Beyond Hard-to-Abate: Matching Models to Transition Bottlenecks

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Highlights

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- Energy-intensive transitions stall at three bottlenecks: process, firm, sector
- Bottlenecks reinforce one another vertically, so difficulty is configurational
- System-level optimisation resolves process detail but stops at the firm level
- Match each bottleneck to a model family; agent-based fills the firm-level gap
- Reframe hard-to-abate as hard-to-transition, a property of the pathway

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ABSTRACT

In energy-intensive industry, the difficulty of decarbonising is not a uniform property of the emissions involved but a property of the pathway, conditional on identifiable bottlenecks at three interlocking levels. At the process level, heterogeneous products and coupled processes multiply the low-carbon option space. At the firm level, financing premiums and coordination failures across the supply chain govern who invests and when. At the sector level, competition is shaped by trade policy and security of supply, and the politics of the transition by the regional employment these industries sustain. These bottlenecks reinforce one another across levels, so the difficulty becomes a property of the configuration rather than of any single constraint. Representing this configuration demands matching the "right" model to each bottleneck. Dominant optimisation frameworks are built for system-level analyses and resolve process detail well but collapse firm heterogeneity into a single planner and treat demand and global competition as exogenous rather than as co-evolving with the transition. Path-dependent first-mover investments and their regional employment effects fall outside cost-optimising frameworks with exogenous demand, leaving the firm level largely missing. Across sectors, shared inputs such as hydrogen and methanol create reinforcing learning curves that only models with endogenous, shared learning capture. We therefore argue for a shift in framing, from hard-to-abate, a property of emissions, to hard-to-transition, a property of the pathway, where viable solutions exist but have not been deployed. The reframe converts the problem into an actionable task, matching each bottleneck to a model that can address it.

1. Introduction

Reaching net-zero CO_2 requires decarbonising every sector, but difficulty varies widely. In Europe, power and transport have established, increasingly cost-competitive transition pathways. However, a residual set of emissions, concentrated in energy-intensive industry (EII), does not (Wesseling et al., 2017; Davis et al., 2018; Azevedo et al., 2021). These are commonly referred to as hard-to-abate sectors (Yang et al., 2022; Edelenbosch et al., 2024; Meng et al., 2025; He et al., 2026), with alternative names difficult-to-eliminate (Davis et al., 2018) or hard-to-decarbonise (Azevedo et al., 2021). EII assets such as blast furnaces and steam crackers often operate for over forty years, so an investment made today either commits a plant to a high-carbon route for decades or builds in the capability to decarbonise, and both can strand assets (Bataille et al., 2018; Seto et al., 2016). This makes the transition uniquely time-sensitive.

These pressures are compounded within the European energy context. Rising gas prices following the Russian invasion of Ukraine in 2022 (Bajo-Buenestado et al., 2025) and the March 2026 oil price spike following the closure of the Strait of Hormuz have shifted policy towards affordability and security of supply. European EII are especially exposed to global disruptions because they rely predominantly on imported fossil fuels (75% of oil and 53% of natural gas is imported), unlike North America, which is a net exporter (IEA, 2023). Production in the four most energy-intensive EU industries, including chemicals and basic metals, fell by 12% between 2021 and 2023, with direct

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consequences for employment in the regions hosting them (European Commission, 2024). The feasible option space may be narrower still, as recent analysis argues that carbon capture and storage (CCS), low-carbon hydrogen, and carbon dioxide removal (CDR) cannot scale up to the levels projected in long-term emission-reduction scenarios, leaving industry to decarbonise largely through a limited budget of emission-free electricity (Edwards et al., 2026; Allwood, 2026; Paltsev et al., 2021). Policy therefore requires that decarbonisation investment continue without eroding the industrial base (EU, 2021), even though the scale and speed of redeployment are unprecedented and slowed by market and coordination barriers even for mature options (Emanuelsson et al., 2025).

The label hard-to-abate is part of the problem. Buck et al. (2023) document substantial residual emissions in national net-zero strategies and argue for clear criteria for using the label. A definition is given by Dufour-Décieux et al. (2025), where an emission is hard-to-abate if, at the date of net-zero pledges, no mitigation option is more cost-effective and energy-efficient than direct air carbon capture and storage (DACCS). This process-level benchmark tests whether a cheaper or less energy-intensive option exists in principle, not whether that option can actually be deployed, and deliberately excludes the political, social, and institutional factors that determine deployment. What holds deployment in place is self-reinforcing inertia, the carbon lock-in that arises when technologies, institutions, and behaviour co-evolve and increasing returns favour the incumbent configuration (Unruh, 2000; Seto et al., 2016). Transitions stall at identifiable bottlenecks rather than failing uniformly, which undermines the use of the label "hard to abate"; these bottlenecks can be targeted, for example through public funding and demand support (Bataille et al., 2025).

