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CBAM cost-at-risk 2026–2034: a Monte Carlo simulation with global sensitivity analysis

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ABSTRACT

This study estimates the distribution of the payments due under the EU Carbon Border Adjustment Mechanism (CBAM) on Moroccan goods imported in 2026–2034 and how much of their risk EU allowance (EUA) futures could hedge. A Monte Carlo model applies the definitive-period legal parameters to the 78 CN codes of Moroccan CBAM goods. The certificate price follows the EUA futures curve of 23 October 2026 as a geometric Brownian motion (GBM), a mean-reverting or a two-factor process; the verification share, actual emissions, phase-out path and default-value revision are drawn from stated ranges or fixed on a scenario grid. Group Sobol indices decompose the variance. The mean 2026 payment is EUR 19.1 million, as tonnage fell by almost half in January–August 2026; from 2027, on 2025 volumes, it rises to EUR 122.9 million in 2034, with a 95th percentile of EUR 352.4 million under the GBM and EUR 241.5 million with a three-year half-life. The price explains 86%, 63% or 58–77% (two factors) of the variance of the cumulative payment. Under stated conditions this first-order index equals the variance share removed

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by an ideal average-price hedge. With zero basis, a static hedge with ICE Endex futures listed to December 2032 removes 80% or 55%, and 62% or 29% for 2034 imports; rolling into contracts listed later removes almost the ideal share. Emission data and rules set the level of the payment more than its risk. The results concern the payment due from EU declarants, not its incidence on exporters.

Keywords: *carbon border adjustment mechanism; cost-at-risk; Sobol indices; hedging; Morocco.*

JEL codes: F13; F18; G32; Q54; Q58; C63

1. Introduction

1.1 Research problem, scope and objectives

Since 1 January 2026, importers of cement, iron and steel, aluminium, fertilisers, hydrogen and electricity into the EU must surrender certificates under the Carbon Border Adjustment Mechanism (CBAM), for the first time by 30 September 2027 for goods imported in 2026 (Regulation (EU) 2023/956, Art. 22(1)). What a tonne of goods costs depends on four things: the price of a certificate, the embedded emissions declared, the free-allocation adjustment that mirrors the free allowances still given to EU producers, and the rules that tie them together. In October 2026 none of the four was fixed for the period to 2034. Certificates for goods imported from 2027 are priced at a weekly average of EU allowance (EUA) auction prices, so the price depends on when they are bought (Regulation (EU) 2023/956, Art. 21(1); Implementing Regulation (EU) 2025/2548, Art. 5(1)). Embedded emissions are either verified actual emissions or default values with a mark-up, and the choice is made importer by importer. The free-allocation adjustment falls to zero by 2034 under current law, but a proposal under negotiation would slow its phase-out (European Commission, 2026a), the benchmarks behind it are due to be updated for 2027 imports, and the default values are to be revised by December 2027 (Implementing Regulation (EU) 2025/2621, recital 11). A proposal to extend the CBAM to downstream steel and aluminium products from 2028 was in trilogue (European Commission, 2025a; Agence Europe, 2026).

A point estimate of the CBAM payment therefore says little about the risk it carries. For non-financial firms, the finance literature measures such risk with cash-flow-at-risk, the

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analogue of value-at-risk for operating cash flows (Stein et al., 2001), and explains why they hedge by taxes, contracting costs and investment incentives (Smith & Stulz, 1985) and by the cost of cash shortfalls when external finance is expensive (Froot et al., 1993). The CBAM payment is a product of two uncertain quantities. The price of a certificate is tied to EUA auction prices, for which futures trade on ICE Endex up to the December 2032 contract (ICE Endex, 2026; TradingView, 2026). The number of certificates depends on volumes, on whether emissions are verified and how high they are, and on rules not yet set: the phase-out path, the benchmarks, the default values and the goods covered. Hedging a price when the quantity is uncertain is a classic problem (McKinnon, 1967): production variability can make a hedge of the full expected output too large for a utility-maximising producer (Rolfo, 1980), and optimal hedges depend on the volatilities of prices and quantities and on their correlation (Brown & Toft, 2002).

Morocco is a useful case for measuring this risk. CBAM goods and electricity made up EUR 1,034 million, or 4.1%, of EU imports from Morocco in 2025, and fertilisers 81% of that value; Morocco supplied 64% of the diammonium phosphate (DAP) imported by the EU from outside the Union (authors' calculations from Eurostat, 2026). Existing estimates of what the CBAM costs Moroccan exports are deterministic. Morchid et al. (2024) use an input–output model with 2019 data, and the United Nations Economic and Social Commission for Western Asia applies the 2025 default values at a constant price (Chemingui et al., 2026). None says how wide the range of outcomes is or what drives it.

The wider literature on the CBAM is mostly deterministic as well. Studies of its incidence on trade partners use trade-network or multi-regional input–output models at given carbon prices (Beaufils et al., 2023; Magacho et al., 2024; Zhong & Pei, 2022), and reviews of border adjustments focus on leakage and competitiveness (Böhringer et al., 2022; Branger & Quirion, 2014). Stochastic simulations have appeared only recently. Paek and Kim (2026) simulate EUA prices as a geometric Brownian motion to value the one-week predictability of the certificate price for the timing of purchases. Two working papers propagate EU ETS price uncertainty. Faloore (2026) studies four exporting countries, Nigeria, South Africa, Brazil and Chile, and reports for South Africa the median and interquartile range of the cumulative CBAM burden over 600 price paths; Bidinot et al. (2026) cost the phase-out of free allocation for EU installations under a mean-reverting

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jump-diffusion price. To our knowledge, none treats the non-price parameters of the CBAM as uncertain or separates the part of the risk that listed futures can hedge from the part they cannot.

This paper does both for Morocco. We simulate the payment due on the 78 CN codes of CBAM goods imported by the EU from Morocco in 2025, for each import year from 2026 to 2034, with the legal parameters of the definitive period. We separate two kinds of uncertain inputs. The certificate price and import volumes are market risks, which we calibrate on data. The share of imports declared with verified emissions, the ratio of actual to default emissions, the phase-out path and a revision of the default values are known to producers or will be set by regulators, but are unknown to us; we draw them from stated ranges for a global sensitivity analysis and also fix them on a grid of scenarios. We report the distribution of the payment and its 95% cost-at-risk under a geometric Brownian motion (a random walk in the log price) and a mean-reverting price, with a two-factor price as a variant, group Sobol indices (Saltelli et al., 2010; Sobol', 2001) and the effect of an ideal hedge and of hedges with listed futures, static or rolled.

The paper makes three contributions. First, it gives a legally detailed stochastic model of the CBAM payment for one exporting country, which adds the non-price uncertainties of the definitive period to price-only simulations. Second, it shows that, under stated conditions (price independent of quantity, a payment linear in the price and an instrument that pays the average price at which certificates are bought), the first-order and total Sobol indices of the price group equal the shares of variance removed by a minimum-variance hedge and by fixing the price of the certificates actually needed. This restates the classic result in the terms of global sensitivity analysis; we then measure how far a static hedge with the contracts listed today, and one rolled into contracts listed later, fall short of it. Third, it describes how the composition of the risk changes from 2026 to 2034, conditional on the price model and the input distributions. The mean 2026 payment is EUR 19.1 million on the imports observed in January–August. From 2027 the price explains most of the variance of the payment, 86% of that of the cumulative payment under a geometric Brownian motion and 63% with a three-year half-life of mean reversion, and EUA futures can hedge most of it, if a hedge placed today is rolled into contracts listed later.

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1.2 Regulatory background: how the payment is set and when it is priced

An authorised CBAM declarant surrenders, for each tonne of goods, certificates equal to its specific embedded emissions minus the specific embedded free allocation, net of any carbon price paid abroad, with a floor at zero (European Commission, 2026b, s. 2.4.2). Embedded emissions are determined either from verified actual emissions or by reference to default values (Regulation (EU) 2023/956, Art. 7(2)). The default values are set by good and country of origin; countries without a value for a good take the value for "Other countries and territories" (Implementing Regulation (EU) 2025/2621, Annex I, as corrected by Implementing Regulation (EU) 2026/1740). They carry a mark-up of 1% for fertilisers from 2026 and, for cement, iron and steel, aluminium and hydrogen, of 10% in 2026, 20% in 2027 and 30% from 2028 (Implementing Regulation (EU) 2026/1740, Annex I). The free-allocation adjustment is the product of the CBAM factor, the cross-sectoral correction factor (CSCF) and a benchmark; for goods declared with default values it uses the Column B benchmark of the production route attached to the default value (Implementing Regulation (EU) 2025/2620, Art. 3 and Annex). The CBAM factor is 97.5% in 2026 and falls to 95, 90, 77.5, 51.5, 39, 26.5 and 14% in 2027–2033 and to zero from 2034 (Directive 2003/87/EC, Art. 10a(1a)); the CSCF is 100% for 2026–2030 (Commission Implementing Decision (EU) 2026/1862), and no value has been set for later years.

The price rules differ between 2026 and later years. For emissions declared in respect of 2026, the price is "the quarterly average of the closing prices of EU ETS allowances on the auction platform … of the quarter of importation of the goods" (Regulation (EU) 2023/956, Art. 21(1a), inserted by Regulation (EU) 2025/2083). From 2027 it is the average of those prices "for each calendar week" (Art. 21(1)). The implementing act defines both as volume-weighted averages of auction clearing prices, excluding cancelled auctions (Implementing Regulation (EU) 2025/2548, Arts 1 and 5). The quarterly prices for 2026 were EUR 75.36, 75.28 and 82.32 for the first three quarters; the fourth was due on 4 January 2027 (European Commission, 2026c). Certificates are sold on a common central platform from 1 February 2027 at the price calculated under Article 21 (Arts 20(1) and 20(4)): the quarterly price of the quarter of importation for 2026 imports and the weekly price for later imports. From 2027, a declarant must hold at the end of each quarter certificates for at least 50% of the embedded emissions of its imports since the start of the

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year, net of the free-allocation adjustment (Art. 22(2)), and must surrender the rest by 30 September of the following year (Art. 22(1)). Certificates can be sold back at their purchase price only within limits (Art. 23). Two consequences follow for risk. The price of a 2026 import is known once its quarter is over, and on 23 October 2026 only the fourth-quarter price was still unknown. For imports from 2027, the price paid depends on when the declarant buys, between the first quarter-end of the import year and September of the next, so the timing of purchases is itself a hedging choice.

A carbon price paid in the country of production can be deducted, but only where embedded emissions are determined from actual emissions; for goods declared with default values, a reduction can be claimed "only by a reference to yearly default carbon prices", which the Commission "may" set from 2027 (Regulation (EU) 2023/956, Art. 9(1) and 9(4)). The implementing act on this deduction had not been adopted by 21 October 2026 (European Commission, 2026d). Morocco had no carbon price in October 2026. A carbon tax announced with the 2026 finance bill was left until its modalities were set (Le360, 2025); the Finance Law for 2026 contains none (Royaume du Maroc, 2025), nor do the fiscal measures of the 2027 finance bill presented in October 2026 (La Quotidienne, 2026). The Economic, Social and Environmental Council reports a planned tax of 5–10 dollars (which we read as US dollars) per tonne of CO_2-equivalent (Conseil Économique, Social et Environnemental [CESE], 2025, p. 24).

Several of the parameters were open in October 2026. The proposal COM(2026) 616 would reintroduce part of the free allocation removed by the CBAM factor from 2028 and delay its phase-out until 2038 (European Commission, 2026a); in Parliament it awaited a committee decision, with amendments tabled on 13 October 2026 and a plenary vote forecast for 14 December 2026 (European Parliament, 2026). The CBAM benchmarks are due to be updated for goods imported from 1 January 2027 (Implementing Regulation (EU) 2025/2620, recital 10), but no draft had been published (European Commission, 2026e); the final EU ETS benchmark for grey clinker for 2026–2030, 0.656, is lower than the 0.666 used in the CBAM benchmark, while the ammonia benchmark is kept at 1.522 (Implementing Regulation (EU) 2026/1412). The Commission's proposal to extend the CBAM to downstream goods lists 180 steel- and aluminium-intensive products, from wire and cables to machinery, vehicle parts and metal furniture (Council of the European Union,

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2025, 2026); the first trilogue, on 20 October 2026, produced no agreement (Agence Europe, 2026). Evidence from the transitional period suggests that importers move quickly to actual values when they can: only 8–11% of importers reported actual values at the start, but the share of imports reported with actual values reached 46% in the third quarter of 2024 and 53% in the second quarter of 2025, and 90–93% from the third quarter of 2024 for consignments of more than 1,000 tonnes (European Commission, 2025b, p. 9). Verification of these emissions starts only in the definitive period (European Commission, 2025b, p. 7).

1.3 Related literature

Our model draws on four literatures. The first models the EUA price. EUA returns are non-Gaussian, with skewness, excess kurtosis and shifting volatility regimes (Benz & Trück, 2009), stylised facts for which Paolella and Taschini (2008) propose a dedicated econometric model; spot prices have been persistently low relative to futures since late 2008 (Bredin & Parsons, 2016), and futures carry a risk premium (Trück & Weron, 2016). Options-implied volatility (the Carbon VIX) averaged 55% a year between September 2013 and December 2022, ranging between 28% and 87% (Fuchs et al., 2026, p. 2). Market design moves the price level and its variability: the Market Stability Reserve can increase price variability (Perino & Willner, 2016), abatement-related fundamentals leave about 90% of the variation in EUA price changes unexplained (Koch et al., 2014), and prices respond strongly to political events (Koch et al., 2016). Whether the price reverts to a mean is disputed. In a stochastic equilibrium model of the EU ETS, the discounted allowance price should be a martingale (Seifert et al., 2008), unlike the prices of commercial commodities such as copper and oil, which show strong mean reversion (Schwartz, 1997); variance-ratio tests found Phase I of the EU ETS inefficient and early Phase II closer to efficiency (Montagnoli & de Vries, 2010). Bidinot et al. (2026) nevertheless simulate a mean-reverting jump-diffusion, calibrated to 2013–2025 EUA dynamics and centred on long-run targets of EUR 60–150, to cost the phase-out of free allocation for some 9,800 EU installations. None of these studies models the CBAM certificate price itself, a quarterly and then weekly average of auction prices; Paek and Kim (2026) compare the two prices directly and find that the one-week window in which the

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weekly price is known lets declarants time their purchases, a "predictability benefit" of 4.36% on average under typical market conditions in their GBM simulations.

The second literature measures and hedges risk in costs rather than in portfolios. Cash-flow-at-risk applies the logic of value-at-risk to the cash flows of non-financial firms (Stein et al., 2001), and exposure-based versions map cash flows to macroeconomic and market variables (Andrén et al., 2005). Value-at-risk and expected shortfall have been computed for the EU ETS costs of a single cement plant (Abadie et al., 2017), and climate value-at-risk for financial assets (Dietz et al., 2016). The theory of corporate hedging explains why the tail of a cost distribution matters (Froot et al., 1993; Smith & Stulz, 1985). When the quantity exposed is itself uncertain, the correlation between price and quantity is crucial for the optimal hedge (McKinnon, 1967; Moschini & Hennessy, 2001). With production variability, a hedge below expected output can be optimal (Rolfo, 1980), and firms facing both hedgeable price risk and unhedgeable quantity risk should set their hedges according to price and quantity volatilities and their correlation, sometimes with exotic rather than vanilla contracts (Brown & Toft, 2002). For carbon allowances, hedges with regime-switching (state-dependent) ratios outperform single-regime hedges (Philip & Shi, 2016).

