# CARBON AS A CAPITAL RISK FACTOR

## A DISTRIBUTION-BASED FRAMEWORK FOR STRATEGIC INVESTMENT DECISIONS UNDER THE EU EMISSIONS TRADING SYSTEM (EU ETS)

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## EXECUTIVE SUMMARY

Carbon pricing under the EU ETS is evolving from a compliance cost into a structural capital risk factor for long-lived assets — aircraft, industrial facilities, transport infrastructure, energy-intensive equipment.

The relevant uncertainty is no longer whether decarbonisation will occur. The critical uncertainty is how tightening policy architecture translates into operating cost volatility across the asset's economic lifetime.

Unlike a conventional tax, the EU ETS operates as a declining quantity constraint. As allowance supply tightens and historical banking is exhausted, price formation increasingly reflects scarcity mechanics rather than marginal abatement cost alone. This creates the potential for non-linear cost escalation and widening valuation dispersion well before 2050.

This paper presents an actuarial framework that translates climate policy design into probability distributions of future cost exposure.

The model does not produce a single carbon price forecast. It generates distributions across thousands of stochastic policy and market paths, integrating:

- Long-term climate ambition anchored in NGFS scenarios
- Explicit EU ETS cap trajectories
- Endogenous allowance banking and Market Stability Reserve dynamics
- Scarcity-driven price formation
- Short-term energy market interactions.

The output is a distribution of carbon cost exposure from 2025 to 2050, allowing decision-makers to assess not only expected outcomes, but also tail risk, regime shifts, and refinancing-cycle exposure.

Two policy-consistent scenarios illustrate the strategic sensitivity:

### GREEN SCENARIO – CAP REACHES ZERO ~2039

Under current structural assumptions, median EUA prices approach €2,000/t$CO_2$ by 2050. Dispersion widens materially after 2040 as banking flexibility is depleted and scarcity premiums dominate.

### BLUE SCENARIO – CAP EXTENDED LINEARLY TO 2050

Median 2050 prices reduce to approximately €1,600/t$CO_2$, with a flatter trajectory and narrower tail risk. The difference arises from regulatory design choices, not technological assumptions.

Three implications follow for CFOs and investment committees:

1. Carbon cost risk crystallises within standard refinancing and amortisation cycles (2035–2045), not only at the 2050 horizon
2. Valuation dispersion increases as allowance scarcity emerges, creating residual value risk and potential debt-tenor mismatch for carbon-exposed assets
3. Policy architecture becomes a material sensitivity variable in capital allocation, underwriting, and portfolio construction.

The framework is designed as a strategic decision tool. It allows firms, lenders, insurers, and asset owners to quantify policy-induced transition risk under unchanged rules — before those constraints become binding.