Whether these bottlenecks become visible depends on the models that guide investment and policy, especially energy system optimisation models (ESOM) and integrated assessment models (IAM) (Pfenninger et al., 2014; Keppo et al., 2021). These frameworks resolve individual process steps and indicate what a least-cost decarbonised system looks like. What they do not structurally capture is how heterogeneous firms invest under financing constraints and global competitive pressure, or how the transition itself restructures that competition (Mercure et al., 2016). The sustainability-transitions literature has long described such change as socio-technical, multi-level, and sustained by lock-in (Geels, 2002; Shove, 2010; Köhler et al., 2019), but efforts to connect it with quantitative models have so far produced more interdisciplinary learning than results decision makers can act on (Hirt et al., 2020).

This paper makes three connected arguments. First, the hard-to-abate label, applied at the sector level, conflates a property of an emission with a property of a pathway. This paper therefore distinguishes hard-to-abate from hard-to-transition, where a cheaper option exists but remains undeployed because of self-reinforcing inertia. Second, the inertia sits at three interacting levels, process, firm, and sector, so transitions stall at specific bottlenecks. Third, dominant optimisation frameworks can resolve the process level but systematically misrepresent firm-level dynamics and how global competition reshapes domestic production, so the model must be matched to the bottleneck it addresses. Using primary steel and petrochemicals as examples, the analysis identifies the models these sectors need and proposes extending the approach to other hard-to-transition sectors, defined as those with significant hard-to-abate emissions.

Repositioning these emissions as hard-to-transition is constructive, because an emission only falls into this category when a viable solution exists but has not been deployed. The task is therefore to identify and analyse each bottleneck with the right model and to address it with suitable policy instruments, in line with the principle that the model should match the question being addressed.

2. The complex transition of energy-intensive sectors

The sectors in which the transition is visibly succeeding, decarbonise largely through small modular technologies such as solar panels, batteries, which are small, replicable units that spread incrementally on short replacement cycles (Wilson et al., 2020). Within EII, several structural features reinforce one another: pronounced economies of scale encourage long investment cycles (asset lifetimes of over 40 years), which inter alia reinforce brownfield dominance and, in turn, raise the hurdle for the disruptive innovation needed for deep decarbonisation (Wesseling et al., 2017). Decades of co-evolution with regional and unionised labour markets, suppliers, and political economies have embedded these features institutionally, creating carbon lock-in: a path-dependent techno-institutional complex creating increasing returns to the incumbent configuration (Unruh, 2000; Seto et al., 2016).

Cutting EII emissions therefore requires coordinated change across three interacting levels: the coupled processes themselves, the firms that invest in them, and the surrounding markets and infrastructure (Davis et al., 2018). At each level a transition can stall at a transition bottleneck, which we define as a constraint or coupled cluster of constraints held in place by reinforcing inertia (Table 1). Figure 1 shows how these characteristics distinguish EII from power generation at all three levels.