The third literature is global sensitivity analysis. Variance-based indices measure the share of output variance due to each input or group of inputs, alone (first-order) or with all its interactions (total) (Saltelli et al., 2010; Sobol', 2001), and the lower (closed) index of a group equals the variance of the output's conditional expectation given that group (Owen, 2013). These indices assume independent inputs. Shapley effects give each input one share of the variance, which lies between its first-order and total indices when inputs are independent (Owen, 2014) and remains meaningful when they are not (Song et al., 2016). Variance is not the only target: moment-independent measures look at the whole output distribution (Borgonovo, 2007), and quantile-oriented indices at a chosen quantile (Fort et al., 2016). One-at-a-time sensitivity can mislead when inputs interact (Harenberg et al., 2019; Saltelli et al., 2019). Global sensitivity analysis has been applied to integrated assessment models, with Sobol indices in Butler et al. (2014) and from Monte Carlo output in Anderson et al. (2014), but not, as far as we know, to CBAM costs.

The fourth concerns who bears carbon costs and how they are measured. Pass-through of carbon costs is high in electricity, where emissions costs were "almost fully passed-

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through" in Spain (Fabra & Reguant, 2014), and estimated at 40–100% of CO_2 costs in the power sector in an early empirical and model-based study (Sijm et al., 2006); for industry, Cludius et al. (2020) find significant pass-through in cement, iron and steel and refineries, with rates that differ across products and countries, and Ganapati et al. (2020) estimate that about 70% of energy-cost changes pass through to prices in the short to medium run in the US manufacturing industries they study. These estimates concern a cost borne by a whole market. The incidence of a border charge on one foreign supplier depends instead on its cost relative to that of the marginal supplier and on elasticities; Faloore (2026) computes the burden on exporting countries from differences in the emission intensity of their exports. Exporters may also reduce their EU sales: high-emission Indian steel firms reduced both quantities and revenues exported to the EU during the CBAM reporting phase (Vriz et al., 2026). On measurement, Mehling and Ritz (2023) question the use of default carbon intensities, Fowlie et al. (2021) find, for electricity imports into California, a tension between accuracy in assessing the carbon intensity of imports and a significant potential for leakage through resource shuffling, Liu et al. (2015) find emission factors for Chinese coal 40% lower on average than the IPCC default values, and the costs of monitoring, reporting and verification show economies of scale (Heindl, 2015).

1.4 Structure of the paper

Section 1.1 states the problem, and Sections 1.2 and 1.3 give the regulatory background and the related literature. Section 2 describes the methods: the model and the data. Section 3 reports the results, Section 4 discusses them and Section 5 concludes.

2. Methods

2.1 Payment due

For a good g of sector s imported from Morocco in year t, a share θ_s of the tonnage is declared with verified actual emissions and the rest with default values. The certificates due per tonne are

$$n_{g,t} = \theta_s \max\left(0;\ \min\left[r_g\, DV_g;\ \delta_t DV_g\left(1+m_{s,t}\right)\right] - CF_t\, CSCF_t\, BM_g^B\right) + (1-\theta_s)\max\left(0;\ \delta_t DV_g\left(1+m_{s,t}\right) - CF_t\, CSCF_t\, BM_g^B\right) \quad (1)$$

where DV_g is Morocco's default value (the value for "Other countries and territories" where Morocco has none), $m_{s,t}$ the mark-up, CF_t the CBAM factor, $CSCF_t$ the cross-

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sectoral correction factor, BM^B_g the Column B benchmark of the route attached to the default value, r_g the ratio of actual emissions to the current default value and δ_t a revision factor of the default values, equal to one before 2028. A declarant with verified data declares the lower of its actual emissions, r_g DV_g, and the revised default value with its mark-up; a revision changes the default values, not the emissions of installations. The payment due on Moroccan goods in import year t is

$$Y_t = \bar{P}_t C_t, \qquad C_t = \sum_g n_{g,t} Q_g V_{s,t} \tag{2}$$

where $\bar{P}_t$ is the average price paid per certificate, C_t the number of certificates, Q_g the net mass imported by the EU in 2025 and $V_{s,t}$ a volume factor. We call Y_t the payment due, or the payment; it is owed by EU declarants, and Section 4.3 discusses who bears it. The model works at the level of products and sectors: one verification share and one quantile of the actual-to-default ratio apply to all goods of a sector, which treats a sector as one declarant and rules out diversification across firms within it. Section 3.6 therefore adds an illustration for a single exporter. Four simplifications are made. With actual emissions, the free-allocation adjustment is computed from Column A benchmarks and precursors; we keep the Column B benchmark, which in our calculations gives about the same adjustment for DAP, but which overstates the adjustment for an installation on a less emission-intensive route than the one assigned to the default value. We ignore verification costs and the 50-tonne exemption, which covers no more than 1% of the emissions embedded in imported goods EU-wide (Regulation (EU) 2025/2083, recital 5); annual trade data do not show how much of Morocco's steel and aluminium it would cover. We hold the CSCF at 100% after 2030, where no value has been set, and report 90% as a variant. And we express the payment as a share of the value of the goods at 2025 unit values, although product prices may move with carbon and energy prices.

2.2 Certificate price

The information set is that of 23 October 2026. We simulate the EUA price at monthly steps from November 2026 to September 2035 under two processes with the same expected path, the EUA futures curve. The first is a geometric Brownian motion (GBM), a random walk in the log price:

$$P_m = F(0,\tau_m)\exp\left(\sigma W_{\tau_m} - 1/2\,\sigma^2\tau_m\right) \tag{3}$$

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where τ_m is the time in years since October 2026, W a standard Brownian motion and F (0, τ) the futures price for delivery at τ. The second replaces σW by an Ornstein– Uhlenbeck deviation of the log price from the curve, with mean-reversion speed $\kappa = \ln 2/3$ (a half-life of three years) and stationary standard deviation $\sigma/\sqrt{(2\kappa)}$, about 0.44 at $\sigma = 0.30$. In both, σ is drawn once per path and is the same for all maturities, so that the model has a single price factor, and the monthly prices are point prices that stand for the weekly averages of auction clearing prices. The curve is interpolated log-linearly between the December contracts of ICE Endex as displayed on 23 October 2026, from EUR 85.40 for 2026 to EUR 109.32 for 2032, on a page that shows no quote date (TradingView, 2026). Beyond December 2032 it is extended at the average log carry between the December 2027 and December 2032 contracts, 4.2% a year; a flat extension is a variant. Centring the distribution on the curve is a market-consistent choice, not a forecast: futures prices carry a risk premium (Trück & Weron, 2016), so the cost-at-risk we report is a quantile under a distribution centred on futures prices. The volatility σ is drawn uniformly between 24.5% and 36.4%, the lowest and highest calendar-year volatilities of daily EUA returns in 2023–2026 (SendeCO_2, 2026).

The same data do not settle the choice between the two processes. The variance ratios of daily log prices fall from 0.98 at five days to 0.92 at 10, 0.83 at 20, 0.77 at 60 and 0.60 at 120 days, which points to mean reversion, but none differs significantly from one (Lo & MacKinlay, 1988; heteroskedasticity-robust z statistics between −0.94 and −0.29; 977 daily returns), and a rejection of the random walk would not by itself support a mean-reverting model (Lo & MacKinlay, 1988). Taken at face value, the 60- and 120-day ratios would imply a half-life of about 3.5 months for a pure Ornstein–Uhlenbeck process, but four years of data cannot distinguish such short-lived deviations from lasting shifts in the price level. We therefore report the GBM and a three-year half-life side by side, and half-lives of 0.5, 1 and 10 years as variants. Short half-lives in a one-factor model have a cost: they tie long-dated prices to the futures curve of 23 October 2026, so that with a half-life of half a year the 2034 price paid has a 90% interval of only EUR 94–147. A two-factor variant avoids this (Schwartz & Smith, 2000): a short-term Ornstein–Uhlenbeck deviation with the 3.5-month half-life that the variance ratios imply for a pure Ornstein–Uhlenbeck process, and a random-walk level, both around the futures curve. The short-term factor carries half of the instantaneous variance in one variant and 80% in another; the two

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factors are independent, and the long-term level makes futures of all maturities move together, so the variant also measures what a single factor leaves out: the spread between December contracts and the gap between a December contract and the price at purchase. A GBM with σ set to 55%, the 2013–2022 average of options-implied volatility (Fuchs et al., 2026), is a stress case only: that index targets a horizon of about 120 days, in a different price regime, and says little about volatility several years ahead.

The price paid follows the legal timing. For 2026 imports, $\bar{P}_{2026}$ is the mean of the four quarterly prices, the first three observed and the fourth equal to the mean of the October price and the simulated November and December prices, which approximates the volume-weighted average of auction clearing prices that the rules prescribe. The quarters are weighted equally, as if imports were spread evenly over the year; weights taken from the monthly import data for 2026 would raise the expected 2026 price by 0.6%. For 2027–2034 imports, declarants buy at each quarter-end the certificates required by the 50% holding rule and the rest evenly from January to September of the following year; $\bar{P}_t$ is the corresponding weighted average of monthly prices. Buying everything during the import year and buying everything at the surrender deadline are reported as alternative strategies, since early purchase is itself a physical hedge (Section 3.5).

2.3 Other inputs

Table 1 lists the inputs. The price and the volumes are market risks for a declarant, calibrated on data. The verification share, the actual-to-default ratio, the phase-out path and the revision of the default values are of another kind: the first is largely a decision of importers and producers, the second is known to producers but not to us, and the last two are regulatory outcomes. We treat them in two ways. In the global analysis, all inputs are drawn from the distributions of Table 1, and the Sobol indices describe the model under those distributions; they are properties of the model, not measurements of the world. In the scenario analysis, the four non-market inputs are fixed on a grid and only the market inputs are random, so that each scenario gives a distribution of the payment conditional on known data and rules. The grid crosses a verification share of 0, 0.5 or 0.9 in every sector, the lowest, middle or highest quantile of the actual-to-default ratio (which does not matter when nothing is verified), current law or the proposed phase-out, and a revision of the default values of −10%, 0 or +10%: 42 distinct scenarios for each price process.

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The verification share θ_s is drawn uniformly between 0.5 and 0.95 for each sector, the range suggested by the transitional-period evidence of Section 1.2; a variant uses U (0, 1). The ratio r_g is drawn, with one quantile u_s per sector, between the ratio of the benchmark to the default value, the level of an installation as efficient as the benchmark, and 1.1: $r_g = r_g^{lo} + u_s\,(1.1 - r_g^{lo})$. The lower bound is 0.62 for DAP, 0.74 for clinker, 0.27–0.40 for steel goods, which take the values for other countries, and 0.13–0.30 for aluminium; the embedded emissions of DAP inferred from the producer's cost estimates reported by the CESE give a ratio of 0.82 (authors' calculations). The phase-out path is $CF_t = \lambda\, CF_t^{proposal} + (1 - \lambda)\, CF_t^{current}$, with λ uniform on [0, 1]; the proposed factors are 97.5, 95, 91.5, 81, 59, 48, 37.5, 27 and 15% for 2026–2034, as reported by A&O Shearman (2026, p. 12). The operative text of the proposal was not readable on EUR-Lex, but these factors match the statement of its explanatory memorandum that 15% of the free allocation phased out by the CBAM factor is reintroduced from 2028 (for 2030, 51.5% + 0.15 × 48.5% ≈ 59%). The default values are multiplied from 2028 by a factor drawn uniformly between 0.9 and 1.1. A range-scaling check multiplies the widths of these four ranges by 0.5 and by 2 around their centres, under both price processes; doubled ranges are cut at 1 for θ and at 0 for r, which moves both means, and they extend λ to [−0.5, 1.5], that is, to faster and slower paths than the two schedules, with the resulting CBAM factor kept between 0 and 100%.

Volumes combine a persistent level shift by sector and independent annual noise, each with half of the variance: $\ln V_{s,t} = \sigma_s(\sqrt{0.5}\,\eta_s + \sqrt{0.5}\,\varepsilon_{s,t}) - \sigma_s^2/2$, with η_s and $\varepsilon_{s,t}$ standard normal. The log standard deviation σ_s equals that of the sector's EU imports from Morocco, all 78 codes, around their 2019–2025 mean (Eurostat, 2026): 0.29 for fertilisers, 0.38 for cement, 0.45 for steel and 0.20 for aluminium. With seven observations these values are imprecise (95% interval for fertilisers, 0.19–0.63). A variant uses the values computed on the largest codes only (0.29, 0.40, 0.25 and 0.17), which cover more than 90% of the 2025 tonnage of fertilisers and cement but only 8% of that of steel and 33% of that of aluminium; fully persistent and fully independent volumes are also variants.

From 2027, the volumes of every year are centred on 2025, so that the results describe the payment on a year of imports of 2025 size: this is a normalisation, not a forecast. For 2026, the monthly data available on the evaluation date tell a different story. In January–August 2026, EU imports from Morocco of the 20 largest codes by 2025 value and one further cement code, which together carry 98.5% of the 2025 tonnage, were 48% below the same

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months of 2025 in tonnage (31% in value): 45% lower for fertilisers, 78% for cement, 19% for steel and 14% for aluminium (Eurostat, 2026). The data do not say why, nor whether the fall will last. The 2026 volumes are therefore conditioned on these data, $V^c_{s,2026} = o_s + b_s\, r_s\, V_{s,2026}$, where o_s and b_s are the January–August 2026 and September–December 2025 tonnages as shares of the 2025 tonnage, r_s the ratio of January–August 2026 to January–August 2025 tonnage and $V_{s,2026}$ the annual draw. Two variants use 2025 volumes for 2026, and the January–August ratio for every year.

All inputs are independent in the base case. Three variants introduce dependence: verification is made more likely where the actual-to-default ratio is low (the quantile of θ_s is one minus that of u_s), and the volumes of each year are correlated with the log-price deviation of that year (measured in July, and in December for 2026), with a coefficient of +0.3 or −0.3. A last group of variants changes rules: the grey-clinker benchmark is set from 2027 at the final EU ETS value, 0.656 instead of 0.666 (Implementing Regulation (EU) 2026/1412), the CSCF is set at 90% after 2030, and the phase-out is fixed at current law or at the proposal.

Table 1. Uncertain inputs.