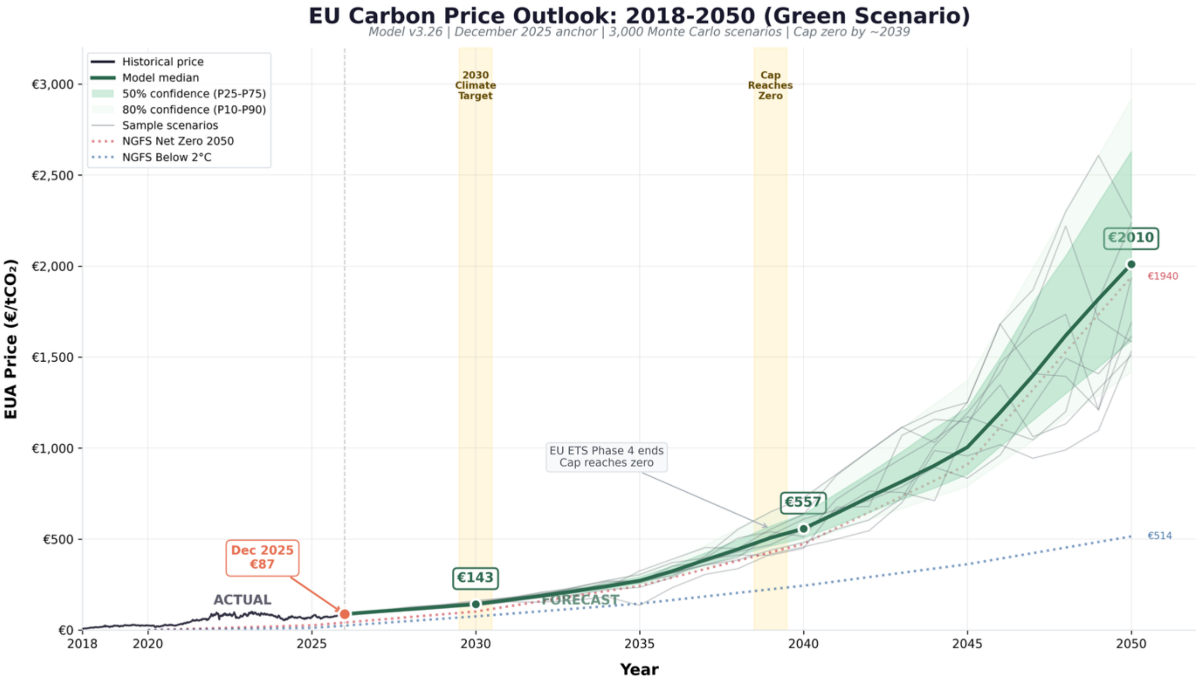
In this sense, the model performs the same function as pension sustainability or sovereign debt projection models: it quantifies the conditional consequences of existing rules and provides a structured basis for capital planning under uncertainty.

Under quantity-constrained systems such as the EU ETS, carbon pricing is no longer merely an environmental variable. It is emerging as a capital risk factor.

The following section illustrates the distribution under the current regulatory trajectory.

## GREEN SCENARIO: EU ETS CARBON PRICE DISTRIBUTION UNDER CURRENT DESIGN

The figure below presents the distribution of future EU carbon prices under the current regulatory architecture of the EU ETS. It integrates market dynamics, regulatory supply mechanics, and evolving policy ambition into a single forward-looking distribution of potential price outcomes between 2026 and 2050.




The solid green line represents the median expected path. The shaded bands represent the central 50% and 80% ranges of possible outcomes. This figure should be interpreted as a distribution of capital exposure, not as a single-point forecast.

Under unchanged structural assumptions:

- The emissions cap reaches zero around 2039
- Allowance banking is progressively depleted
- Scarcity dynamics increasingly dominate price formation.

The widening dispersion after 2040 reflects structural uncertainty in a quantity-constrained system approaching supply exhaustion.

The strategic implication is not confined to the 2050 endpoint. The critical transition occurs in the 2035–2045 window, when carbon cost uncertainty materially increases within standard refinancing and amortisation cycles for long-lived assets.

The sections below explain the structural drivers behind this distribution and their relevance for capital planning.

## MARKET-ANCHORED STARTING POINT

The projection begins from the observed EUA market price on 31 December 2025 (€87/t$CO_2$).

Near-term dynamics are anchored in empirical relationships observed between carbon and energy markets during the 2020–2024 period, including the post-pandemic recovery and the 2022 energy crisis. Carbon prices are modelled as economically linked to fossil fuel markets, reflecting fuel-switching and demand interactions.

This approach ensures that early-year price behaviour reflects how the market has historically adjusted under stress conditions. Over time, however, short-term energy-driven deviations diminish in influence. Beyond the early 2030s, regulatory supply constraints become the dominant structural driver of price formation.

For capital planning purposes, this implies that:

- The near term reflects market co-movement and volatility
- The longer term reflects regulatory design.