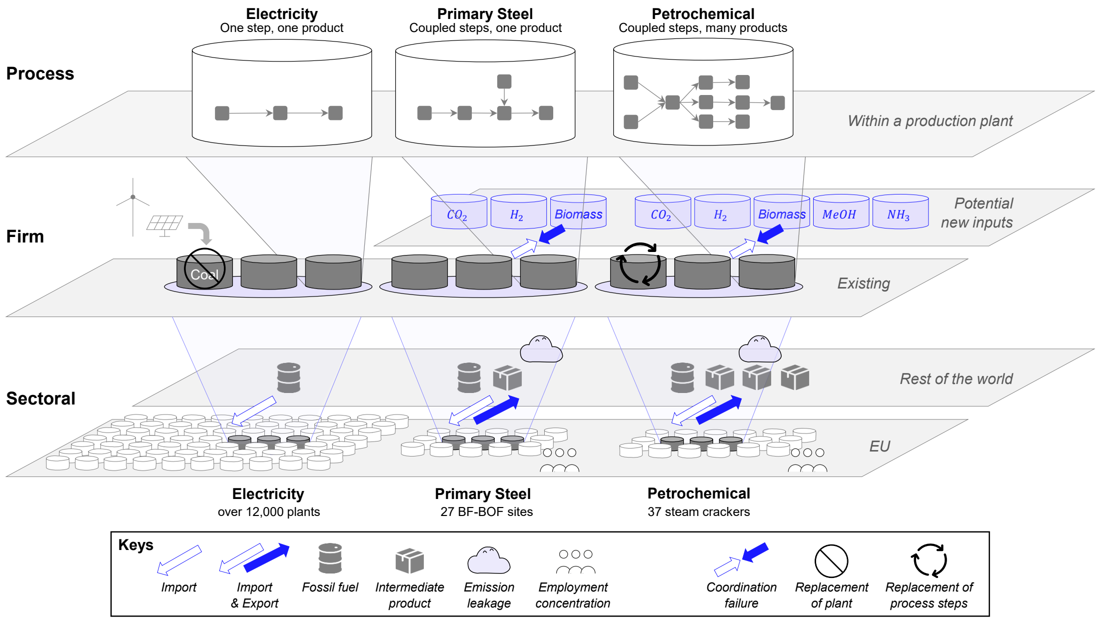

Figure 1: Structural barriers to decarbonisation intensify from power to primary steel and petrochemicals, and compound across the process, firm, and sector levels. Columns show the three sectors, using power as the reference sector for comparison with primary steel and petrochemicals, and rows show the three levels, from sector to firm and process level. **At the sector level**, power is generated across over 12,000 largely non-traded utility plants with a dispersed workforce, and it faces neither import competition nor a carbon leakage risk (Gotzens et al., 2019). Relative to this baseline, primary steel and petrochemicals are produced at significantly fewer sites, around 27 integrated BF-BOF plants and 37 steam cracker plants (Eurofer, 2019; Europe-Petrochemicals, 2026). Both are globally traded commodities, with emissions arising at multiple stages across their intermediate products, which creates risks of emission leakage. The two industries differ in the form of that exposure, since steel imports amount to close to 29% of European consumption whereas petrochemicals run a trade surplus of 47.3 billion euro, and employment is regionally concentrated in both, at around 300,000 direct jobs in steel and for petrochemical production 1.2 million jobs across the 150 chemical parks (Eurofer, 2026; Cefic, 2025), rather than dispersed as in power. **At the firm level**, the low-carbon transition in power is continuing, since renewables are cost-competitive and deploying at scale, with grid expansion being one of the main remaining constraints. For primary steel and petrochemicals, the analogous shift from the incumbent plant to a low-carbon input is instead obstructed. This illustrates a coordination failure: no producer is willing to commit before reliable supplies and demand are secured, and no supplier is willing to commit before such demand is in place. In addition, the potential hydrogen and carbon dioxide networks that this new input relies on have yet to be developed. The low-carbon source differs between the two industries, since steel could depend on hydrogen input whereas petrochemicals depend on a coupled set of methanol, ammonia and carbon inputs. **At the process level**, the electricity sector converts an energy input into a single homogeneous product. Primary steel passes ore together with a carbon reductant through coupled stages to one standardised commodity, and petrochemicals convert carbon supplied as a feedstock rather than only as a fuel, routing it through a cracker into a branched and coupled slate of products. Reading the three sectors in order therefore moves from one output, to coupled stages yielding one product, to a branched slate.
Data refer to the EU-27, or to Europe where the underlying data are reported at that scale. Underlying data and full references are provided in Supplementary Table S1.

The process-level constraint is product and process heterogeneity. EII spans many distinct products, each made in a specialised plant whose process steps are tightly coupled (Bataille et al., 2018; Wesseling et al., 2017). In petrochemicals, where carbon is a feedstock, decarbonisation means defossilisation, replacing fossil carbon with non-fossil sources (Schneider et al., 2025). Here the low-carbon options are highly branched and interdependent across the integrated cluster (Janipour et al., 2020).

Table 1
Transition bottlenecks at three levels in the primary steel and petrochemical sectors (not exhaustive).
BF, blast furnace; BOF, basic oxygen furnace; BF-BOF, integrated blast-furnace/basic-oxygen-furnace route; EAF, electric arc furnace; DR, direct reduction; DRI, direct-reduced iron; H_2-DRI, hydrogen-based direct reduction; FOAK, first-of-a-kind; CBAM, Carbon Border Adjustment Mechanism.

