- Not a diagnostic tool, business case, or due diligence process

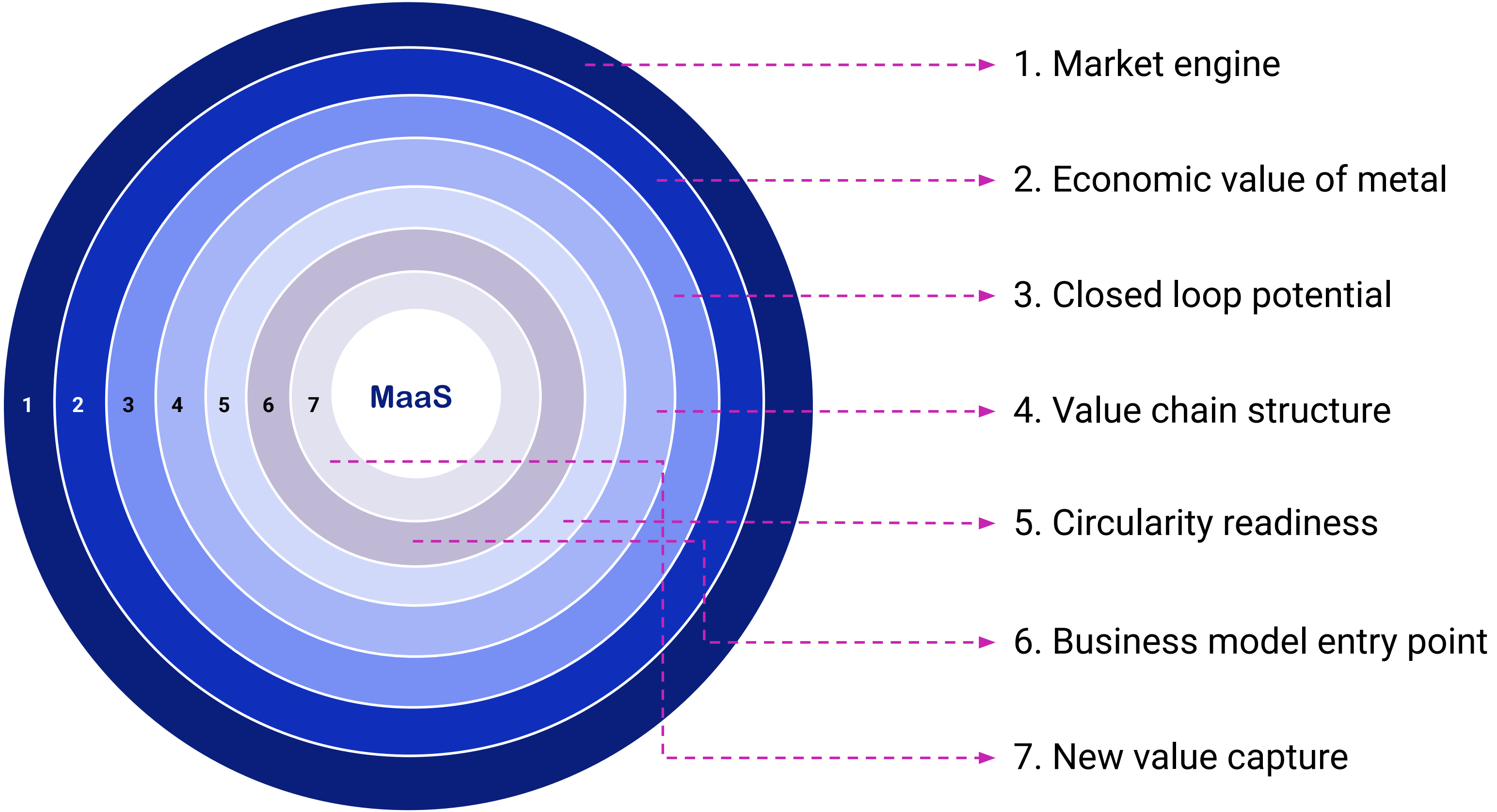
A framework to progress from broad interest in MaaS to a light-touch assessment of where it may be worth deeper investigation