## EXPLICIT REGULATORY SUPPLY MECHANICS

The EU ETS operates as a declining quantity constraint rather than as a fixed tax. The model incorporates:

- The statutory annual reduction in the emissions cap
- The Total Number of Allowances in Circulation (TNAC), representing cumulative banking by market participants
- The Market Stability Reserve (MSR), which withdraws allowances when surpluses exceed thresholds and releases limited volumes during scarcity
- Permanent cancellation mechanisms that reduce cumulative supply.

Allowance banking plays a central role in determining long-term price dynamics. As long as substantial banking exists, prices broadly reflect marginal abatement costs. As banking is drawn down, the availability of tradable allowances becomes increasingly binding.

Under the current structural assumptions, the emissions cap reaches zero around 2039. Beyond that point, no new allowances enter the system and market clearing must occur through residual banking and emissions adjustment.

This transition introduces non-linear price behaviour and increasing dispersion.

The widening uncertainty band after 2040 is therefore not a modelling artefact; it is the mechanical consequence of a quantity-constrained market approaching supply exhaustion.

## POLICY EVOLUTION AS A CONTINUOUS VARIABLE

Long-term price levels are anchored to two reference scenarios from the NGFS Phase 5 dataset (GCAM 6.0, EU27 region):

- **NET ZERO 2050,** representing the EU's stated full-ambition pathway consistent with the European Green Deal and climate neutrality objectives.
- **BELOW 2°C,** representing a more moderate global ambition pathway consistent with the Paris Agreement's minimum temperature objective.

The Green Scenario in this paper aligns closely with the Net Zero 2050 pathway by 2050, while the distribution reflects uncertainty in how closely realised policy tracks either trajectory over time. The slight divergence reflects EU-specific scarcity effects within a quantity-constrained regional market.

Rather than selecting a single scenario, the framework treats policy ambition as a continuously evolving variable.

This reflects observed characteristics of climate governance:

- Policy ambition generally tightens over successive political cycles
- Implementation typically progresses incrementally rather than discretely
- Elections, economic cycles, and geopolitical events introduce uncertainty.

Calibration draws on publicly available sources including the IEA World Energy Outlook and Climate Action Tracker assessments, as well as observed policy adjustments since 2015. This approach avoids deterministic scenario selection while preserving the structural consistency embedded in integrated assessment models.

For capital allocators, the result is a distribution that reflects plausible policy evolution rather than a binary choice between predefined pathways.

## FROM STRUCTURE TO DISTRIBUTION

These three structural elements — market anchoring, regulatory supply mechanics, and evolving policy ambition — are combined in a stochastic simulation framework. 3,000 forward paths are generated for the period 2026–2050. Each simulation reflects:

- A plausible policy trajectory
- Energy market interactions
- Emissions response to price changes
- Allowance banking and MSR operations
- Scarcity pricing as supply tightens.

The output is a probability distribution of future carbon prices rather than a single deterministic path. Uncertainty bands widen over time because structural constraints interact with compounding policy and market uncertainty.

This widening dispersion is a central output of the framework and a key input into capital planning.

## STRATEGIC INTERPRETATION FOR CAPITAL PLANNING

Under the Green Scenario:

- The emissions cap reaches zero around 2039
- Median carbon prices approach €2,000/t$CO_2$ by 2050
- Price dispersion increases materially after 2040.

The most relevant feature for capital planning is not the 2050 endpoint, but the structural transition during the 2035–2045 window.

For assets with multi-decade lifetimes, this period often coincides with:

- Refinancing cycles
- Residual value assessments
- Debt tenor extensions
- Strategic reinvestment decisions.

As allowance banking is exhausted, carbon cost uncertainty increases precisely during these capital decision points.

Under quantity-constrained systems, carbon pricing therefore evolves from an operating expense variable into a capital risk factor.

## PRACTICAL APPLICATION IN CAPITAL PLANNING

The framework is intended to support strategic capital allocation rather than operational compliance management. Its primary use is to inform valuation, financing, and risk governance decisions for assets exposed to the EU ETS over multi-decade horizons.