Group	Input	Distribution	Source	Kind
Price	EUA price path; volatility σ	GBM, or mean reversion with half-life 3 years, on the futures curve (EUR 85.40 for December 2026 to 109.32 for December 2032, then +4.2% a year); σ ~ U(24.5%, 36.4%)	Futures quotes read on 23 October 2026 (secondary); daily EUA prices 2023–2026	Market risk; hedgeable with EUA futures, static or rolled (on 23 October 2026, listed on ICE Endex up to December 2032)
Volumes	$V_{s,t}$, four sectors × nine years	Lognormal, mean 1 (2027–2034); persistent level shift and annual noise, each half of the variance; log s.d. 0.20–0.45; 2026 conditioned on January–August	Eurostat Comext, 2019–2025 annual, January 2025–August 2026 monthly	Market risk; not hedgeable in markets
Verification share	θ_s, four sectors	U(0.5, 0.95); grid 0, 0.5, 0.9	Transitional-period shares (European Commission, 2025b); mapping to verified shares illustrative	Decision of importers and producers
Actual-to-default ratio	r_g, one quantile per sector	U(BM^B_g/DV_g, 1.1); grid: lowest, middle, highest quantile	Illustrative rule	Known to producers, unknown to us

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Group	Input	Distribution	Source	Kind
Phase-out	λ	U(0, 1); grid 0, 1	Directive 2003/87/EC; COM(2026) 616 as reported by A&O Shearman (2026); λ illustrative	Regulation
Default-value revision	δ from 2028	U(0.9, 1.1); grid 0.9, 1, 1.1	Illustrative; revision due by December 2027	Regulation

Notes: *inputs are independent in the base case; Section 2.3 lists the dependence variants. GBM, geometric Brownian motion.*

2.4 Cost-at-risk

We use three measures. The 95% cost-at-risk, CaR = $q_{0.95}(Y)$, is the level of the payment that is exceeded with a probability of 5%. The unexpected cost, $q_{0.95}(Y) - E(Y)$, is its excess over the expected payment. The expected shortfall is the mean of Y above its 95th percentile. We report the level and the excess, hedged and unhedged. Measured on 23 October 2026, the CaR of a 2034 payment covers eight years of price risk, which matters for long-term planning but not for liquidity. For liquidity we also report a one-year-ahead CaR with price-only conditioning: the 95th percentile of a year's payment when the price path up to December of the previous year is known and equal to its expected value. The price risk that remains runs 21 months, from December of the previous year to the last purchases in September of the next year, the purchases themselves spanning the 19 months from March of the import year; volumes and emission data keep their full uncertainty, although by then a declarant would know more about them. The sum over 2026–2034 is undiscounted and is reported as a summary of the period, not as a liquidity measure. These are aggregates over all EU declarants of Moroccan goods; the measures that matter for a firm are those of Section 3.6.

2.5 Variance decomposition and hedging

For a group G of inputs X_G, the first-order (closed) index $S_G = \mathrm{Var}(E[Y \mid X_G])/\mathrm{Var}(Y)$ is the share of variance explained by G alone, and the total index $T_G = 1 - \mathrm{Var}(E[Y \mid X_{\sim G}])/\mathrm{Var}(Y)$ adds all interactions of G with the other inputs (Owen, 2013; Saltelli et al., 2010). We estimate both with the pick-freeze design of Saltelli et al. (2010): two independent N × d matrices of uniform draws A and B, and for each group a matrix A_B^G

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with the columns of G taken from B. There are d = 158 inputs in six groups: 108 for the price (σ and 107 monthly shocks), 40 for volumes (four level shifts and 36 annual shocks), four each for the verification share and the actual-to-default ratio, and one each for the phase-out and the revision; with the aggregate of the non-price groups, the design requires 9N model evaluations. The first-order index uses the estimator of Saltelli et al. (2010, Table 2, row b), the total index that of Jansen (1999), row (f) of the same table, with $N = 2^{16}$ plain Monte Carlo draws rather than quasi-random sequences, and 95% confidence intervals from 200 bootstrap resamples. On the Ishigami function (Ishigami & Homma, 1990), the estimator recovers the analytical indices, as does SciPy's implementation (Virtanen et al., 2020); the SciPy check was run on that test function only.

The price group admits a closed form that links it to hedging. Write X_P for the price inputs and X_N for all other inputs.

Proposition 1. Let $Y = \Sigma_t \bar{P}_t C_t$ with finite second moments, where $\bar{P} = g(X_P)$, $C = c(X_N)$ and X_P is independent of X_N, and let instrument t pay $\bar{P}_t - E[\bar{P}_t]$. (a) Positions $h_t = E[C_t]$ minimise the variance of the hedged payment, which is then $(1 - S_{price})\ \mathrm{Var}(Y)$. (b) If the price of every certificate actually needed is fixed at $E[\bar{P}_t]$, the payment has variance $(1 - T_{price})\ \mathrm{Var}(Y)$.

Proof. (a) By independence, $\mathrm{Cov}(\bar{P}_s, Y) = \Sigma_t E[C_t]\ \mathrm{Cov}(\bar{P}_s, \bar{P}_t)$, so $h = E[C]$ solves the least-squares problem, and the hedged payment $Y - \Sigma_t E\underline{C_t}$ has variance $\mathrm{Var}(Y) - \mathrm{Var}(\Sigma_t E[C_t]\ \bar{P}_t)$. Since $E[Y \mid X_P] = \Sigma_t E[C_t]\ \bar{P}_t$, the variance removed is $S_{price}\ \mathrm{Var}(Y)$. (b) The payment becomes $\Sigma_t E[\bar{P}_t]\ C_t = E[Y \mid X_N]$, whose variance is $(1 - T_{price})\ \mathrm{Var}(Y)$ by the definition of the total index. ■

Mean independence, $E[C \mid X_P] = E[C]$ for (a) and $E[\bar{P} \mid X_N] = E[\bar{P}]$ for (b), is enough; zero correlation is not, because the co-moment of price deviations and quantities also enters the optimal position. This is the minimum-variance case of the problem of hedging under price and output uncertainty (McKinnon, 1967; Moschini & Hennessy, 2001; Rolfo, 1980), written in Sobol indices, and we claim no more for it. The proposition holds in population: in a finite sample, the pick-freeze estimates and the closed form $\mathrm{Var}(\Sigma_t E[C_t]\ \bar{P}_t)/\mathrm{Var}(Y)$ differ by sampling error, and we report the closed form as S_{price} and T_{price} (Section 3.2). The difference $T_{price} - S_{price}$ is the interaction that a static position cannot hedge; a position rebalanced as imports are observed would capture part of it. Each condition can fail. With

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dependence between prices and quantities, $E[Y \mid X_P]$ is no longer linear in the prices and S_{price} is only an upper bound on what a hedge whose payoff depends on X_P alone removes; we then report the simulated hedges only. Linearity fails in the tax scenarios, where the deduction is capped. And no listed instrument pays $\bar{P}_t$: a December contract pays the December price, not the weekly averages at which the certificates of an import year are bought over 19 calendar months, from March of the import year to September of the next, and on 23 October 2026 we found no quote for a contract beyond December 2032. The rules of the European Energy Exchange provide for the current and the next eight December contracts, which would reach December 2034 (European Energy Exchange [EEX], 2026b).

We therefore compute three hedges. The ideal hedge uses the instrument of the proposition, an average-price swap, with notional $E[C_t]$. The static hedge is placed on 23 October 2026 with the December contracts listed that day and is never rolled: for a purchase in month m up to December 2032, a position in the December contract of that year, closed at m, with its size scaled by the ratio of futures prices; for later purchases, the December 2032 contract held to expiry. The rolled hedge differs only for purchases after December 2032: it holds the December 2032 contract until the December contract of the purchase year is listed, then switches to that contract and closes it at m. We assume that ICE Endex keeps seven December contracts listed and adds one each December, so that the December 2033, 2034 and 2035 contracts trade from December 2026, 2027 and 2028. The notionals of the static and rolled hedges are minimum-variance ratios estimated on the simulated sample, one per contract leg and import year. In a one-factor model, a rolled position replicates the ideal hedge (exactly under the GBM, almost exactly under mean reversion), and so does the static hedge whenever every purchase falls before December 2032. The gap between the static and the ideal hedge therefore measures the price risk that cannot be locked in on 23 October 2026 at that day's futures prices, not risk that futures cannot hedge; what a rolled hedge leaves is calendar-spread risk, which a one-factor model sets to zero and the two-factor variant measures. All three hedges assume zero basis between auction clearing prices and futures prices, which favours them; we did not obtain a series of auction clearing prices by date with which to measure that basis, and report instead variants with independent monthly basis noise and with a persistent basis. A futures position locks in the futures price, not the expected price paid; the two coincide here

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because the distribution is centred on the curve, and with a risk premium a hedge would change the expected cost as well as its variance.

Because shares of variance need not match contributions to a quantile, we also report how much the 95th percentile falls when each group is fixed at its central value (the expected price path for the price group). This is a one-at-a-time check, informative only next to the global indices; it is a simple complement to the moment-independent and quantile-oriented measures of Borgonovo (2007) and Fort et al. (2016).

2.6 Firm-level illustration

The aggregate treats each sector as one declarant. To show the problem at the level where decisions are taken, we compute the payment per tonne for a single DAP exporter whose annual quantity is known, under current law and without revision of the default values. It declares either default values ($\theta = 0$), with 0.5555 certificates per tonne before the adjustment (the default value of 0.55 with its 1% mark-up), or verified emissions at 0.82 times the default value ($\theta = 1$). The Column B benchmark is 0.339 and the 2025 unit value EUR 639.17 per tonne (Eurostat, 2026). With a known quantity, the payment per tonne is the price paid times a fixed number of certificates, and the hedge question reduces to the instrument.

2.7 Data and computation

The 78 CN codes and their default values, benchmarks and 2025 import volumes, worth EUR 1,013.4 million, are taken from Eurostat's Comext database for EU imports from Morocco and from the Commission's file of 6 August 2026 for the default values. With all goods declared with default values ($\theta = 0$), current law ($\lambda = 0$), no revision ($\delta = 1$), 2025 volumes ($V = 1$) and a constant price of EUR 77.65, the model reproduces its totals to the cent: EUR 48.85 million in 2026 and EUR 102.54 million in 2034. Seven codes worth EUR 1,800 in total are dropped for lack of a benchmark or a net mass, and electricity is left out because Comext records no quantity for it, which explains the difference from the EUR 1,034 million cited in Section 1. Daily EUA prices for 2023–2026 come from the SendeCO_2 series, whose annual means, 83.50, 65.29 and 73.95 for 2023–2025, match the spot averages of 83, 65 and 74 reported by the European Securities and Markets Authority (ESMA, 2025, 2026) and the auction averages of 83.60 for 2023 and 64.74 for 2024

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reported by the Commission (European Commission, 2024, 2025c). In 2026, the series is within EUR 0.43 of the final settlement prices of five monthly EEX EUA futures on their expiry days (European Energy Exchange [EEX], 2026a), and its quarterly means for the second and third quarters, EUR 75.23 and 82.33, are within EUR 0.05 of the corresponding CBAM certificate prices (EUR 76.12 against 75.36 for the first quarter). All distributions use $N = 2^{16}$ draws with the same seed, so that each variant is compared with the base case on the same draws (common random numbers) and its changes carry paired standard errors; the scenario grid uses 2^{14} draws per scenario and the range-scaling check 2^{15}. Monte Carlo standard errors come from bootstrap resamples. The code is written in Python with NumPy and SciPy and is available with the data.

Research ethics. The study uses only published and aggregated statistics and public price data. It involves no human or animal subjects, so no ethical clearance was required.

3. Results

3.1 Distribution of the payment

Table 2 reports the distribution of the payment due by import year under the two price processes. In 2026 the two coincide. On the imports observed in January–August, the mean 2026 payment is EUR 19.1 million and its 95% cost-at-risk EUR 27.3 million, EUR 8.2 million above the mean. This is 61.0% below the payment computed with default values for all goods, 2025 volumes and a constant price of EUR 77.65 (EUR 48.85 million). Three effects combine: lower volumes reduce the expected number of certificates by 44.7%, verified declarations reduce it by a further 31.1%, and the expected price for 2026, EUR 79.59, is 2.5% above 77.65. On 2025 volumes the mean 2026 payment would be EUR 34.5 million.

From 2027 the volumes are centred on 2025, and the two distributions part. Their expected values are the same, because both processes are centred on the futures curve: the simulated means are EUR 72.3 million in 2030, 122.9 million in 2034 and 641.4 million summed over 2026–2034 under the GBM, and differ by less than 0.5% under mean reversion. Their tails are not. The 95% cost-at-risk of the 2030 payment is EUR 172.9 million under the GBM and EUR 140.7 million under mean reversion; for 2034 it is EUR 352.4 and 241.5 million, and for the sum over 2026–2034 EUR 1,512.9 and 1,119.5 million. Under the GBM the distribution is strongly skewed: in 2034 the median, EUR 82.6 million, is 33%

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below the mean, and the expected shortfall beyond the 95th percentile reaches EUR 566.5 million (Figure 1). Monte Carlo error is small next to these differences: the bootstrap standard error of the 95th percentile is EUR 1.0 million for 2030 and EUR 8.6 million for the sum under the GBM. If the January–August 2026 ratio of imports applied to every year, the mean sum would be EUR 347.8 million, 46% less (Table 9).

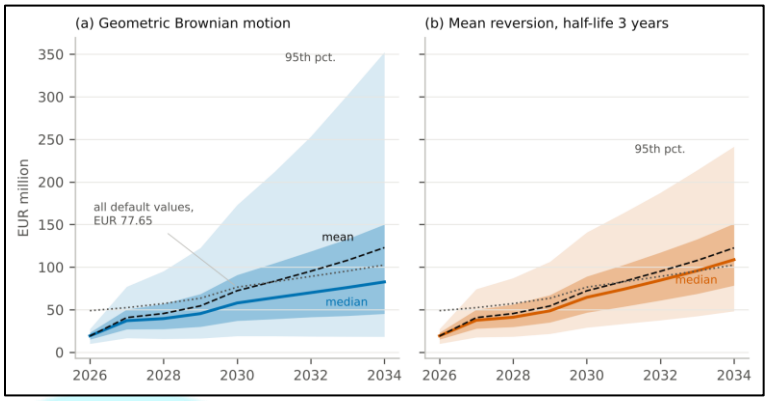


Figure 1. *Distribution of the payment due on Moroccan goods by import year, EUR million: median (solid), mean (dashed), 25th–75th and 5th–95th percentiles (shaded); 2026 conditioned on the imports of January–August, 2027–2034 on 2025 volumes. Dotted line: all goods declared with default values, current law, 2025 volumes and a constant price of EUR 77.65 per certificate. (a) Geometric Brownian motion; (b) mean reversion with a half-life of three years. Source: authors' simulation (N = 65,536).*

Table 2. Payment due on Moroccan goods by import year (EUR million).