A layered logic: from market signal to value capture

What the Framework assesses

What the Framework assesses

A layered assessment



What the Framework assesses

The seven questions

#	Question	What it tests
1	Is there a **market engine** to drive action?	If there is a stable or growing market for the product or infrastructure that uses on the metal
2	Is there sufficient **economic value in the metal**?	If the metal has durable current and future economic value
3	Can the value chain be configured as a **closed loop**?	If the value chain be configured as a metal circularity closed loop – curtailing leakage and mitigating traceability complexities
4	Can the **value chain structure** be clearly mapped?	The business logic of actors, material flows, ownership points, and technology use or readiness
5	How has **circularity** already been adopted in the value chain?	Existing use of circularity in the value chain, in similar value chains or wider industry
6	Where is there a **business model entry** point?	If payment mechanism exist which can carry 'metal-as-a-service' rental or leasing
7	Can MaaS unlock **new value capture**?	If MaaS can unlock forms of value that the current model does not fully capture

What the Framework assesses

Should we expand the tool beyond the seven questions?

Enabling conditions:

- Policy
- Regulation
- Governance
- Infrastructure
- Data availability
- Stakeholder readiness

Safeguards & legitimacy:

- Host-country implications
- Community considerations
- Wider value chain governance

A promising opportunity is not only commercially attractive; it is also credible, legitimate and capable of progressing

One framework, three user perspectives

Applying the Framework

Applying the framework across user groups

User group	Core question	Potential output	Example
Corporates	Where could MaaS create strategic value in key market segments?	Prioritised list of value chain segments	Copper company looking at long range opportunity scanning
Entrepreneurs / solution providers	Where are our capabilities most relevant?	Opportunity areas and capability fit	TechCo offering digital traceability capabilities. EV battery recycler.
Investors / financial institutes	Where might deeper diligence be justified?	Comparative opportunity profile	An investor comparing value chain segments

The underlying logic is the same. The lens changes with the user.

The framework is an entry point, not an endpoint.

From market discovery to deeper design

The MaaS development pathway

From discovery to design

Discover	Prioritise	Deepen	Design & test
• Identify MaaS-relevant characteristics in a value chain.	• Compare and shortlist opportunities.	• Business model, legal, financial, stakeholder and policy analysis.	• Reference architectures, pilots, value chain test beds.

The Market Discovery Framework supports the first two stages. Later stages require more detailed, context-specific work.

This is where we need your input

Shaping the Framework

How you can shape the framework

Are these the right criteria?
Do the seven core questions capture what matters most in MaaS opportunity identification?

Which value chains would you test first?
Where do you see the strongest near-term MaaS relevance?

What outputs would be most useful?
A readiness profile, heatmap, shortlist, narrative assessment or comparative view?

What evidence would make the framework credible?
What data, standards or evidence would you need to trust and use the framework?

How you can shape the framework?

- Are these the right assessment criteria?
- Which value chains should be tested first?
- What evidence would make the framework useful to decision-makers?
- What outputs would be most useful: heatmap, shortlist, narrative assessment, weighted score, or readiness profile?

- Do these assessment criteria reflect the practical realities of metals value chains?
- Which value chains or asset classes should be used to test the framework?
- What form of output would be most useful for decision-making?
- What evidence would increase confidence in the assessment?
- Where could the framework support future collaboration, pilots or deeper analysis?

- What metal/material problem would MaaS help you solve?
- What would make you participate in a pilot?
- What risks would stop you?
- What would need to be true for your organisation to allocate funding/time?
- Would you participate in a hackathon, challenge or accelerator?

Q&A

Thanks for listening

Knowledge and Experience Sharing

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