The distributional output allows decision-makers to move beyond single carbon price assumptions and instead incorporate quantified uncertainty into financial analysis.

The principal applications are outlined below.

### PROJECT VALUATION AND NPV SENSITIVITY

Traditional project appraisal typically incorporates a deterministic carbon price path or a small set of scenario stress tests.

The distribution generated by this framework allows carbon costs to be treated as a stochastic input to discounted cash flow (DCF) models.

Instead of assuming a single carbon trajectory, firms may:

- Apply the median path as a central case
- Stress test against upper confidence bands
- Evaluate downside resilience under adverse scarcity conditions
- Quantify the probability that carbon costs exceed defined thresholds within the investment horizon.

This allows carbon exposure to be incorporated into internal hurdle rate assessments, capital budgeting decisions, and portfolio optimisation exercises in a manner consistent with established financial risk management practices.

## RESIDUAL VALUE AND ASSET LIFE ASSUMPTIONS

For long-lived assets, terminal value assumptions often extend into periods where structural carbon scarcity may emerge. Under the Green Scenario, dispersion widens materially during the 2035–2045 window — a period that frequently coincides with:

- Residual value determination
- Mid-life reinvestment decisions
- Lease renewal negotiations
- Asset life extension assessments.

The framework enables residual value analysis to incorporate a distribution of carbon cost outcomes rather than a single extrapolated trend.

For example, in capital-intensive transport sectors such as aviation, higher long-term carbon cost dispersion may translate into:

- Increased uncertainty in aircraft residual values
- Adjustments to leasing rate factors
- Higher risk premia in long-dated lease structures.

More broadly, any asset whose competitiveness depends materially on carbon intensity may experience valuation sensitivity as allowance scarcity approaches.

## DEBT STRUCTURING AND REFINANCING RISK

Carbon cost risk may crystallise within standard refinancing cycles rather than only at the 2050 horizon.

If allowance banking declines materially in the 2030s, cost volatility may increase during periods when:

- Project finance structures are refinanced
- Bonds mature and require rollover
- Covenant headroom is reassessed.

The widening distribution shown in the Green Scenario indicates increasing variance rather than merely increasing mean cost. For lenders and credit committees, variance is as material as expected value.

The framework can therefore support:

- Carbon-adjusted debt service coverage ratio stress testing
- Long-term covenant design
- Risk-weight calibration for carbon-exposed portfolios.

### PORTFOLIO-LEVEL EXPOSURE MAPPING

At a portfolio level, the distribution can be used to:

- Identify concentration of exposure in assets whose economic life overlaps with high-dispersion periods
- Compare carbon intensity across business units or asset classes
- Inform capital reallocation between lower- and higher-exposure segments.

In this context, carbon pricing becomes analogous to interest rate or commodity price risk — a systematic factor that can be quantified and managed rather than assumed away.

### INTEGRATION INTO GOVERNANCE PROCESSES

The framework is not designed to replace scenario analysis required under regulatory disclosure regimes. Rather, it complements existing climate scenario reporting by introducing probabilistic cost distributions into capital planning.

Used appropriately, it can support:

- Investment committee deliberations
- Risk committee oversight
- Strategic planning exercises
- Board-level discussion of long-term exposure under defined regulatory architectures.

## MODEL SCOPE AND LIMITATIONS

The Green and Blue scenarios isolate the impact of alternative cap trajectories while holding other structural parameters constant. In practice, changes in regulatory ambition may also affect:

- The EU-specific premium relative to global carbon prices
- The trajectory of policy progress over time
- Market expectations embedded in energy and carbon price dynamics.

The Blue Scenario therefore models the direct mechanical effect of a less aggressive cap trajectory. It does not incorporate second-order adjustments in policy credibility or market structure that might accompany such a shift.

Accordingly, the results should be interpreted as conditional distributions under specified design assumptions, rather than as comprehensive political economy forecasts.

The framework is designed to quantify exposure under defined regulatory architectures. It does not attempt to model endogenous policy reaction functions.