Import year	Mean	Standard deviation	Median	95th pct. (CaR)	CaR − mean	Expected shortfall	Mean, % of value	95th pct., % of value
2026	19.1 / 19.1	5.3 / 5.3	19.3 / 19.3	27.3 / 27.3	8.2 / 8.2	29.0 / 29.0	3.2	4.3 / 4.3
2027	40.7 / 40.7	19.3 / 17.9	37.1 / 37.6	77.0 / 74.2	36.3 / 33.5	93.7 / 88.5	4.0	7.0 / 6.7
2028	45.5 / 45.4	26.4 / 22.2	39.6 / 41.1	95.3 / 87.1	49.7 / 41.7	122.1 / 107.0	4.5	8.9 / 8.0
2029	54.4 / 54.3	36.3 / 27.4	45.4 / 48.7	122.5 / 106.3	68.0 / 52.0	162.8 / 131.0	5.4	11.7 / 9.9
2030	72.3 / 72.1	54.6 / 36.6	57.9 / 64.5	172.9 / 140.7	100.6 / 68.6	238.5 / 175.7	7.2	16.6 / 13.1
2031	83.3 / 83.1	70.8 / 42.8	64.0 / 74.0	211.3 / 163.5	128.0 / 80.4	301.6 / 204.4	8.3	20.4 / 15.3
2032	95.2 / 95.1	90.1 / 49.6	70.0 / 84.6	253.3 / 187.3	158.1 / 92.2	375.9 / 236.8	9.5	24.6 / 17.5

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Import year	Mean	Standard deviation	Median	95th pct. (CaR)	CaR − mean	Expected shortfall	Mean, % of value	95th pct., % of value
2033	108.0 / 107.8	113.2 / 56.5	76.1 / 95.7	302.3 / 213.8	194.3 / 106.0	461.7 / 269.3	10.7	29.2 / 19.9
2034	122.9 / 122.6	142.9 / 64.4	82.6 / 108.7	352.4 / 241.5	229.5 / 118.9	566.5 / 306.4	12.2	34.5 / 22.7
2026–2034	641.4 / 640.3	491.5 / 258.7	512.2 / 595.6	1,512.9 / 1,119.5	871.4 / 479.2	2,144.3 / 1,340.6		

Notes: *GBM / mean reversion (half-life three years) in each cell; N = 65,536 draws. 2026 conditioned on the imports of January–August 2026; 2027–2034 on 2025 volumes. CaR, 95% cost-at-risk; expected shortfall, mean above the 95th percentile. Value of the goods at 2025 unit values, scaled by volumes; the mean share of value differs by at most 0.1 point between the processes (GBM shown). Bootstrap standard errors (GBM, 200 resamples): of the mean, 0.02 for 2026 to 1.9 for the sum; of the 95th percentile, 0.03 to 8.6. Source: authors' calculations.*

As a share of the value of the goods at 2025-unit values, the payment averages 3.2% in 2026, 7.2% in 2030 and 12.2% in 2034. Its 95th percentile in 2034 is 34.5% under the GBM and 22.7% under mean reversion, a ratio that overstates the burden if product prices rise with carbon prices. Fertilisers carry 77% of the mean payment in 2026 and 73% in 2034. The cement payment rises fastest, from a mean of EUR 0.8 million to EUR 21.7 million, as its mark-up reaches 30%, the adjustment for clinker falls and its volumes return to their 2025 level.

Table 3 shows the distribution of the average price paid per certificate behind these figures. Under the GBM, the 2034 price has a 5% probability of being below EUR 19.5 and a 1% probability of being above EUR 611; under mean reversion its 90% interval is EUR 54–217. The EU ETS has no price floor or ceiling, but the supply adjustments of the Market Stability Reserve, which the model ignores, would act on both tails, so the GBM tails are best read as a stress on dispersion rather than as a forecast.

Table 3. Average price paid per certificate by import year (EUR).

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Import year	Expected price	5th pct.	Median	95th pct.	99th pct.
2026	79.6	77.4 / 77.4	79.5 / 79.5	82.0 / 82.0	83.3 / 83.2
2027	88.8	53.0 / 57.6	85.1 / 86.2	139.1 / 130.4	172.8 / 156.2
2028	92.4	42.0 / 51.3	84.7 / 87.9	170.6 / 150.1	231.7 / 189.8
2030	100.4	30.4 / 48.8	83.8 / 93.2	225.8 / 175.6	344.3 / 229.3
2032	109.4	23.9 / 50.9	83.4 / 100.6	280.3 / 196.4	467.4 / 263.1
2034	119.0	19.5 / 54.3	83.1 / 109.2	334.9 / 216.9	611.2 / 289.9

Notes: *GBM / mean reversion in each cell except the expected price, which is the same under both by construction. Average price paid for the certificates of an import year under the purchase schedule of Section 2.2. Source: authors' calculations (N = 65,536).*

3.2 What drives the variance

Figure 2 and Table 4 show how the sources of variance change over time. In 2026 the price explains almost none of the variance, because three quarterly prices are known and the fourth is close to being known. Once 2026 volumes are conditioned on the January–August data, the actual-to-default ratio explains 0.81 of the variance alone and 0.85 with its interactions, volumes 0.09 and 0.11, and the verification share 0.04 and 0.07. On 2025 volumes, the ratio would explain 0.48 and 0.54, volumes 0.42 and 0.47 and the verification share 0.03 and 0.05 (N = 32,768). These figures follow from the 2026 pricing rule and the information set; they describe what the 2026 payment depends on once its price is set, not a general property of CBAM risk.

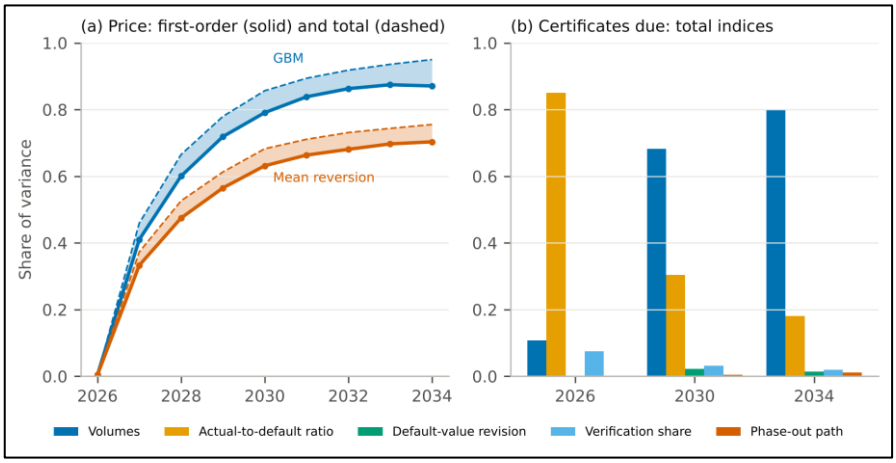


Figure 2. *(a) First-order (solid) and total (dashed) indices of the price group for the payment due, closed-form estimates; the shaded band is the interaction between price and quantity. (b) Total Sobol indices of the non-price inputs for the number of certificates due (pick-freeze estimates; the certificates do not depend on the price process). Source: authors' simulation (N = 65,536).*

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From 2027 the price takes over, by an amount that depends on the process. Under the GBM, its first-order and total indices are 0.41 and 0.46 in 2027, 0.79 and 0.86 in 2030, 0.87 and 0.95 in 2034 and 0.86 and 0.91 for the sum over 2026–2034. Under mean reversion they are 0.33 and 0.37, 0.63 and 0.68, 0.70 and 0.76 and 0.63 and 0.67. Mean reversion leaves the non-price inputs a larger share: for the sum, the total index of volumes is 0.20 against 0.08 under the GBM, and that of the actual-to-default ratio 0.15 against 0.06. The 95% bootstrap intervals of the pick-freeze and closed-form price indices overlap for every output of Table 4 except the total index of the 2034 payment under the GBM, 0.93 against 0.95; for so heavy-tailed an output, bootstrap intervals can understate the error of the pick-freeze estimator, and we report the closed form, which does not depend on the pick-freeze design.

Table 4. Sobol indices of the groups of inputs.

Group	Payment 2026	Payment 2030	Payment 2034	Payment 2026–2034	Certificates 2030
Panel A. Geometric Brownian motion					
Price (closed form)	0.00 [0.00, 0.00] / 0.00 [0.00, 0.01]	0.79 [0.78, 0.81] / 0.86 [0.85, 0.86]	0.87 [0.82, 0.92] / 0.95 [0.95, 0.95]	0.86 [0.84, 0.88] / 0.91 [0.90, 0.91]	–
Price (pick-freeze)	0.01 / 0.00	0.79 / 0.84	0.84 / 0.93	0.84 / 0.89	–
Verification share	0.04 / 0.07	0.00 / 0.01	0.00 / 0.00	0.00 / 0.01	0.01 / 0.03
Actual-to-default ratio	0.81 / 0.85	0.04 / 0.06	0.01 / 0.02	0.03 / 0.06	0.27 / 0.30
Volumes	0.09 / 0.11	0.09 / 0.14	0.04 / 0.09	0.05 / 0.08	0.65 / 0.68
Default-value revision	–	0.00 / 0.00	0.00 / 0.00	0.00 / 0.00	0.02 / 0.02
Phase-out path	–	0.00 / 0.00	0.00 / 0.00	0.00 / 0.00	0.00 / 0.00
All non-price inputs	0.99 / 0.99	0.14 / 0.20	0.05 / 0.11	0.10 / 0.14	1.00 / 1.00
Panel B. Mean reversion, half-life 3 years					
Price (closed form)	0.00 [0.00, 0.00] / 0.00 [0.00, 0.00]	0.63 [0.62, 0.64] / 0.68 [0.68, 0.69]	0.70 [0.69, 0.71] / 0.76 [0.75, 0.76]	0.63 [0.62, 0.64] / 0.67 [0.66, 0.67]	–
Price (pick-freeze)	0.01 / 0.00	0.64 / 0.68	0.70 / 0.75	0.63 / 0.66	–
Verification share	0.04 / 0.07	0.00 / 0.01	0.00 / 0.01	0.01 / 0.02	0.01 / 0.03
Actual-to-default ratio	0.81 / 0.85	0.09 / 0.11	0.04 / 0.05	0.13 / 0.15	0.27 / 0.30
Volumes	0.09 / 0.11	0.20 / 0.25	0.19 / 0.23	0.18 / 0.20	0.65 / 0.68
Default-value revision	–	0.01 / 0.01	0.00 / 0.00	0.01 / 0.01	0.02 / 0.02
Phase-out path	–	0.00 / 0.00	0.00 / 0.00	0.00 / 0.00	0.00 / 0.00
All non-price inputs	0.99 / 0.99	0.32 / 0.36	0.24 / 0.29	0.34 / 0.37	1.00 / 1.00

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Notes: *first-order / total indices. Closed-form price indices from the decomposition of Section 2.5, with 95% bootstrap intervals (1,000 resamples) in brackets; all other indices from the pick-freeze estimators, N = 65,536, 200 bootstrap resamples (the largest half-width of the 95% intervals of the non-price indices is 0.04). The closed-form first-order price index for the sum under the GBM is 0.84 at N = 4,096, 0.86 at 16,384 and 0.86 at 65,536. "–" denotes an input that cannot affect the output. The non-price groups are identical in the two panels for the certificates, which do not depend on the price. Source: authors' calculations.*

Within the non-price inputs, which set the number of certificates, volumes account for the largest share: their total index for the certificates due in 2030 is 0.68, against 0.30 for the actual-to-default ratio, 0.02 for the revision of the default values and 0.03 for the verification share. The verification share matters little in the global analysis because its range, 0.5–0.95, is narrow; with ranges twice as wide, its total index for the 2026 payment rises from 0.07 to 0.18 (Section 3.3). The phase-out path explains almost none of the variance, but this follows from drawing λ uniformly between two schedules that differ by a known amount: the mean sum is 6.5% lower with the phase-out fixed at the proposal than at current law (Section 3.7).

Variance shares need not match contributions to the tail. Fixing the price at its expected path lowers the 95th percentile of the sum from EUR 1,512.9 million to EUR 903.4 million under the GBM (by 40.3%) and from EUR 1,119.5 million under mean reversion (by 19.3%). Fixing volumes lowers it by 2.2% and 4.9%, and fixing the actual-to-default ratio by 1.1% and 2.8%. For 2026, fixing the ratio lowers the 95th percentile from EUR 27.3 million to EUR 22.9 million and fixing volumes to EUR 26.1 million, while fixing the verification share leaves it at EUR 27.2 million. Apart from the price, the two groups whose fixing lowers the 95th percentile most are, in the same order, the two with the largest total indices, for 2026 and for the sum and under both processes. Since this check moves one group at a time, it complements the variance decomposition rather than replacing it.

3.3 Scenarios and the width of the illustrative ranges

Table 5 fixes the four non-market inputs and leaves only the price and volumes random. These inputs move the level of the payment a great deal. Over the 42 distinct scenarios, the mean sum over 2026–2034 ranges under the GBM from EUR 297 million, with 90% of imports verified at the benchmark level, the proposed phase-out and default values revised

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down by 10%, to EUR 975 million, with all imports declared with default values revised up by 10% under current law, a factor of 3.3; under mean reversion the means are at most 0.7% lower. Averaged over the other inputs, raising the verification share from 0 to 0.9 lowers the mean sum by 32%; where part of the tonnage is verified, moving the actual-to-default ratio from the lowest to the highest quantile raises it by 84%; a revision of +10% rather than −10% raises it by 17%; and the proposed phase-out lowers it by 6.3% relative to current law. Within each scenario, the composition of the remaining risk barely changes. The price explains 0.91–0.92 of the variance of the sum under the GBM and 0.75–0.78 under mean reversion, the static hedge removes 0.85–0.86 and 0.66–0.69 and the rolled hedge 0.92–0.93 and 0.76–0.78, and the ratio of the 95th percentile of the sum to its mean is 2.28–2.48 and 1.66–1.74. This stability is close to mechanical: price and quantity are independent and only volumes remain random in the quantity, so the non-market inputs scale the distribution rather than reshape it. Conditional on known data and rules, the hedgeable share is larger than in the global analysis (0.86 and 0.63), where part of the variance comes from not knowing which scenario holds.

Table 5. Payment with the non-market inputs fixed: selected scenarios (EUR million).

Scenario (θ, ratio quantile, λ, δ)	Mean 2030	95th pct. 2030	Mean 2026–2034	95th pct. 2026–2034	S_{price} 2026–2034	Static hedge, variance removed 2026–2034
All default values, current law, no revision (0, 0.5, 0, 1)	99.5	233.0 / 187.1	876.7	2,023.8 / 1,456.2	0.92 / 0.77	0.86 / 0.69
Half verified, median ratio (0.5, 0.5, 0, 1)	83.1	194.5 / 156.3	736.9	1,715.4 / 1,229.9	0.91 / 0.77	0.86 / 0.68
Transitional evidence: 90% verified, median ratio (0.9, 0.5, 0, 1)	70.0	164.1 / 132.0	625.0	1,468.3 / 1,047.4	0.91 / 0.76	0.85 / 0.67
90% verified at benchmark level, proposal, revision −10% (0.9, 0, 1, 0.9)	32.1	75.0 / 60.5	296.6	730.9 / 511.0	0.92 / 0.78	0.85 / 0.66
90% verified at ratio 1.1, current law, revision +10% (0.9, 1, 0, 1.1)	102.9	241.9 / 194.4	899.8	2,071.4 / 1,499.7	0.91 / 0.76	0.86 / 0.68
All default values, current law, revision +10% (0, 0.5, 0, 1.1)	112.8	264.3 / 212.1	974.9	2,249.0 / 1,622.1	0.92 / 0.77	0.86 / 0.69
Range over the 42 scenarios	32.1–112.8	75.0–264.3 / 60.5–212.1	296.6–974.9	730.9–2,249.0 / 511.0–1,622.1	0.91–0.92 / 0.75–0.78	0.85–0.86 / 0.66–0.69

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Scenario (θ, ratio quantile, λ, δ)	Mean 2030	95th pct. 2030	Mean 2026–2034	95th pct. 2026–2034	S_{price} 2026–2034	Static hedge, variance removed 2026–2034
Global analysis, inputs drawn from Table 1	72.3	172.9 / 140.7	641.4	1,512.9 / 1,119.5	0.86 / 0.63	0.80 / 0.55

Notes: θ, verification share in every sector; ratio quantile, quantile of the actual-to-default ratio within its range (0, benchmark level; 1, 1.1 times the default value); λ, 0 for current law and 1 for COM(2026) 616; δ, revision of the default values from 2028. Price and volumes random, N = 16,384 per scenario. GBM / mean reversion where two values are given; means under the GBM, those under mean reversion being lower by 0.7% at most. S_{price}, closed-form first-order index of the price. The last row is the global analysis of Tables 2 and 4 (N = 65,536). Source: authors' calculations.