Level	Primary steel	Petrochemicals
Process	**Ore quality.** Hydrogen-based DRI prefers DR-grade ore (≥67% Fe); only 4% of seaborne supply qualifies (Devlin et al., 2023). Because gangue is inert to hydrogen and the solid-state shaft cannot slag it off as the blast furnace does, ordinary ore carries impurities into the EAF, loses iron to slag, and forces ore beneficiation or an added smelting furnace (Devlin et al., 2023; Kim et al., 2025). **Residual carbon.** Even hydrogen-based steel production needs a carbon source for EAF carburisation, and the route is inseparable from hydrogen production, transport, and storage that does not yet exist (Vogl et al., 2018; Wesseling et al., 2017). **Scrap availability and quality.** The BOF already charges 15–25% scrap (IEA, 2020), so raising that share is a short-term abatement lever. However, scrap is finite (Pauliuk et al., 2013), and every extra tonne used in the primary route is one fewer available to the secondary route. End-of-life scrap also carries tramp elements, above all copper, that cannot be removed once melted, capping secondary-steel quality and how far it can displace primary (Daehn et al., 2017; Wagner et al., 2026).	**Coupled product slate.** Conventional crackers co-produce multiple outlet streams (ethylene, propylene, C4s, aromatics, etc.) and the integrated site is built and optimised around that joint output (IEA, 2018). Defossilised routes, such as based on methanol or biomass, usually target a narrow set of molecules, so they cannot be dropped in one-for-one: Replacing a cracker with one of these processes might cause a ripple effect through to the downstream units. The rebuild reconfigures the whole site, not a single unit **Carbon as feedstock.** Fossil carbon is feedstock, not just fuel, so electrification alone cannot abate; a non-fossil carbon source (biomass, captured CO_2 or recycled plastic) is unavoidable. Routing olefins and aromatics through methanol alone would imply a roughly 25-fold rise in methanol supply plus large volumes of non-fossil CO_2 (Mayer et al., 2025).
Firm	**FOAK under coordination failure.** First hydrogen-DRI plants carry a large FOAK premium (+73% per tonne of reduced iron); no producer commits before low-cost hydrogen is assured, and none supplies hydrogen before demand is (Bataille et al., 2024; Seto et al., 2016). **Relocation and portfolio allocation.** Because low-carbon cost tracks local renewable supply, the cost-minimal move can be to relocate the first (sponge-iron) step abroad rather than retrofit in place (Verpoort et al., 2024). Firms operating both BF-BOF and EAF assets manage this as a portfolio, siting FOAK plants in regions with the strongest policy incentives (Bachorz et al., 2026), while the incumbent route continues elsewhere.	**Invest, wait, or relocate.** A cracker operator chooses among methanol-to-olefins at FOAK premiums (+34% on an ethanol-to-olefins basis; +106% green ammonia), waiting for competitors to clarify costs, or relocating; the rebuild changes the feedstock, not merely the plant (Bataille et al., 2024; Mercure et al., 2019). **Slow learning.** Complex, customised technologies (CCS, electrolysers, methanol-to-olefins) show systematically lower learning rates than modular technologies (Malhotra and Schmidt, 2020).
Sector	**Trade-exposed politics.** Steel is internationally traded with tight margins and concentrated regional employment (0.3 m direct and up to 1.55 m indirect EU jobs; imports 29% of consumption), the structural conditions for leakage concern and protective policy even where measured ex-post leakage is small (Branger et al., 2016; Eurofer, 2026). **Demand exceeds feasible supply.** Paris-compliant feasible steel supply meets only 58–65% of expected 2050 baseline demand (Watari et al., 2023).	**Sector competition and dynamics.** The European sector is already under acute pressure from feedstock-advantaged production in the US and Middle East and from Chinese overcapacity, which has already materialised in site closures. In this environment of eroding margins and shrinking market share, European producers face an environment where investing in costly, unproven defossilised technology is especially risky. (Cefic, 2025). **Coverage gap.** CBAM covers only ammonia, hydrogen, and fertilisers, leaving most organics and polymers exposed (Cefic, 2025).

The firm-level constraint is coordination failure. The routes capable of deep decarbonisation often involve a new conversion route or a different feedstock rather than an incremental improvement to the existing process, making them often radical and capital-intensive, and they rarely deliver the economic co-benefit, such as energy or materials saving, that would justify the investment regardless of the emissions reduction (Wesseling et al., 2017). Firms cannot justify the lumpy, full-scale investment in a single plant alone (Bataille et al., 2018), and without assured demand for low-carbon products investment stalls (Wesseling et al., 2017). A first-of-a-kind (FOAK) plant faces substantial cost premiums, underscoring that the binding constraint is financial rather than technological (Bataille et al., 2024). A second premium can arise on the financing side, where a borrower faces a risk markup over the benchmark interest rate for borrowers, reflecting the risks specific to the project, the sector and the country together with the capacity of the firm to carry further debt, and a wave of decarbonisation investment potentially raises both the debt of a sector and its cost of capital (Mercure et al., 2019; Egli, 2026). Since this cost cannot be recovered through a product premium, the first mover bears it without market reward, creating a behavioural and institutional lock-in in addition to the financial one (Dobrev and Gotsopoulos, 2010; Zhang et al., 2022).

The sector-level constraint is the political economy of trade exposure. Steel and bulk chemicals are traded globally and compete largely on price, which leaves them exposed to carbon leakage, the prospect that climate costs imposed in one jurisdiction shift production and its emissions to competitors that face no such costs. Governments protect these industries to secure their supply, the local employment they sustain, and the regional economies built around them, and it is this political economy of protection that shapes the transition (European Commission, 2024).

The three levels can also reinforce one another. A steel producer cannot commit to hydrogen direct reduction until the new inputs it depends on are in place. This requires coordination with new actors, regulatory approval, and new certification. If these are not all assured at the point of decision a firm potentially defers. That deferral bolsters the sector-wide case for protective measures that safeguard competitiveness and jobs while the transition stalls, and those measures in turn entrench the existing production route. Where constraints couple in this way, difficulty becomes a property of the whole configuration rather than of any single constraint. This extends the horizontal co-evolution of lock-in types examined by Seto et al. (2016) into a vertical dimension, and mirrors the clustered, sunk-cost, and policy-inconsistent lock-in observed in chemicals by Janipour et al. (2020).