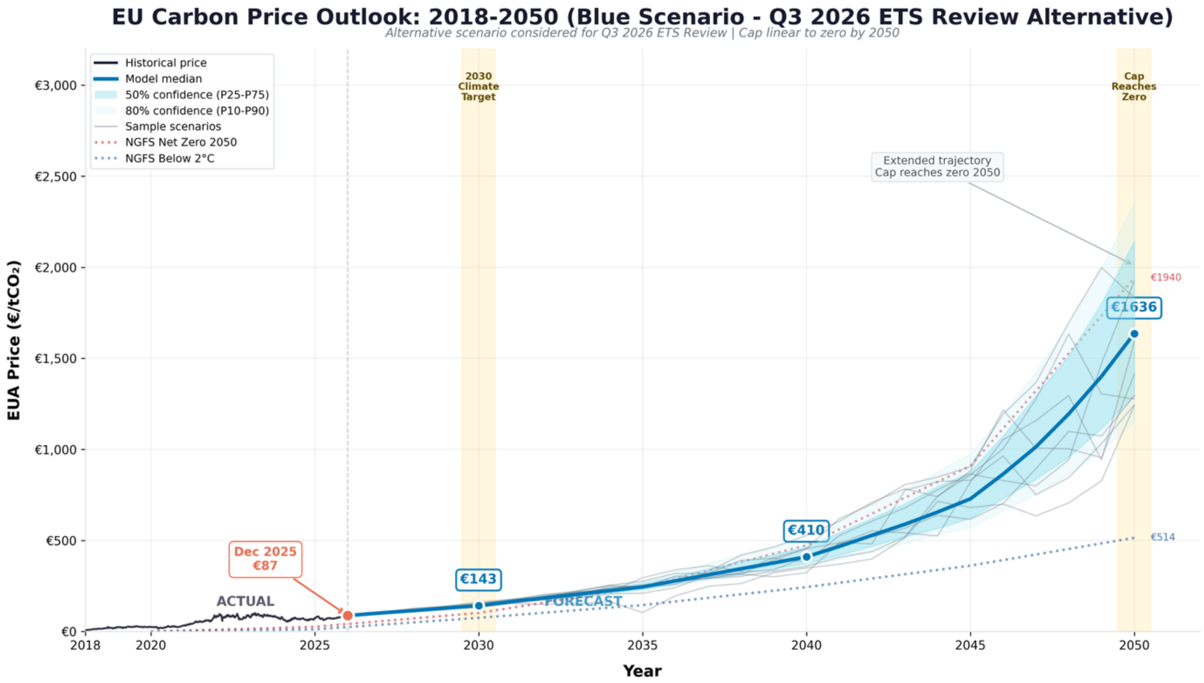
## CONCLUSION

Under a quantity-constrained regulatory regime such as the EU ETS, carbon pricing evolves from a marginal compliance variable into a structural determinant of capital allocation. As allowance supply tightens and banking flexibility diminishes, cost dispersion increases within standard refinancing and reinvestment cycles.

Incorporating probabilistic carbon cost distributions into capital planning allows firms to quantify exposure before constraints become binding. In this context, carbon pricing should be treated not as a distant policy consideration, but as an emerging capital risk factor within long-term investment horizons.

## ANNEX A: ALTERNATIVE POLICY DESIGN SCENARIO (BLUE SCENARIO)

The alternative scenario presented in Annex A illustrates the sensitivity of long-term price distributions to regulatory design adjustments.




In this scenario, the emissions cap declines linearly to zero in 2050 rather than 2039. The resulting distribution shows:

- A flatter trajectory through the 2030s and 2040s
- Lower median prices by 2050 (~€1,600/t$CO_2$)
- Narrower dispersion in later years.

The difference arises from regulatory design rather than technological assumptions. This sensitivity analysis highlights that long-term carbon cost exposure is materially influenced by policy architecture.