The global indices depend on the widths of the illustrative ranges (N = 32,768 in each run). Halving the four widths raises the first-order index of the price for the sum from 0.86 to 0.90 under the GBM and from 0.63 to 0.72 under mean reversion; doubling them lowers it to 0.79 and 0.51. The total index of all non-price inputs for the sum moves from 0.14 to 0.10 and 0.21 under the GBM, and from 0.37 to 0.28 and 0.50 under mean reversion. In 2026 the actual-to-default ratio stays the first source of variance, with a total index of 0.67 with halved ranges and 0.83 with doubled ones. For the payments we decompose from 2027 on (2027, 2028, 2030 and 2034), the price remains the largest single source of variance with halved ranges under both processes and with doubled ranges under the GBM, narrowly for 2027; under mean reversion with doubled ranges, the actual-to-default ratio overtakes it for the 2027 payment.

3.4 Hedging

Table 6 compares four positions. The ideal average-price hedge, with notional $E[C_t]$, removes the share S_{price} of the variance, as Proposition 1 states: 0.79 of the variance of the 2030 payment and 0.86 of that of the sum under the GBM, and under mean reversion 0.63 for 2030 and 0.63 for the sum. In this one-factor model with zero basis, the static hedge with the contracts listed on 23 October 2026 does as well up to 2031 imports, whose certificates are bought by September 2032. It falls short when purchases extend beyond December 2032: the variance removed is 0.84, 0.74 and 0.62 for 2032, 2033 and 2034 imports under the GBM, against 0.85, 0.87 and 0.89 for the ideal hedge, and 0.47 and 0.29 for 2033 and 2034 imports under mean reversion, against 0.69 and 0.71. For the sum over 2026–2034, the static hedge removes 0.80 of the variance under the GBM and 0.55 under mean reversion. This shortfall is the price risk that cannot be locked in on 23 October 2026

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at that day's futures prices. A hedge rolled into the December 2033, 2034 and 2035 contracts once they are listed closes it: it removes 0.89 of the variance of the 2034 payment and 0.86 of that of the sum under the GBM, and 0.71 and 0.63 under mean reversion, almost the same as the ideal hedge. In the two-factor variant with half of the instantaneous variance on the short-term factor, which lets December contracts diverge and the price at purchase depart from the December contract, the rolled hedge removes 0.77 of the variance of the sum against 0.77 for the ideal hedge and 0.72 for the static hedge: calendar-spread risk costs little here, because the long-term factor drives futures of all maturities.

Basis risk also costs little in these variants, though for different reasons. Independent monthly noise of 5% between the price paid and futures prices leaves the static hedge, removing 0.80 of the variance of the sum under the GBM, because it averages out over the purchase months. A persistent basis, one lognormal level per path with a standard deviation of 1% or 2%, changes the share removed by the static hedge by 0.001 at most, because a basis of that size is small next to the dispersion of prices several years ahead. A known, constant basis would change only the expected cost; a larger or time-varying basis would lower the shares, and we have no data to calibrate one.

Table 6. Hedging the payment due (EUR million).

Import year	Unhedged	Ideal average-price hedge	Static hedge, contracts listed on 23 October 2026	Rolled hedge	Price of certificates fixed
Panel A. Geometric Brownian motion					
2027	77.0 (36.3)	66.6 (25.9); 0.41	66.6 (25.9); 0.41	66.6 (25.9); 0.41	66.0 (25.4); 0.46
2030	172.9 (100.6)	111.8 (39.5); 0.79	111.8 (39.5); 0.79	111.8 (39.5); 0.79	109.9 (37.7); 0.86
2032	253.3 (158.1)	144.7 (49.5); 0.85	147.4 (52.2); 0.84	145.0 (49.8); 0.86	142.0 (46.8); 0.92
2033	302.3 (194.3)	163.6 (55.6); 0.87	188.1 (80.1); 0.74	163.7 (55.7); 0.87	160.0 (52.2); 0.94
2034	352.4 (229.5)	184.8 (61.9); 0.89	237.7 (114.8); 0.62	184.2 (61.3); 0.89	180.7 (58.2); 0.95
2026–2034	1,512.9 (871.4)	923.4 (282.0); 0.86	963.6 (322.1); 0.80	924.1 (282.7); 0.86	903.4 (263.2); 0.91
Panel B. Mean reversion, half-life 3 years					
2027	74.2 (33.5)	66.4 (25.7); 0.33	66.4 (25.7); 0.33	66.4 (25.7); 0.33	66.0 (25.4); 0.38
2030	140.7 (68.6)	110.8 (38.7); 0.63	110.6 (38.5); 0.63	110.6 (38.5); 0.63	109.9 (37.7); 0.68

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Import year	Unhedged	Ideal average-price hedge	Static hedge, contracts listed on 23 October 2026	Rolled hedge	Price of certificates fixed
2032	187.3 (92.2)	143.5 (48.4); 0.68	145.8 (50.7); 0.65	143.3 (48.1); 0.68	142.0 (46.8); 0.73
2033	213.8 (106.0)	161.5 (53.7); 0.69	181.0 (73.2); 0.47	161.2 (53.4); 0.69	160.0 (52.2); 0.74
2034	241.5 (118.9)	182.5 (59.9); 0.71	220.7 (98.1); 0.29	182.2 (59.7); 0.71	180.7 (58.2); 0.76
2026–2034	1,119.5 (479.2)	911.5 (271.3); 0.63	942.2 (301.9); 0.55	911.0 (270.7); 0.63	903.4 (263.2); 0.67

Notes: *95th percentile (95th percentile minus mean, in brackets), EUR million; share of variance removed after the semicolon. Ideal hedge: instruments paying the average price paid for each import year, notional $E[C_t]$. Static hedge: positions in the December EUA futures listed on 23 October 2026, closed at each purchase date up to December 2032, the December 2032 contract held to expiry for later purchases, with minimum-variance notionals. Rolled hedge: as the static hedge, but for purchases after December 2032 the December 2032 contract is held until the December contract of the purchase year is listed (assumed December 2026, 2027 and 2028 for 2033, 2034 and 2035) and that contract is held until the purchase. All with zero basis. Price fixed: every certificate actually needed bought at the expected price paid. The shares removed by the ideal hedge and by fixing the price are sample estimates of S_{price} and T_{price}; they lie within the bootstrap intervals of the closed-form values of Table 4 (largest gap: 2034 under the GBM, 0.89 against 0.87, interval 0.82–0.92). N = 65,536. Source: authors' calculations.*

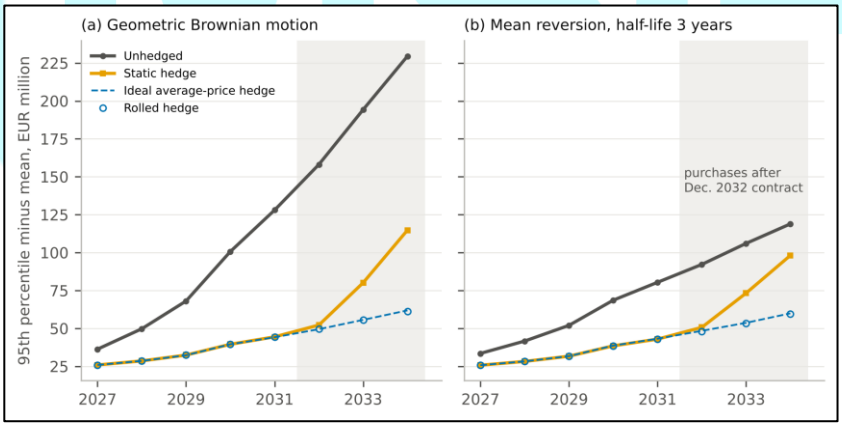


Figure 3. *Unexpected cost of the payment due (95th percentile minus mean), EUR million, by import year: unhedged, with the ideal average-price hedge, with the rolled hedge (which coincides with it in these one-factor models) and with the static hedge in the EUA futures listed on 23 October 2026 (zero basis). Shaded: import years whose certificates are partly bought after the December 2032 contract, the last listed on ICE Endex on 23 October 2026. (a) Geometric Brownian motion; (b) mean reversion. Source: authors' simulation (N = 65,536).*

The hedges cut the excess over the mean more than the level of the cost-at-risk. Under the GBM, the static hedge lowers the 95th percentile of the sum from EUR 1,512.9 million to EUR 963.6 million (by 36%) and the unexpected cost from EUR 871.4 million to EUR 322.1 million (by 63%). Under mean reversion it lowers the 95th percentile from EUR

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1,119.5 million to EUR 942.2 million (by 16%) and the unexpected cost from EUR 479.2 million to EUR 301.9 million (by 37%). After the static hedge, the two processes give a similar 95th percentile, about EUR 950 million, and the rolled hedge lowers it to EUR 924.1 and 911.0 million. What the static hedge leaves is quantity risk and the price risk of the purchases that the contracts listed on 23 October 2026 do not reach: quantity risk is 47% of the remaining variance of the sum under the GBM and 75% under mean reversion. Fixing the price of every certificate actually needed at its expected value, which is the same under both processes, gives a 95th percentile of EUR 903.4 million, only slightly below that of the ideal hedge, since the interaction between price and quantity is small: $T_{price} - S_{price}$ is 0.046 for the sum under the GBM and 0.034 under mean reversion.

3.5 Purchase timing and one-year-ahead cost-at-risk

The purchase schedule is itself a hedge. If declarants buy all certificates during the import year, the price explains 0.29 of the variance of the 2027 payment (first-order index), against 0.41 with the base schedule and 0.58 if they buy at the surrender deadline. Early purchase also lowers the expected payment, by 2.0% for the sum, because the futures curve rises by about 4% a year, while late purchase raises it by 3.0%. The saving is a cost of carry, not a free gain: early purchase ties up cash, and certificates bought in excess can be sold back only within the limits of Article 23.

Table 7. One-year-ahead cost-at-risk (EUR million).

Case	Mean	95th pct.	95th pct. − mean
2030 payment, information of 23 October 2026, GBM	72.3	172.9	100.6
2030 payment, price path known to December 2029, GBM	72.0	126.1	54.1
2030 payment, information of 23 October 2026, mean reversion	72.1	140.7	68.6
2030 payment, price path known to December 2029, mean reversion	72.1	122.3	50.2
2034 payment, information of 23 October 2026, GBM	122.9	352.4	229.5
2034 payment, price path known to December 2033, GBM	122.5	210.2	87.7
2034 payment, information of 23 October 2026, mean reversion	122.6	241.5	118.9
2034 payment, price path known to December 2033, mean reversion	122.5	203.2	80.7

Notes: price-only conditioning: the price path up to December of the previous year is set at its expected value and the rest is random; volumes and emission data keep their full uncertainty. N = 65,536. Source: authors' calculations.

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Table 7 shows what a shorter horizon changes. If the price path is known up to December 2029, the 95th percentile of the 2030 payment is EUR 126.1 million under the GBM and EUR 122.3 million under mean reversion, EUR 54.1 million and EUR 50.2 million above the mean, against EUR 172.9 and 140.7 million seen from October 2026. For 2034, with the price known to December 2033, it is EUR 210.2 and 203.2 million. With 21 months of price risk left, the two processes give similar tails.

3.6 A single DAP exporter

Table 8 shows the payment per tonne for a DAP exporter whose quantity is known. With default values it needs 0.225 certificates per tonne in 2026, costing EUR 17.9 per tonne on average, 2.8% of the 2025 unit value. As the adjustment falls, the number rises to 0.556 in 2034, and the expected payment to EUR 66.1 per tonne, 10.3% of the unit value, with a 95th percentile of EUR 186.0 under the GBM and EUR 120.5 under mean reversion (29.1% and 18.8% of the unit value). Verified emissions at 0.82 times the default value save 0.105 certificates per tonne in every year. In expectation this lowers the payment by 46% in 2026 but by only 19% in 2034, because the saving is fixed while the payment grows; and it leaves the price risk unchanged in kind. Since the quantity is known, the price is the only risk left in the model. In this one-factor model with zero basis, the static hedge removes all of it for 2030 imports (1.00 under both processes) but only 0.71 under the GBM and 0.41 under mean reversion for 2034 imports, while the rolled hedge removes all of it (1.00 under both processes).

Table 8. Payment per tonne for a single DAP exporter.

Declaration	Import year	Certificates per tonne	Mean, EUR/t	95th pct., EUR/t	Mean, % of unit value	95th pct., % of unit value	Static hedge, variance removed	Rolled hedge, variance removed
Default values	2026	0.225	17.9	18.5 / 18.4	2.8	2.9 / 2.9	–	–
	2027	0.233	20.7	32.5 / 30.4	3.2	5.1 / 4.8	1.00 / 1.00	1.00 / 1.00
	2030	0.381	38.2	86.0 / 66.9	6.0	13.5 / 10.5	1.00 / 1.00	1.00 / 1.00
	2034	0.556	66.1	186.0 / 120.5	10.3	29.1 / 18.8	0.71 / 0.41	1.00 / 1.00
Verified, 0.82 × default value	2026	0.120	9.6	9.9 / 9.9	1.5	1.5 / 1.5	–	–
	2027	0.129	11.5	17.9 / 16.8	1.8	2.8 / 2.6	1.00 / 1.00	1.00 / 1.00
	2030	0.276	27.7	62.4 / 48.5	4.3	9.8 / 7.6	1.00 / 1.00	1.00 / 1.00
	2034	0.451	53.7	151.0 / 97.8	8.4	23.6 / 15.3	0.71 / 0.41	1.00 / 1.00

Notes: *DAP, CN 3105 30 00; default value 0.55 tCO_2e/t with a 1% mark-up, Column B benchmark 0.339, unit value EUR 639.17/t in 2025 (Eurostat, 2026); current law, no revision of the default*

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values. GBM / mean reversion where two values are given. Mean: expected payment, the number of certificates times the expected price paid. Static and rolled hedges as in Table 6, with the known quantity. For 2026 the price is almost known, so the hedge has little to remove. Source: authors' calculations (N = 65,536).