3. Where optimisation fits, and where it stops

ESOMs address a well-defined optimisation problem: Given a set of technologies, their costs, and relevant constraints, what is the least expensive system that meets demand and emission targets? Bottom-up, technology-rich frameworks such as PyPSA-Eur, TIMES, and OSeMOSYS compute this as a least-cost optimisation of the energy system (Hörsch et al., 2018; Luxembourg et al., 2025; Howells et al., 2011). IAMs, such as REMIND, MESSAGEix, GCAM, widen the boundary to the economy, land use, and climate, some extending the same optimising logic and others clearing markets across sectors (Supplementary Table S2). In their dominant formulations, both families are normative instruments, specifying what a planner would choose rather than what heterogeneous firms will build (Mercure et al., 2016). Table 2 locates where ESOMs and IAMs cease to represent each level.

System-level optimisation is strongest at the process level. A technology-detailed framework decomposes production into discrete process steps, each with specified inputs, outputs, and emissions, resolves linear feedbacks between energy carriers and conversion processes, and can capture the lumpy, non-divisible character of EII through mixed-integer formulations, though the integer constraints are costly and often relaxed for tractability (DeCarolis et al., 2017). Taking the social-planner view, it returns a system-wide least-cost configuration and a marginal abatement cost curve derived from the whole system, which keeps the baseline consistent and captures how measures interact (Kesicki and Ekins, 2012).

The firm level falls outside the objective current frameworks optimise. A least-cost planner is not a population of profit-maximising firms, each optimising a portfolio of plants across jurisdictions (Mercure et al., 2016; DeCarolis et al., 2017), so the firm-level bottlenecks do not surface. This feature stems from current least-cost formulation rather than of optimisation as such, since complementarity formulation impose the optimality conditions of each producer under common market-clearing conditions. The boundary is a modelling choice rather than a limit of optimisation, since game-theoretic methods can handle the firm level. It binds hardest in EII, where only a small number of plants and firms drive the transition, and IAMs inherit the same abstraction through representative agents (Baumstark et al., 2021; Calvin et al., 2019).

The sector level enters only in reduced form. Service demands are often set exogenously by scenario, and competition enters as import bounds, trade prices, or leakage coefficients; more elaborate game-theoretic models add price-based regional competition though these remain idealised. For EII, the drivers behind protective policy, security of supply and regional employment lie outside the objective, demand and competition enter as fixed inputs, and welfare is absent from ESOMs and aggregated to a representative consumer in general-equilibrium IAMs, so none of the three co-evolves with the transition. Some IAMs add macroeconomic and, in general-equilibrium versions, trade feedback, but material demand remains growth-driven and trade stays stylised, so the same political-economy drivers remain unrepresented (Pehl et al., 2024; Keppo et al., 2021).

Table 2
Levels at which energy system optimisation models (ESOMs) and integrated assessment models (IAMs) reach their respective limits.

Level	Where ESOM stops	Where IAM stops
Process	Strongest domain: resolves process steps, heat integration, and emissions and returns a least-cost configuration. But each technology is a fixed input–output (Leontief) process and each commodity a homogeneous carrier (Howells et al., 2011; Luxembourg et al., 2025), so ore-grade heterogeneity, the gangue chemistry, and the carbon-in-product requirement cannot be encoded (Bataille et al., 2018).	Coarser still: steel and chemicals enter as aggregated subsectors with stylised processes and material demand driven by economic growth, not plant-level routes (Pauliuk et al., 2017; Edelenbosch et al., 2017). Recent modules add explicit steel and chemical subsectors (Pehl et al., 2024), but resolution stays well above the plant.
Firm	No firm in it: a single least-cost optimiser with a uniform discount rate and perfect foresight has no profit-and-loss, financing, or strategic behaviour, so firm heterogeneity, the FOAK risk premium, strategic deferral, and chicken-and-egg coordination cannot surface (Mercure et al., 2016; DeCarolis et al., 2017).	Representative agents throughout: whether optimal-growth or energy-system optimisation under perfect foresight (REMIND, MESSAGEix) or recursive market clearing (GCAM, IMAGE), none represents heterogeneous firms, balance sheets, financing risk, or first-mover penalties (Baumstark et al., 2021; Krey et al., 2020; Huppmann et al., 2019; Calvin et al., 2019).
Sector	Service demands are often set by scenario, and competition enters only as exogenous import bounds or trade prices. Outside the objective lie both the security and employment drivers behind protective policy and the risk that the zero-emission inputs the net-zero routes require, namely renewable electricity, green hydrogen, and CO_2 transport and storage, cannot be supplied at the scale the assumed demand implies (Watari et al., 2023).	Adds macroeconomic and, in general-equilibrium variants, trade feedback, but material demand stays largely exogenous or growth-driven and trade is stylised (Armington), so political-economy drivers remain outside the objective (Pehl et al., 2024; Keppo et al., 2021).

These boundaries compound across levels and are structural. The planner assumption eliminates firm-level heterogeneity, so the FOAK risk premium, strategic deferral, and the coordination failure cannot arise as behaviour within the least-cost formulation. The foresight assumption compounds this, since perfect foresight understates the cost of the staged decisions firms actually face, while recursive-dynamic formulations trade that bias for one rooted in limited foresight (Fuso Nerini et al., 2017; Keppo and Strubegger, 2010). These are structural rather than parametric limitations, and they create the need for a firm-level, non-equilibrium complement.

4. Modelling needs for hard-to-transition sectors

There is no single modelling family addressing bottlenecks at all three levels, and the appropriate response is not a universal model but a conscious mapping between the model and the question it must answer (Hepburn et al., 2025; Mercure et al., 2016). Structural uncertainty is smaller at the process level, which optimisation resolves well, and larger at the firm and sector levels, where heterogeneity, coordination, and competition are absent by construction.

At the process level the existing tools are adequate. Technology-rich optimisation captures process steps, heat integration, and lumpy investment, and is most effectively paired with material-flow models that capture the product heterogeneity, stock turnover, and scrap dynamics a demand-driven optimiser omits (Pauliuk et al., 2017; Pehl et al., 2024); open dynamic material-flow tools are available here (Dürrwächter et al., 2026). For steel this layer must resolve the composition of scrap and not only its quantity, which stock-based accounting rarely does (Daehn et al., 2017; Wagner et al., 2026). A cost-optimal pathway does not necessarily mirror the transition that actually occurs, so this layer should be viewed as an essential input rather than as a forecast (Trutnevyte, 2016).

The firm level is the least served bottleneck. Three model families each address one aspect of it. Evolutionary diffusion models capture technology substitution through replicator dynamics, generating the S-curves and path dependence that optimisation assumes exogenously (Mercure et al., 2019). Real-options analysis prices the capital-allocation decision, showing how uncertainty raises the hurdle rate and rewards deferral (Löfgren et al., 2008; Haas et al., 2023). Game theory recasts the first-mover problem as a coordination game, though solving for equilibrium becomes intractable as heterogeneous firms multiply (Ruiz et al., 2014; Zhang et al., 2022).

Agent-based models (ABM) provide the missing firm level. Rather than substituting for these tools, an ABM provides an architecture that embeds their mechanisms as firm-level decision rules. Heterogeneous firms with balance sheets, financing constraints, and adoption rules then generate investment timing, deferral, and lock-in as emergent outcomes rather than assumptions (Lamperti et al., 2018; Reissl et al., 2025), and the agent-based energy system model MUSE shows this is possible without sacrificing the technological detail of an ESOM (Giarola et al., 2022). This gain converts structural uncertainty into parametric uncertainty, because behavioural rules must be calibrated against sparse firm-level data and different rule sets can reproduce the same aggregate path (Lamperti et al., 2018). The appropriate standard therefore becomes robustness across parameterisations rather than a single calibrated fit (Haas et al., 2023). Robustness could be assessed by sampling the parameter space, for example with Monte Carlo ensembles, while calibration with sparse data could rely on Bayesian methods that yield parameter distributions rather than point estimates.

Sector level effects require model coupling. Trade exposure, leakage, asymmetries in competitor routes, and the employment and regional impacts of plant-level decisions are increasingly addressed via model coupling. Soft-linking a diffusion or optimisation framework to a macro-econometric model translates investment into output and employment, as in the E3ME-FTT Steel coupling (Vercoulen et al., 2023; Mercure et al., 2018), while macroeconomic ABMs reveal the distributional and stability consequences a single system-cost objective cannot (Wieners et al., 2026; Lamperti et al., 2020). Hard-linked energy-economy models such as IMACLIM-R solve the technology and macro layers as one system with shared variables, at the cost of aggregating the technology detail that a soft-linked chain preserves (Sassi et al., 2010).

Shared inputs create cross-sector learning curves. A further channel runs across sector boundaries, since steel, petrochemicals, and adjacent sectors such as shipping increasingly draw on the same emerging inputs, potentially low-carbon hydrogen, methanol, ammonia, and shared CO_2 infrastructure, whose unit costs fall with cumulative deployment across all uses. Demand in one sector therefore cheapens adoption in the others through a shared learning curve. Capturing this requires endogenous learning pooled across the sectors using these inputs (Behrens et al., 2024; Pasqualino et al., 2024; Bataille et al., 2025), with the caveat that global learning rates are easily overstated for complex, customised technologies (Malhotra and Schmidt, 2020).