3.7 Robustness

Table 9 reports the variants, each computed on the same draws as the base case, so that its changes carry paired standard errors. The half-life of mean reversion matters most. With half-lives of 0.5, 1 and 10 years, the first-order index of the price for the sum is 0.09, 0.27 and 0.80, against 0.63 at three years and 0.86 under the GBM. The static hedge then removes 0.06, 0.19 and 0.74 of the variance of the sum, and 0.00, 0.04 and 0.52 of that of the 2034 payment, while a rolled hedge removes about the share S_{price}; the 95th percentile of the sum is EUR 921, 959 and 1,340 million. A short half-life leaves little price risk because it ties long-dated prices to today's futures curve (Section 2.2). With half of the instantaneous variance on the short-term factor, the two-factor variant sits between the processes: the price explains 0.77 of the variance of the sum and the 95th percentile of the sum is EUR 1,276 million. With 80%, the price explains 0.58, less than with a three-year half-life, and the 95th percentile of the sum is EUR 1,084 million. In both, the rolled hedge removes nearly what the ideal hedge removes (0.77 against 0.77, and 0.58 against 0.58), and the static hedge less (0.72 and 0.54). Holding the futures curve flat after December 2032 lowers the mean 2034 payment by 8.1% and the mean sum by 2.4%. A 55% volatility raises the 95th percentile of the sum to EUR 2,081 million (38% above the base case) and the price indices to 0.94 and 0.98. The structure of volume risk matters for the sum, though not for single years: with independent annual shocks the first-order index of the price is 0.92 under the GBM and 0.75 under mean reversion, against 0.86 and 0.63 in the base case; with a permanent level shift it is 0.81. Volume standard deviations computed on the largest codes only change the 95th percentile of the sum by −0.1%. Making verification more likely where the actual-to-default ratio is low lowers the mean sum by 3.3%, and drawing the verification share from U (0, 1) raises it by 9.9%. In the price–volume variants, the correlation between the logarithms of the price paid and of the certificates due is 0.23 for 2027, 0.32 for 2030 and 0.35 for 2034 under the GBM with a coefficient of +0.3. This dependence changes the mean sum by +6.4% (+0.3) or −5.9% (−0.3) and its 95th percentile by +14.3% or −13.2%. A notional of $E[C_t]$ is then no longer the minimum-variance position: with +0.3, it removes 0.85 of the variance of the sum under the GBM,

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against 0.89 with least-squares notionals, and the static hedge removes 0.82, against 0.80 in the base case; with −0.3 the three shares are 0.77, 0.83 and 0.77. Under mean reversion the static hedge removes 0.64 and 0.45, against 0.55. Among the rules, the phase-out path moves the mean most: from current law to the proposal, the mean sum falls from EUR 663.1 million to EUR 619.8 million (6.5%) and the mean 2034 payment by 9.1%. A CSCF of 90% after 2030 raises the mean sum by 1.2%, and setting the grey-clinker benchmark at its final EU ETS value by 0.1%.

Table 9. Robustness checks (EUR million).

Variant	Mean 2030	95th pct. 2030	Mean 2026–2034	Change in mean 2026–2034, % (s.e.)	95th pct. 2026–2034	Change in 95th pct. 2026–2034, % (s.e.)	S_{price} / T_{price} 2026–2034	Static; rolled hedge, variance removed 2026–2034
Base case	72.3	172.9 / 140.7	641.4	–	1,512.9 / 1,119.5	–	0.86 / 0.91; 0.63 / 0.67	0.80; 0.86 / 0.55; 0.63
Curve flat after December 2032	72.3	172.9 / 140.7	626.0	−2.4 (0.0)	1,471.1 / 1,092.4	−2.8 (0.1)	0.86 / 0.91; 0.63 / 0.66	0.80; 0.86 / 0.56; 0.63
Mean reversion, half-life 0.5 years	72.1	– / 114.6	640.1	−0.0 (0.1)	– / 921.0	−17.7 (0.2)	–; 0.09 / 0.10	– / 0.06; 0.09
Mean reversion, half-life 1 year	72.1	– / 121.2	640.1	−0.0 (0.1)	– / 958.8	−14.4 (0.2)	–; 0.27 / 0.28	– / 0.19; 0.26
Mean reversion, half-life 10 years	72.2	– / 160.0	640.8	+0.1 (0.1)	– / 1,339.9	+19.7 (0.3)	–; 0.80 / 0.84	– / 0.74; 0.80
Volatility 55%	72.5	246.0	644.9	+0.5 (0.5)	2,081.5	+37.6 (0.6)	0.94 / 0.98	0.81; 0.94
Purchases during the import year	70.9	164.9	628.9	−2.0 (0.0)	1,440.1	−4.8 (0.2)	0.85 / 0.89	0.81; 0.85
Purchases at the surrender deadline	74.5	190.0	660.9	+3.0 (0.1)	1,628.8	+7.7 (0.3)	0.87 / 0.92	0.77; 0.88
Two price factors, half of the variance short-term	72.3	147.4	640.8	−0.1 (0.1)	1,276.2	−15.6 (0.2)	0.77 / 0.81	0.72; 0.77
Two price factors, 80% of the variance short-term	72.2	128.1	640.5	−0.1 (0.2)	1,084.4	−28.3 (0.3)	0.58 / 0.61	0.54; 0.58
Basis noise, 5% a month (iid)	72.3	172.8	641.3	−0.0 (0.0)	1,511.6	−0.1 (0.1)	n.a.	0.80; 0.86
Persistent basis, s.d. 1%	72.3	172.8	641.4	−0.0 (0.0)	1,514.1	+0.1 (0.1)	n.a.	0.80; 0.86
Persistent basis, s.d. 2%	72.3	172.9	641.4	−0.0 (0.0)	1,514.1	+0.1 (0.1)	n.a.	0.80; 0.86
Verification share U(0, 1)	79.8	189.6 / 154.4	705.2	+9.9 (0.0)	1,648.8 / 1,214.5	+9.0 (0.3)	0.87 / 0.91; 0.66 / 0.69	0.81; 0.87 / 0.58; 0.66
Verification more likely where the ratio is low	69.9	169.2	620.4	−3.3 (0.0)	1,481.3	−2.1 (0.2)	0.83 / 0.89	0.77; 0.83
Volumes: independent annual shocks	72.4	173.9 / 141.3	641.7	+0.0 (0.1)	1,495.5 / 1,080.4	−1.1 (0.3)	0.92 / 0.94; 0.75 / 0.77	0.85; 0.91 / 0.65; 0.74
Volumes: permanent level shift	72.1	171.8	641.1	−0.0 (0.0)	1,537.1	+1.6 (0.3)	0.81 / 0.87	0.76; 0.82
Volume s.d. from the largest codes only	72.3	172.7 / 140.6	641.4	+0.0 (0.0)	1,511.8 / 1,118.7	−0.1 (0.1)	0.86 / 0.91; 0.64 / 0.67	0.80; 0.86 / 0.56; 0.63
2026 volumes not conditioned (2025 volumes)	72.3	172.9 / 140.7	656.8	+2.4 (0.0)	1,531.2 / 1,140.7	+1.2 (0.1)	0.85 / 0.90; 0.62 / 0.65	0.79; 0.85 / 0.54; 0.61

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Variant	Mean 2030	95th pct. 2030	Mean 2026–2034	Change in mean 2026–2034, % (s.e.)	95th pct. 2026–2034	Change in 95th pct. 2026–2034, % (s.e.)	S_{price} / T_{price} 2026–2034	Static; rolled hedge, variance removed 2026–2034
January–August 2026 ratio applied to every year	38.3	92.1 / 75.3	347.8	−45.8 (0.0)	811.0 / 607.2	−46.4 (0.1)	0.84 / 0.89; 0.59 / 0.63	0.78; 0.84 / 0.52; 0.59
Price–volume correlation +0.3 (levels)	76.4	198.0 / 157.8	682.1	+6.4 (0.1)	1,729.7 / 1,236.7	+14.3 (0.2)	n.a.; n.a.	0.82; 0.89 / 0.64; 0.72
Price–volume correlation −0.3 (levels)	68.4	150.0 / 125.0	603.5	−5.9 (0.0)	1,313.7 / 1,005.0	−13.2 (0.1)	n.a.; n.a.	0.77; 0.83 / 0.45; 0.52
Benchmark update for grey clinker from 2027	72.4	173.2	642.3	+0.1 (0.0)	1,514.6	+0.1 (0.0)	0.86 / 0.91	0.80; 0.86
CSCF 90% after 2030	72.3	172.9	648.8	+1.2 (0.0)	1,531.6	+1.2 (0.1)	0.86 / 0.91	0.80; 0.86
Phase-out: current law	74.7	178.4	663.1	+3.4 (0.0)	1,567.3	+3.6 (0.1)	0.87 / 0.91	0.80; 0.87
Phase-out: COM(2026) 616	69.9	167.1	619.8	−3.4 (0.0)	1,459.6	−3.5 (0.1)	0.86 / 0.90	0.80; 0.86

***Notes**: N = 65,536, the draws of the base case (common random numbers); changes against the base case of the same price process, with paired standard errors of the ratio of means (delta method; mean) and bootstrap standard errors (95th percentile, 100 resamples) in brackets. GBM unless stated, with mean reversion after the slash where computed; rows with only a mean-reversion value report it in the first columns. S_{price} / T_{price} from the closed form; not computed (n.a.) for the price–volume variants, where the closed form fails, and for the basis variants. Last column: share of the variance of the sum removed by the static hedge and, after the semicolon, by the rolled hedge (Table 6). Two price factors: short-term deviation with a half-life of 3.5 months and random-walk level, the short-term factor carrying the stated share of the instantaneous variance. Source: authors' calculations.*

A Moroccan carbon tax lowers the payment by the amount credited (Table 10). At 10 US dollars per tonne of CO_2-equivalent from 2027, about EUR 8.69, credited only on verified tonnage, the mean sum over 2026–2034 falls by 7.8%; if the Commission also set a default carbon price for Morocco equal to the tax, by 10.7%. At 5 dollars the reduction is 3.9%. The tax paid on the emissions of goods exported to the EU is EUR 69.2 million over 2027–2034 at 10 dollars, of which EUR 49.9 million (72%) is credited with verified tonnage only and EUR 68.7 million (99%) if default tonnage is credited too. The credited part moves revenue from the EU to Morocco without changing the combined amount of tax and CBAM payment on these goods; the uncredited part, EUR 19.3 million in the first case, adds to it. The model does not compute the tax on output sold in Morocco or exported elsewhere.

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Table 10. Moroccan carbon tax scenarios (EUR million).

Tax scenario (from 2027)	Mean payment 2026–2034	Change vs no tax	Amount credited 2027–2034	Tax paid on EU-bound output 2027–2034
None	641.4	0.0%	0.0	0.0
USD 5, credited on verified tonnage	616.4	−3.9%	25.0	34.6
USD 10, credited on verified tonnage	591.5	−7.8%	49.9	69.2
USD 10, also credited on default tonnage	572.7	−10.7%	68.7	69.2

Notes: *the tax applies from 2027, the first year for which the Commission may set default carbon prices (Regulation (EU) 2023/956, Art. 9(4)), to the actual emissions of all goods exported to the EU, converted at USD 1.151 per euro (Bank for International Settlements, 2026; September 2026 average). The credit is capped, for each good and year, at the payment left after the free-allocation adjustment; on default tonnage it assumes that the Commission sets a default carbon price for Morocco equal to the tax and caps the credit at the tax paid. Sums over 2027–2034, EUR million, undiscounted. Source: authors' calculations (N = 65,536).*

4. Discussion

4.1 What the decomposition says

Seen from October 2026, how much of the risk of the aggregate payment comes from the price depends above all on how the price behaves. Under the GBM and with a three-year half-life, the price is the largest single source of variance of every payment we decompose from 2027 on (2027, 2028, 2030 and 2034), and it explains more than half of the variance from 2028 under the GBM and from 2029 under mean reversion; for the sum over 2026–2034 its first-order index is 0.86 and 0.63, and 0.77 or 0.58 in the two-factor variants. Faster mean reversion in a single factor lowers it further, to 0.09 with a half-life of half a year, but only by assuming that the futures curve of October 2026 fixes the price level eight years ahead. The data do not settle the choice (Section 2.2), nor the persistence of volume shocks and the purchase schedule, which also move the shares. The shares are properties of the model under stated input distributions; with doubled illustrative ranges and mean reversion, the actual-to-default ratio overtakes the price for 2027. The scenario analysis is the better guide to the non-market inputs. There, the verification share, the actual emissions, the phase-out path and the revision of the default values set the level of the payment, by a factor of 3.3 between the most and least favourable scenarios, while the shape of its distribution changes little. Verified, installation-level data therefore matter mainly for the expected payment; in the global analysis, the variance they appear to remove is the variance we assigned to our own ignorance of them.

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The 2026 result needs the same care. The price explains almost none of the 2026 variance because three of the four quarterly prices were known on the evaluation date, and once 2026 volumes are conditioned on the trade data for January–August, most of the remaining variance comes from the actual emissions we do not observe. Both are consequences of the 2026 pricing rule and of the information set. The fall in imports in 2026 matters for the level of the payment as much as any single input we vary: if it lasted, the payment would be about half of what 2025 volumes imply. From 2027, the share of the price also depends on when certificates are bought, between 0.29 and 0.58 for the 2027 payment depending on the schedule.

4.2 What can be hedged, and by whom

Proposition 1 makes the link between the indices and hedging exact only for an instrument that does not exist, an average-price swap. Listed December futures come close. A static hedge placed on 23 October 2026 with the contracts then listed does as well for imports up to 2031, but less for later years, whose purchases run past the last contract: in a one-factor model with zero basis it removes 0.62 of the variance of the 2034 payment under the GBM and 0.29 with a three-year half-life, and 0.80 and 0.55 for the sum. That shortfall is price risk that cannot be locked in today at today's futures prices, not risk that futures cannot hedge: a hedge rolled into the December 2033 to 2035 contracts once they are listed removes as much as the ideal hedge in a one-factor model, and nearly as much in the two-factor variants, where calendar spreads can move. A basis between auction clearing prices and futures larger or more variable than the cases we test would lower these shares; and if price shocks are mostly transient, there is less price risk to hedge in the first place. Measured on the 95th percentile, the static hedge lowers the level of the cumulative cost-at-risk by 36% or 16%, much less than the excess over the mean, and leaves a 95th percentile of about EUR 950 million under both processes. Practitioners describe EUAs as an imperfect hedge because the certificate price follows average auction prices rather than market prices (Maleski, 2025). Early purchase of certificates is an alternative, constrained by the cash it ties up and by the repurchase limits of Article 23.

The party exposed is not always the one that can hedge. The payment is due from the EU declarant, which can trade EUA futures; a Moroccan exporter is exposed only to the extent that contracts pass the cost back to it and would have to hedge through instruments

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available under Moroccan exchange regulations, which we do not examine. At the level of one exporter, the problem is simpler than in the aggregate. For the DAP exporter of Section 3.6, the quantity is a commercial decision and the emissions are known, so the price is the only risk left in the model; in a one-factor model with zero basis, a static hedge removes all of it for imports up to 2031 and 0.71 or 0.41 of it for 2034, while a rolled hedge removes all of it (1.00 under both processes). A futures hedge locks in the futures price; if futures carry a risk premium (Trück & Weron, 2016), hedging changes the expected cost as well as its variance. Whether a firm should hedge depends on its financing constraints (Froot et al., 1993), on which we have no evidence for Moroccan exporters, and the argument is weakest for a large producer with access to external finance.

4.3 Who bears the payment

We model the payment due from EU declarants, not the cost borne by Moroccan exporters. If a share ρ of the payment is passed on to EU buyers, exporters bear $(1 - \rho)$ times the payment, and no estimate of ρ exists for Moroccan goods. The pass-through estimates of Section 1.3 concern costs that hit a whole market. A border charge on imports from one origin is different: its incidence depends on the charge relative to the carbon cost of the marginal supplier, EU producers with their residual ETS cost and other origins with their own CBAM payments, and on the elasticities of demand and supply. Exporters may also respond with quantities rather than prices (Vriz et al., 2026), which the price–volume variants only begin to capture. A simple multiplier with an arbitrary distribution would add nothing to these results, so we leave incidence to a model of competing suppliers.