The answer is a linked architecture, not a new model class. At the process level, optimisation defines the least-cost frontier within the material constraints that flow analysis supplies, and relaxing perfect foresight through myopic or rolling-horizon formulations better reflects staged decisions firms face (Keppo and Strubegger, 2010; Fuso Nerini et al., 2017; Ruiz Manuel et al., 2026). An agent-based layer with embedded diffusion, option, and strategic rules tests whether heterogeneous firms would move along the frontier, and macro coupling carries the consequences into trade and employment. The linking should run in both directions. Where the firm layer reveals delayed adoption or financing premiums, these re-enter the optimisation as revised availability dates and adjusted discount rates, so the frontier is corrected iteratively (Trutnevyte, 2016; Keppo et al., 2026). Such a hybrid mixes prescriptive and descriptive paradigms, so the linked system requires an explicit interpretation stage of its own (Keppo et al., 2026). For steel each layer exists and the task is integration, building on FTT:Steel and its macro coupling (Vercoulen et al., 2023). For petrochemicals the firm layer is largely absent, and a heterogeneous-firm investment model over coupled feedstock routes is the clearest gap.

5. Concluding Remarks

This paper is, to the authors' knowledge, the first to treat the difficulty of decarbonising energy-intensive industry as a property of the transition pathway rather than of the emission, and to match that difficulty to the models needed to represent it. The argument (i) distinguished hard-to-abate from hard-to-transition, (ii) located the self-reinforcing inertia that stalls deployment at three interacting levels, and (iii) showed that dominant optimisation frameworks resolve the process level but leave unrepresented the firm level and the way global competition reshapes domestic production. What the three levels add, beyond a taxonomy, is that they reinforce one another vertically as well as horizontally, so a transition stalls at identifiable bottlenecks rather than failing uniformly, and this structural rather than parametric feature of the single-planner formulation creates the need for a firm-level, non-equilibrium complement. From this it follows that hard-to-transition sectors require not a new model class but a linked architecture, within which ABMs could host the firm-level mechanisms that optimisation omits and learning pooled across sectors is made endogenous. The transition bottleneck is where these threads converge, the point at which abatement options and carbon lock-in mechanisms meet, and its structure indicates both the class of instrument that could relieve it and the class of model that could represent it.

Reframing these emissions as hard-to-transition also clarifies why the residual category cannot simply be assumed away. Net-zero targets permit a residual of emissions that abatement is assumed unable to eliminate, to be balanced by CDR (Buck et al., 2023). Yet removal capacity is finite and already over-subscribed in net-zero pledges (Dooley et al., 2024; Edwards et al., 2026), and removals committed to offsetting residual emissions cannot also deliver the net-negative drawdown needed to reverse an overshoot (Schleussner et al., 2024). Reserving that scarce capacity for genuinely irreducible emissions therefore depends on not misclassifying as residual those emissions that are merely hard-to-transition, where a viable option exists but has not been deployed.

The linked architecture set out above makes tractable a question that current frameworks close off, namely whether a proposed instrument engages the coordination failure that actually binds a given transition, or merely raises the cost of the incumbent route without moving the alternative into place. Which failure binds is itself a finding of the architecture, whether the producer–buyer market for near-zero material has yet to form, whether the hydrogen and CO_2 networks on which a plant depends are sequenced too late, or whether a FOAK investment carries a financing premium producers will not underwrite. This is the challenge European industrial policy now confronts, as competitiveness, security of supply, and decarbonisation are pursued together (European Commission, 2024). Answering them is within closer reach for steel, where a stylised firm-level modelling layer already exists to build on, than for petrochemicals, where the coupled feedstock chemistry means that layer must still be constructed. Developing and linking such models, with an explicit account of what each component can and cannot answer, is the contribution this paper asks the modelling community to take forward.

CRediT authorship contribution statement

Lukas Schirren: Conceptualisation, Methodology, Investigation, Writing – original draft, Visualisation, Writing – review & editing, Project administration. **Leander Müller:** Conceptualisation, Investigation, Validation, Writing – review & editing. **Alaa Al Khourdajie:** Conceptualisation, Methodology, Writing – review & editing. **Lukas Gast:** Investigation, Validation, Writing – review & editing. **Florian Egli:** Conceptualisation, Supervision, Writing – review & editing. **Adam Hawkes:** Conceptualisation, Supervision, Investigation, Validation, Writing – review & editing.

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Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used Claude for English-language editing and clarity improvement, including phrasing refinement and paragraph-level concision. All conceptual development, analytical design, data analysis, and final editorial decisions were carried out by the authors, who reviewed all AI-assisted text and take full responsibility for the content of the article.

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Supplementary Material

Table S1

Structural characteristics of two EU energy-intensive industries contrasted with two reference sectors. The table provides the evidence base for Figure 1. Energy-intensive industries: primary steel and petrochemicals. Reference sectors: heavy-duty road transport and power. Numbers refer to the EU-27 unless marked (Europe); trade- and output-related values are specific to the year stated. Abbreviations: BF–BOF, blast-furnace/basic-oxygen-furnace route; EAF, electric arc furnace; DRI, direct-reduced iron; ETS, EU Emissions Trading System; CBAM, Carbon Border Adjustment Mechanism.

Dimension	Transport	Power	Primary Steel	Petrochemical
Process complexity	Low; on-vehicle combustion, decarbonisation with battery/fuel switch (ACEA, 2025)	Low; homogeneous input and output (Ember, 2026)	High; multi-stage ore reduction (Wesseling et al., 2017)	Very high; multi-stage, multi-input multi-output processes (IEA, 2018; Schneider et al., 2025)
Product heterogeneity	NA. Heterogeneous service through vehicle classes (ACEA, 2025)	Homogeneous commodity (electricity); differs only by carbon intensity (Ember, 2026)	Standardised commodity in many grades and forms (long, flat, coated)	Heterogeneous; olefins, aromatics, plastics (Wesseling et al., 2017)
Number of plants	Very high. Distributed fleet, 6.9 m trucks (Europe) (ACEA, 2025)	High. 12,262 utility-size plants (above 10 MW) (Europe) (Gotzens et al., 2019)	Low. 27 integrated BF-BOF sites, 126 electric arc furnaces (Eurofer, 2019)	Low. 37 steam crackers, declining; 150 chemical parks (Europe-Petrochemicals, 2026; Cefic, 2025)
Lifetime	10-15 yr; fleet average 14 yr (ACEA, 2025; Boehle and Callioni, 2025)	Coal 40-50yr, gas 30 yr (Seto et al., 2016), solar and wind 25-30 yr (Ziegler et al., 2018)	BF-BOF asset life 35-40 yr (Seto et al., 2016; Algers and Åhman, 2024); without reinvestment median is 17 yr (Vogl et al., 2021)	Asset life 40+ yr; mainly brownfield extension (Wesseling et al., 2017)
Employment concentration	NA. Dispersed across operators/drivers EU-wide	Low. Dispersed across sites and grid	High; regional clusters, 298k direct / up to 1.55 m indirect jobs (Eurofer, 2026)	High; 1.2 m across 150 chemical parks (Cefic, 2025)
Trade of intermediaries	NA. Non-traded service	Low. Largely non-traded over distance. Transmission only	High. Globally traded; imports 29% of EU consumption (Q3 2025) (Eurofer, 2026)	High. Globally traded; EU chem. trade surplus €47.3 bn (2024) (Cefic, 2025)
Competitive Pressure	NA	Electricity production fell by 0.5% from 2021 to 2023 (Eurostat, 2026), but is set to increase significantly (IEA, 2026)	Basic metals output fell 10% from 2021 to 2023 (European Commission, 2024)	Chemicals output fell 15% from 2021 to 2023 (European Commission, 2024)
Policy coverage (ETS, CBAM)	Road transport priced under ETS2 from 2027; outside CBAM (EU, 2023)	EU ETS; imported electricity within CBAM scope	EU ETS (free allowances phased out to 2034); CBAM good, charges from 2026 (Johnson et al., 2025)	EU ETS; CBAM covers H_2, ammonia and fertilisers, not organics and polymers (Johnson et al., 2025)
Feedstock dependence	Energy only	Energy only	Coal as reducing agent	Defossilisation required, fossil fuel is a feedstock (IEA, 2018)
Infrastructure dependence	Charging network gap (ACEA, 2025)	Grid expansion and flexibility (European Commission, 2024)	H_2, CO_2 transport & storage, renewables (Wu et al., 2025)	Renewable H_2 + CO_2 feedstock at scale (Wesseling et al., 2017)

Table S2
Objectives, system boundaries, and temporal foresight of energy system optimisation models (ESOM) and integrated assessment models (IAM).

Model	Objective	System boundary	Foresight
ESOMs			
PyPSA-Eur (Hörsch et al., 2018)	Least-cost optimisation	Energy system (power, sector-coupled)	Overnight, myopic, or perfect foresight
TIMES (Luxembourg et al., 2025)	Least-cost optimisation	Energy system	Perfect foresight or myopic / rolling-horizon
OSeMOSYS (Howells et al., 2011)	Least-cost optimisation	Energy system	Perfect foresight or myopic
IAMs			
REMIND (Baumstark et al., 2021)	Intertemporal welfare maximisation (Ramsey growth)	Whole economy (general equilibrium)	Perfect foresight
WITCH (Bosetti et al., 2006)	Intertemporal welfare maximisation with a non-cooperative game among world regions	Whole economy (general equilibrium)	Perfect foresight
MESSAGEix (Krey et al., 2020; Huppmann et al., 2019)	Least-cost energy-system optimisation, coupled to a stylised macroeconomic module (MACRO)	Energy system plus stylised macro feedback	Perfect foresight or recursive (myopic)
GCAM (Calvin et al., 2019)	Market clearing via logit share allocation (not cost minimisation)	Energy, land, water, climate (partial equilibrium)	Recursive (myopic)
IMAGE	Recursive market clearing (partial equilibrium)	Energy, land, water, climate	Recursive (myopic)