4.4 Regulatory and scope risk

The phase-out path, the benchmark update and the CSCF after 2030 shift the expected payment over 2026–2034 by between 0.1% and 6.5%, and the revision of the default values by up to 8% either way in the scenario grid; these shifts matter for planning, though they add little variance under our representation. The largest regulatory unknown may be the scope. The goods on the Commission's list of downstream products that are not covered today were imported by the EU from Morocco for EUR 647.0 million in 2025, 64% of the value of the goods we model, or 2.5% of all EU imports from Morocco. This is an upper bound, since 42 of the 114 codes are covered only in part ("ex" codes); the codes

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covered in full account for EUR 360.4 million, and one of them, road wheels and their parts (CN 8708 70), for EUR 287.3 million (Eurostat, 2026; Council of the European Union, 2025). We do not compute a payment for these goods, because the product list was not final and no default values have been set for them.

4.5 A Moroccan carbon tax

A domestic tax at the rates discussed in Morocco would lower CBAM payments by 3.9–10.7% over 2026–2034, depending on its rate and on whether the Commission sets a default carbon price for Morocco. The reduction grows with the ratio of the tax rate to the certificate price and with the share of tonnage on which the tax can be credited, so it reflects the rates assumed rather than a property of the CBAM. Most of the tax paid on exports to the EU would be credited, 72% with verified tonnage only, so that most of it would move revenue from the EU to Morocco rather than add to the combined tax and CBAM payment on these goods. Its effect on output sold in Morocco or elsewhere, and on producers' competitiveness, is outside the model.

4.6 Limitations

The results depend on choices that we report as such. The price model matters most: the persistence of price deviations is not identified by four years of data, and neither process includes jumps, regime changes or the supply adjustments of the Market Stability Reserve; the two-factor variants rest on an illustrative split of the variance, and the distributions are centred on futures prices rather than on a real-world forecast. The rolled hedge assumes that ICE Endex keeps listing one new December contract a year. Four input ranges are illustrative, and the global indices are conditional on them, which the scenario grid and the range-scaling check make explicit. One verification share and one actual-to-default quantile apply to each sector, so the aggregate ignores diversification across firms. The free-allocation adjustment under actual emissions is approximated by the Column B benchmark. Dependence between inputs is examined only through variants, without Shapley effects. The years 2027–2034 are centred on 2025 volumes, while imports in January–August 2026 were, in tonnage, about half those of the same months of 2025, and the volume volatilities rest on seven annual observations. The one-year-ahead cost-at-risk conditions on the price path only. The futures curve comes from quotes read on 23 October

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2026 on a secondary site that shows no quote date, and the daily EUA series from a broker, although it matches ESMA, Commission and EEX figures; we found no quotes for the later December contracts that EEX's rules provide for. Electricity, the 50-tonne exemption, verification costs and the downstream extension are left out.

5. Conclusion

We estimate the distribution of the CBAM payment due on Moroccan goods imported into the EU from 2026 to 2034, under the legal parameters of the definitive period and the information available on 23 October 2026. The 2026 payment is small, EUR 19.1 million on average, and its price is almost known; its remaining risk comes from emission data. From 2027, on 2025 volumes, the mean payment rises to EUR 122.9 million in 2034, and its 95th percentile depends on the price process: EUR 352.4 million under a GBM and EUR 241.5 million with a three-year half-life of mean reversion.

Under stated conditions, the first-order Sobol index of the price group equals the share of variance that an ideal average-price hedge removes. For the sum over 2026–2034 it is 0.86 under the GBM, 0.63 with a three-year half-life and 0.58–0.77 in the two-factor variants. In a one-factor model with zero basis, a static hedge with the futures listed on ICE Endex on 23 October 2026 removes 0.80 under the GBM and 0.55 with a three-year half-life, and much less for 2033 and 2034 imports, whose certificates are bought after the last contract then listed; rolling into later contracts once they are listed removes about as much as the ideal hedge. Conditional on given emission data and rules, the hedgeable share is higher and stable across scenarios, while the data and rules set the level of the payment.

Implications and further research. For EU declarants, the price risk of the CBAM payment can be locked in today for imports up to 2031; for later imports it can be hedged by rolling into contracts not yet listed, at a calendar-spread and basis risk that our variants find small but cannot calibrate. Whether Moroccan exporters can hedge the part of the payment they bear depends on their contracts and on access to EUA futures, which we do not examine. Early purchase of certificates is an alternative with its own costs. For Moroccan policy, verified emission data and the regulatory files under negotiation matter for the expected payment more than for its risk; the downstream extension, which would cover goods imported for up to EUR 647.0 million in 2025, may matter most, but no payment can yet

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be computed for it. Four extensions would make these results more useful to firms: firm-level data on verification and emissions, evidence on the persistence of EUA price deviations, a model of incidence among competing suppliers, and the auction clearing prices needed to measure the basis between certificates and futures.

Declarations

Conflict of interest: no conflict of interest. Funding: no specific funding.

Declaration on the use of generative AI

The authors used Claude (Anthropic) in October 2026 to search legal, statistical and academic sources. The authors checked every source, figure and reference and take full responsibility for the content.

References

1. A&O Shearman. (2026, July 23). *The revision of the EU Emissions Trading System* [Client briefing]. https://www.mondaq.com/pdf/1821926.pdf

2. Abadie, L. M., Goicoechea, N., & Galarraga, I. (2017). Carbon risk and optimal retrofitting in cement plants: An application of stochastic modelling, MonteCarlo simulation and Real Options Analysis. *Journal of Cleaner Production, 142*(Part 4), 3117–3130. https://doi.org/10.1016/j.jclepro.2016.10.155

3. Agence Europe. (2026, October 22). First talks between European Parliament and EU Council on extending Carbon Border Adjustment Mechanism raise no major issues. *Europe Daily Bulletin*, No. 13965. https://agenceurope.eu/en/bulletin/article/13965/4/first-talks-between-european-parliament-and-eu-council-on-extending-carbon-border-adjustment-mechanism-raise-no-major-issues

4. Anderson, B., Borgonovo, E., Galeotti, M., & Roson, R. (2014). Uncertainty in climate change modeling: Can global sensitivity analysis be of help? *Risk Analysis, 34*(2), 271–293. https://doi.org/10.1111/risa.12117

5. Andrén, N., Jankensgård, H., & Oxelheim, L. (2005). Exposure-based cash-flow-at-risk: An alternative to VaR for industrial companies. *Journal of Applied Corporate Finance, 17*(3), 76–86. https://doi.org/10.1111/j.1745-6622.2005.00046.x

6. Bank for International Settlements. (2026). *US dollar exchange rates (WS_XRU), monthly averages, Morocco and euro area* [Data set]. Retrieved October 21, 2026,

 DOI: *10.5281/zenodo.24151126*

from https://stats.bis.org/api/v1/data/WS_XRU/M.MA+XM..A?startPeriod=2020-01&format=csv

7. Beaufils, T., Ward, H., Jakob, M., & Wenz, L. (2023). Assessing different European Carbon Border Adjustment Mechanism implementations and their impact on trade partners. *Communications Earth & Environment, 4*(1), 131. https://doi.org/10.1038/s43247-023-00788-4

8. Benz, E., & Trück, S. (2009). Modeling the price dynamics of CO2 emission allowances. *Energy Economics, 31*(1), 4–15. https://doi.org/10.1016/j.eneco.2008.07.003

9. Bidinot, G., Billio, M., Dufour, A., & Varotto, S. (2026). *The cost of carbon border adjustment: An installation-level microsimulation of the CBAM free allocation phase-out, 2025–2034* [Working paper]. SSRN. https://doi.org/10.2139/ssrn.7529303

10. Böhringer, C., Fischer, C., Rosendahl, K. E., & Rutherford, T. F. (2022). Potential impacts and challenges of border carbon adjustments. *Nature Climate Change, 12*(1), 22–29. https://doi.org/10.1038/s41558-021-01250-z

11. Borgonovo, E. (2007). A new uncertainty importance measure. *Reliability Engineering & System Safety, 92*(6), 771–784. https://doi.org/10.1016/j.ress.2006.04.015

12. Branger, F., & Quirion, P. (2014). Would border carbon adjustments prevent carbon leakage and heavy industry competitiveness losses? Insights from a meta-analysis of recent economic studies. *Ecological Economics, 99*, 29–39. https://doi.org/10.1016/j.ecolecon.2013.12.010

13. Bredin, D., & Parsons, J. (2016). Why is spot carbon so cheap and future carbon so dear? The term structure of carbon prices. *The Energy Journal, 37*(3), 83–108. https://doi.org/10.5547/01956574.37.3.dbre

14. Brown, G. W., & Toft, K. B. (2002). How firms should hedge. *The Review of Financial Studies, 15*(4), 1283–1324. https://doi.org/10.1093/rfs/15.4.1283

15. Butler, M. P., Reed, P. M., Fisher-Vanden, K., Keller, K., & Wagener, T. (2014). Identifying parametric controls and dependencies in integrated assessment models using global sensitivity analysis. *Environmental Modelling & Software, 59*, 10–29. https://doi.org/10.1016/j.envsoft.2014.05.001

16. Chemingui, M., Daccache, N., & Martella, F. (2026). *Trading under the Carbon Border Adjustment Mechanism: Risks and policy options for Arab economies* (E/ESCWA/CL3.SEP/2026/TP.2). United Nations Economic and Social Commission for Western Asia. https://unescwa.org/sites/default/files/pubs/pdf/trading-under-

 DOI: *10.5281/zenodo.24151126*

carbon-border-adjustment-mechanism-risks-policy-options-arab-economies-english.pdf

17. Cludius, J., de Bruyn, S., Schumacher, K., & Vergeer, R. (2020). Ex-post investigation of cost pass-through in the EU ETS – An analysis for six industry sectors. *Energy Economics, 91*, 104883. https://doi.org/10.1016/j.eneco.2020.104883

18. Commission Implementing Decision (EU) 2026/1862 of 23 July 2026 determining the uniform cross-sectoral correction factor for the adjustment of free allocations of emission allowances for the period 2026 to 2030. *Official Journal of the European Union*, L, 2026/1862, 24.7.2026. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L_202601862

19. Commission Implementing Regulation (EU) 2025/2548 of 10 December 2025 laying down rules for the application of Regulation (EU) 2023/956 of the European Parliament and of the Council as regards the calculation and publication of the price of CBAM certificates. *Official Journal of the European Union*, L, 2025/2548, 22.12.2025. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L_202502548

20. Commission Implementing Regulation (EU) 2025/2620 of 16 December 2025 laying down rules for the application of Regulation (EU) 2023/956 of the European Parliament and of the Council as regards the calculation of the free allocation adjustment to the number of CBAM certificates to be surrendered. *Official Journal of the European Union*, L, 2025/2620, 22.12.2025. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L_202502620

21. Commission Implementing Regulation (EU) 2025/2621 of 16 December 2025 laying down rules for the application of Regulation (EU) 2023/956 of the European Parliament and the Council as regards the establishment of default values. *Official Journal of the European Union*, L, 2025/2621, 31.12.2025. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32025R2621

22. Commission Implementing Regulation (EU) 2026/1412 of 26 June 2026 determining revised benchmark values for free allocation of emission allowances for the period from 2026 to 2030 pursuant to Article 10a(2) of Directive 2003/87/EC of the European Parliament and of the Council. *Official Journal of the European Union*, L, 2026/1412, 29.6.2026. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L_202601412

23. Commission Implementing Regulation (EU) 2026/1740 of 20 July 2026 correcting Implementing Regulation (EU) 2025/2621 as regards Annexes I and IV thereto. *Official Journal of the European Union*, L, 2026/1740, 31.7.2026. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L_202601740

 DOI: *10.5281/zenodo.24151126*

24. Conseil Économique, Social et Environnemental [CESE]. (2025). *L'impact du Mécanisme d'ajustement carbone (MACF) aux frontières européennes sur les exportations au Maroc* (Avis du CESE, Auto-saisine n° 86/2025). https://www.cese.ma/media/2025/11/Avis-MACF.pdf

25. Council of the European Union. (2025, December 17). *Annexes to the Proposal for a Regulation of the European Parliament and of the Council amending Regulation (EU) 2023/956 as regards the extension of its scope to downstream goods and anti-circumvention measures* (Council document 16973/25 ADD 1). https://data.consilium.europa.eu/doc/document/ST-16973-2025-ADD-1/en/pdf

26. Council of the European Union. (2026, June 9). *Draft Regulation of the European Parliament and of the Council amending Regulation (EU) 2023/956 as regards the extension of its scope to downstream goods and anti-circumvention measures – General approach* (Council document 10208/26). https://data.consilium.europa.eu/doc/document/ST-10208-2026-INIT/en/pdf

27. Dietz, S., Bowen, A., Dixon, C., & Gradwell, P. (2016). 'Climate value at risk' of global financial assets. *Nature Climate Change, 6*(7), 676–679. https://doi.org/10.1038/nclimate2972

28. Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a system for greenhouse gas emission allowance trading within the Union and amending Council Directive 96/61/EC. Consolidated version of 5 June 2023. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:02003L0087-20230605

29. European Commission. (2024, November 19). *Report from the Commission to the European Parliament and the Council on the functioning of the European carbon market in 2023* (COM(2024) 538 final). https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52024DC0538

30. European Commission. (2025a, December 17). *Proposal for a Regulation of the European Parliament and of the Council amending Regulation (EU) 2023/956 as regards the extension of its scope to downstream goods and anti-circumvention measures* (COM(2025) 989 final). https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52025PC0989

31. European Commission. (2025b, December 16). *Report from the Commission to the European Parliament and the Council on the application of the Regulation on the Carbon Border Adjustment Mechanism* (COM(2025) 783 final). https://data.consilium.europa.eu/doc/document/ST-16946-2025-INIT/en/pdf

32. European Commission. (2025c, December 3). *Report from the Commission to the European Parliament and the Council on the functioning of the European carbon*

 DOI: *10.5281/zenodo.24151126*

market in 2024 (COM(2025) 735 final). https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52025DC0735

33. European Commission. (2026a, July 17). *Proposal for a Directive of the European Parliament and of the Council amending Directive 2003/87/EC and Decision (EU) 2015/1814 as regards driving competitiveness and cost-effective decarbonisation* (COM(2026) 616 final). https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=COM:2026:616:FIN

34. European Commission. (2026b, August 14). *Guidance document No. 1: Introduction to CBAM concepts*. https://taxation-customs.ec.europa.eu/document/download/031abf60-21a9-4822-b258-ac8b111d8358_en

35. European Commission. (2026c). *Price of CBAM certificates*. Retrieved October 21, 2026, from https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism/price-cbam-certificates_en

36. European Commission. (2026d). *Carbon price paid in a third country under the carbon border adjustment mechanism (CBAM)* [Have your say initiative 14830]. Retrieved October 21, 2026, from https://ec.europa.eu/info/law/better-regulation/brpapi/groupInitiatives/14830

37. European Commission. (2026e). *Rules on the adjustment of CBAM certificates to reflect the EU ETS free allocation* [Have your say initiative 16933]. Retrieved October 24, 2026, from https://ec.europa.eu/info/law/better-regulation/brpapi/groupInitiatives/16933

38. European Energy Exchange [EEX]. (2026a). *EEX final settlement price emission futures* [Final settlement prices of EUA futures, notices dated 27 April, 18 May, 29 June, 27 July and 24 August 2026]. https://www.eex.com/fileadmin/Global/News/EEX/EEX_Customer_Information/2026/20260824_Customer_Information_-_FSP_Emission_Futures_August2026.pdf

39. European Energy Exchange [EEX]. (2026b). *EU ETS spot, futures and options* [Product page: EEX EUA Future, monthly, quarterly and yearly expiries]. Retrieved October 23, 2026, from https://www.eex.com/en/markets/environmentals/eu-ets-spot-futures-options

40. European Parliament. (2026). *Legislative Observatory: Procedure file 2026/0212(COD), EU Emissions Trading System and market stability reserve: competitiveness and cost-effective decarbonisation*. Retrieved October 21, 2026, from https://oeil.europarl.europa.eu/oeil/en/procedure-file?reference=2026/0212(COD)

 DOI: *10.5281/zenodo.24151126*

41. European Securities and Markets Authority [ESMA]. (2025, October 22). *ESMA market report on EU carbon markets 2025* (ESMA50-481369926-30552). https://www.esma.europa.eu/sites/default/files/2025-10/ESMA50-481369926-30552_Carbon_Markets_Report_2025.pdf

42. European Securities and Markets Authority [ESMA]. (2026, July 9). *ESMA market report on EU carbon markets 2026* (ESMA50-481369926-34622). https://www.esma.europa.eu/sites/default/files/2026-07/ESMA50-481369926-34622_Carbon_markets_report_2026.pdf

43. Eurostat. (2026). *Comext database, dataset DS-045409: EU trade since 1988 by HS2-4-6 and CN8* [EU27 imports from Morocco by CN code, annual 2019–2025 and monthly January 2025–August 2026]. Retrieved October 16–24, 2026, from https://ec.europa.eu/eurostat/api/comext/dissemination/sdmx/2.1/dataflow/ESTAT/DS-045409

44. Fabra, N., & Reguant, M. (2014). Pass-through of emissions costs in electricity markets. *American Economic Review, 104*(9), 2872–2899. https://doi.org/10.1257/aer.104.9.2872

45. Faloore, S. (2026). *The CBAM burden: Fiscal incidence and export revenue risk for African and Latin American industrial energy exporters* [Working paper]. SSRN. https://doi.org/10.2139/ssrn.7156178

46. Fort, J.-C., Klein, T., & Rachdi, N. (2016). New sensitivity analysis subordinated to a contrast. *Communications in Statistics – Theory and Methods, 45*(15), 4349–4364. https://doi.org/10.1080/03610926.2014.901369

47. Fowlie, M., Petersen, C., & Reguant, M. (2021). Border carbon adjustments when carbon intensity varies across producers: Evidence from California. *AEA Papers and Proceedings, 111*, 401–405. https://doi.org/10.1257/pandp.20211073

48. Froot, K. A., Scharfstein, D. S., & Stein, J. C. (1993). Risk management: Coordinating corporate investment and financing policies. *The Journal of Finance, 48*(5), 1629–1658. https://doi.org/10.2307/2329062

49. Fuchs, M., Stroebel, J., & Terstegge, J. (2026). Carbon VIX: Carbon price uncertainty and decarbonization investments. *Journal of Financial Economics, 183*, 104328. https://doi.org/10.1016/j.jfineco.2026.104328

50. Ganapati, S., Shapiro, J. S., & Walker, R. (2020). Energy cost pass-through in US manufacturing: Estimates and implications for carbon taxes. *American Economic Journal: Applied Economics, 12*(2), 303–342. https://doi.org/10.1257/app.20180474

 DOI: *10.5281/zenodo.24151126*

51. Harenberg, D., Marelli, S., Sudret, B., & Winschel, V. (2019). Uncertainty quantification and global sensitivity analysis for economic models. *Quantitative Economics, 10*(1), 1–41. https://doi.org/10.3982/QE866

52. Heindl, P. (2015). *The impact of administrative transaction costs in the EU emissions trading system* (ZEW Discussion Paper No. 15-076). ZEW – Leibniz Centre for European Economic Research. https://ideas.repec.org/p/zbw/zewdip/15076.html

53. ICE Endex. (2026). *EUA futures: Expiry calendar*. Retrieved October 23, 2026, from https://www.ice.com/products/197/EUA-Futures/expiry

54. Ishigami, T., & Homma, T. (1990). An importance quantification technique in uncertainty analysis for computer models. In *Proceedings of the First International Symposium on Uncertainty Modeling and Analysis* (pp. 398–403). IEEE Computer Society Press. https://doi.org/10.1109/ISUMA.1990.151285

55. Jansen, M. J. W. (1999). Analysis of variance designs for model output. *Computer Physics Communications, 117*(1–2), 35–43. https://doi.org/10.1016/S0010-4655(98)00154-4

56. Koch, N., Fuss, S., Grosjean, G., & Edenhofer, O. (2014). Causes of the EU ETS price drop: Recession, CDM, renewable policies or a bit of everything?—New evidence. *Energy Policy, 73*, 676–685. https://doi.org/10.1016/j.enpol.2014.06.024

57. Koch, N., Grosjean, G., Fuss, S., & Edenhofer, O. (2016). Politics matters: Regulatory events as catalysts for price formation under cap-and-trade. *Journal of Environmental Economics and Management, 78*, 121–139. https://doi.org/10.1016/j.jeem.2016.03.004

58. La Quotidienne. (2026, October 23). *PLF 2027: les principales nouveautés fiscales pour les ménages et les entreprises*. https://laquotidienne.ma/article/economie/PLF-2027-fiscales

59. Le360. (2025, September 30). *Marquage fiscal, taxe carbone, élargissement de la retenue à la source : voici les principales mesures fiscales et douanières du PLF 2026*. https://fr.le360.ma/economie/marquage-fiscal-taxe-carbone-elargissement-de-la-retenue-a-la-source-voici-les-principales-mesures_DK3TF5KKWVD3NLWOPIMEPI6PMU/

60. Liu, Z., Guan, D., Wei, W., Davis, S. J., Ciais, P., Bai, J., Peng, S., Zhang, Q., Hubacek, K., Marland, G., Andres, R. J., Crawford-Brown, D., Lin, J., Zhao, H., Hong, C., Boden, T. A., Feng, K., Peters, G. P., Xi, F., . . . He, K. (2015). Reduced carbon emission estimates from fossil fuel combustion and cement production in China. *Nature, 524*(7565), 335–338. https://doi.org/10.1038/nature14677

 DOI: *10.5281/zenodo.24151126*

61. Lo, A. W., & MacKinlay, A. C. (1988). Stock market prices do not follow random walks: Evidence from a simple specification test. *The Review of Financial Studies, 1*(1), 41–66. https://doi.org/10.1093/rfs/1.1.41

62. Magacho, G., Espagne, E., & Godin, A. (2024). Impacts of the CBAM on EU trade partners: Consequences for developing countries. *Climate Policy, 24*(2), 243–259. https://doi.org/10.1080/14693062.2023.2200758

63. Maleski, D. (2025, July 23). *Managing CBAM financial risk through hedging* [Presentation slides, Redshaw Advisors]. International Finance Corporation. https://www.ifc.org/content/dam/ifc/doc/2025/eu-cbam-dan-maleski-hedging-risk-presentation.pdf

64. McKinnon, R. I. (1967). Futures markets, buffer stocks, and income stability for primary producers. *Journal of Political Economy, 75*(6), 844–861. https://doi.org/10.1086/259363

65. Mehling, M. A., & Ritz, R. A. (2023). From theory to practice: Determining emissions in traded goods under a border carbon adjustment. *Oxford Review of Economic Policy, 39*(1), 123–133. https://doi.org/10.1093/oxrep/grac043

66. Montagnoli, A., & de Vries, F. P. (2010). Carbon trading thickness and market efficiency. *Energy Economics, 32*(6), 1331–1336. https://doi.org/10.1016/j.eneco.2010.04.001

67. Morchid, W., Haddad, E. A., & Savard, L. (2024). Measuring the cost of the European Union's Carbon Border Adjustment Mechanism on Moroccan exports. *Sustainability, 16*(12), 4967. https://doi.org/10.3390/su16124967

68. Moschini, G., & Hennessy, D. A. (2001). Uncertainty, risk aversion, and risk management for agricultural producers. In B. L. Gardner & G. C. Rausser (Eds.), *Handbook of agricultural economics* (Vol. 1A, pp. 87–153). Elsevier. https://doi.org/10.1016/S1574-0072(01)10005-8

69. Owen, A. B. (2013). Variance components and generalized Sobol' indices. *SIAM/ASA Journal on Uncertainty Quantification, 1*(1), 19–41. https://doi.org/10.1137/120876782

70. Owen, A. B. (2014). Sobol' indices and Shapley value. *SIAM/ASA Journal on Uncertainty Quantification, 2*(1), 245–251. https://doi.org/10.1137/130936233

71. Paek, J., & Kim, B. H. S. (2026). Comparing carbon border adjustment mechanism certificates to EU allowances: Price predictability and arbitrage opportunities. *Climate Policy*. Advance online publication. https://doi.org/10.1080/14693062.2026.2636028

 DOI: *10.5281/zenodo.24151126*

72. Paolella, M. S., & Taschini, L. (2008). An econometric analysis of emission allowance prices. *Journal of Banking & Finance, 32*(10), 2022–2032. https://doi.org/10.1016/j.jbankfin.2007.09.024

73. Perino, G., & Willner, M. (2016). Procrastinating reform: The impact of the market stability reserve on the EU ETS. *Journal of Environmental Economics and Management, 80*, 37–52. https://doi.org/10.1016/j.jeem.2016.09.006

74. Philip, D., & Shi, Y. (2016). Optimal hedging in carbon emission markets using Markov regime switching models. *Journal of International Financial Markets, Institutions and Money, 43*, 1–15. https://doi.org/10.1016/j.intfin.2016.03.003

75. Regulation (EU) 2023/956 of the European Parliament and of the Council of 10 May 2023 establishing a carbon border adjustment mechanism. *Official Journal of the European Union*, L 130, 16.5.2023, p. 52. Consolidated version of 20 October 2025: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:02023R0956-20251020

76. Regulation (EU) 2025/2083 of the European Parliament and of the Council of 8 October 2025 amending Regulation (EU) 2023/956 as regards simplifying and strengthening the carbon border adjustment mechanism. *Official Journal of the European Union*, L, 2025/2083, 17.10.2025. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32025R2083

77. Rolfo, J. (1980). Optimal hedging under price and quantity uncertainty: The case of a cocoa producer. *Journal of Political Economy, 88*(1), 100–116. https://doi.org/10.1086/260849

78. Royaume du Maroc. (2025). Dahir n° 1-25-67 du 19 joumada II 1447 (10 décembre 2025) portant promulgation de la loi de finances n° 50-25 pour l'année budgétaire 2026. *Bulletin officiel*, n° 7465 bis, 16 décembre 2025. https://www.sgg.gov.ma/BO/FR/2873/2025/BO_7465-bis_fr.pdf

79. Saltelli, A., Aleksankina, K., Becker, W., Fennell, P., Ferretti, F., Holst, N., Li, S., & Wu, Q. (2019). Why so many published sensitivity analyses are false: A systematic review of sensitivity analysis practices. *Environmental Modelling & Software, 114*, 29–39. https://doi.org/10.1016/j.envsoft.2019.01.012

80. Saltelli, A., Annoni, P., Azzini, I., Campolongo, F., Ratto, M., & Tarantola, S. (2010). Variance based sensitivity analysis of model output. Design and estimator for the total sensitivity index. *Computer Physics Communications, 181*(2), 259–270. https://doi.org/10.1016/j.cpc.2009.09.018

 DOI: *10.5281/zenodo.24151126*

81. Schwartz, E. S. (1997). The stochastic behavior of commodity prices: Implications for valuation and hedging. *The Journal of Finance, 52*(3), 923–973. https://doi.org/10.1111/j.1540-6261.1997.tb02721.x

82. Schwartz, E., & Smith, J. E. (2000). Short-term variations and long-term dynamics in commodity prices. *Management Science, 46*(7), 893–911. https://doi.org/10.1287/mnsc.46.7.893.12034

83. Seifert, J., Uhrig-Homburg, M., & Wagner, M. (2008). Dynamic behavior of CO2 spot prices. *Journal of Environmental Economics and Management, 56*(2), 180–194. https://doi.org/10.1016/j.jeem.2008.03.003

84. SendeCO2. (2026). *Precios CO2* [Data set; daily EUA prices, 2023–2026, from the yearly "Descargar histórico de precios" files]. Retrieved October 21, 2026, from https://www.sendeco2.com/es/precios-co2

85. Sijm, J., Neuhoff, K., & Chen, Y. (2006). CO2 cost pass-through and windfall profits in the power sector. *Climate Policy, 6*(1), 49–72. https://doi.org/10.1080/14693062.2006.9685588

86. Smith, C. W., & Stulz, R. M. (1985). The determinants of firms' hedging policies. *Journal of Financial and Quantitative Analysis, 20*(4), 391–405. https://doi.org/10.2307/2330757

87. Sobol', I. M. (2001). Global sensitivity indices for nonlinear mathematical models and their Monte Carlo estimates. *Mathematics and Computers in Simulation, 55*(1–3), 271–280. https://doi.org/10.1016/S0378-4754(00)00270-6

88. Song, E., Nelson, B. L., & Staum, J. (2016). Shapley effects for global sensitivity analysis: Theory and computation. *SIAM/ASA Journal on Uncertainty Quantification, 4*(1), 1060–1083. https://doi.org/10.1137/15M1048070

89. Stein, J. C., Usher, S. E., LaGattuta, D., & Youngen, J. (2001). A comparables approach to measuring cashflow-at-risk for non-financial firms. *Journal of Applied Corporate Finance, 13*(4), 100–109. https://doi.org/10.1111/j.1745-6622.2001.tb00430.x

90. TradingView. (2026). *Futures contracts for EUA Futures* [ICE Endex EUA futures; select market data provided by ICE Data Services; quotes undated, read on October 23, 2026]. https://www.tradingview.com/symbols/ICEENDEX-ECF1!/contracts

91. Trück, S., & Weron, R. (2016). Convenience yields and risk premiums in the EU-ETS: Evidence from the Kyoto commitment period. *Journal of Futures Markets, 36*(6), 587–611. https://doi.org/10.1002/fut.21780

 DOI: *10.5281/zenodo.24151126*

92. Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D., Burovski, E., Peterson, P., Weckesser, W., Bright, J., van der Walt, S. J., Brett, M., Wilson, J., Millman, K. J., Mayorov, N., Nelson, A. R. J., Jones, E., Kern, R., Larson, E., . . . SciPy 1.0 Contributors. (2020). SciPy 1.0: Fundamental algorithms for scientific computing in Python. *Nature Methods, 17*(3), 261–272. https://doi.org/10.1038/s41592-019-0686-2

93. Vriz, G. L., Cojoianu, T., Fischer, C., & Taschini, L. (2026). Early signs that the EU carbon border adjustment mechanism is reshaping EU–India steel trade. *Nature Climate Change, 16*(6), 737–741. https://doi.org/10.1038/s41558-026-02607-y

94. Zhong, J., & Pei, J. (2022). Beggar thy neighbor? On the competitiveness and welfare impacts of the EU's proposed carbon border adjustment mechanism. *Energy Policy, 162*, 112802. https://doi.org/10.1016/j.enpol.2022.112802

 DOI: *10.5281/zenodo.24151126*