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Strategic Decarbonization under the EU Carbon Border Adjustment Mechanism: An Evolutionary Game Model for Morocco

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Abstract

The European Union's Carbon Border Adjustment Mechanism (CBAM) entered its definitive phase in 2026, making verified embedded emissions an increasingly relevant determinant of market access for covered imports. Morocco is a useful applied case because it combines close integration with EU value chains, a strategic fertiliser industry, a carbon-pricing system still under development, and substantial renewable-energy ambitions. This study formulates a two-population evolutionary game between an adaptive Moroccan policy response and CBAM-exposed exporting firms. The model extends the government-exporter framework by deriving the firm's incremental CBAM incidence from sectoral EU exposure, commercial cost pass-through, the EU-domestic carbon-price gap and the emissions-intensity differential between high- and low-carbon production. Pure and mixed Nash equilibria, replicator dynamics, corner eigenvalues, nullclines, an interior saddle condition and comparative statics are derived analytically. In the economically relevant coordination regime, active policy and low-carbon production are jointly stable when public benefits cover implementation and incentive costs and when private transition costs are lower than low-carbon gains, policy support, avoided domestic penalties and avoided CBAM incidence. A higher residual CBAM burden lowers the government-activity threshold required for low-carbon adoption, whereas higher transition costs raise it. An illustrative normalised scenario verifies the analytical results without claiming empirical calibration. The framework identifies measurable quantities needed for future sector-level calibration and translates them into policy levers involving MRV, renewable energy, transition finance and carbon pricing.

Keywords: Carbon Border Adjustment Mechanism; Morocco; evolutionary game theory; environmental systems modelling; industrial decarbonisation; carbon pricing;

1 Introduction

Climate policy is increasingly transmitted through trade. The European Union (EU) Carbon Border Adjustment Mechanism (CBAM) is a prominent example: from 1 January 2026, the definitive regime requires covered EU importers to account for embedded emissions through CBAM certificates, with certificate prices linked to the EU Emissions Trading System (EU ETS) and eligible carbon prices paid in the country of origin taken into account [1,2]. The legal obligation is borne by the EU importer, but the economic incidence can be transmitted upstream through contract prices, sourcing decisions and demand. The relevant object for a non-EU producer is therefore not simply the statutory certificate payment, but the share of the resulting carbon-cost differential that reaches its own margin.

Morocco is a particularly useful case for analysing this mechanism. Its production and trade structure is closely connected to Europe, while fertilisers and other emissions-intensive products remain strategically important. Recent OECD evidence reports that the EU absorbs roughly 60% of Moroccan goods exports and that phosphate-based fertilisers accounted for 21% of export revenue in 2025 [3]. At the same time, exposure estimates depend strongly on the classification and product scope used. The OECD Economic Survey of Morocco estimated in 2024 that about 15% of Moroccan exports to the EU were in sectors expected to be covered by CBAM [29], whereas the Moroccan Economic, Social and Environmental Council (CESE) subsequently estimated that products directly covered under the current scope represented about 3.7% of Moroccan exports to the EU, concentrated mainly in fertilisers [4]. These figures should not be treated as interchangeable point estimates; they illustrate why sectoral exposure must be modelled explicitly rather than embedded in a single economy-wide assumption.

The domestic transition context is equally important. The OECD reports that Morocco had no explicit carbon tax or emissions-trading system in place in 2024 and that less than 30% of greenhouse-gas emissions were subject to a positive carbon price; it recommended a broader and more consistent approach to carbon pricing [29]. Morocco also targets a 45.5% emissions reduction by 2030 relative to its reference trajectory and net zero by 2050, while renewable capacity is intended to rise substantially [29]. In industry, OCP Group has announced a MAD 130 billion green investment programme for 2023-2027 and a carbon-neutrality objective before 2040 [6]. CBAM therefore interacts with a domestic transition that is already under way rather than operating as an isolated trade shock.

Existing research offers two complementary modelling traditions. Input-output, partial-equilibrium and computable-general-equilibrium studies quantify carbon-cost transmission, sectoral production effects and distributional impacts [7-12,17-20,27,28,30]. Amendola's multi-regional input-output analysis is especially relevant methodologically because it builds CBAM costs from policy-covered emissions, carbon-price shocks and supply-chain responses rather than treating the border measure as a generic tariff [30]. Evolutionary-game studies address a different problem: how strategic behaviour changes when policy

makers and firms learn from relative payoffs over time [13-16,21-23]. Huang et al. model this government-exporter interaction directly for China and derive replicator dynamics for active/passive policy responses and low-/high-carbon production [13].

A direct country relabelling of that game is not sufficient for Morocco. If CBAM does not enter the exporter payoff through a quantity linked to the actual border mechanism, the model becomes observationally close to a generic tax-subsidy game. This paper therefore introduces a sector-linked CBAM-incidence function and embeds it in the exporter payoff. The extension separates four distinct economic objects: the external EU carbon-price signal, the fraction of that cost borne by Moroccan suppliers, the emissions differential between production technologies, and domestic policy instruments chosen by Morocco.

The research question is: **under what conditions does the Morocco-CBAM system converge toward an active domestic policy response and low-carbon production, and how do sectoral exposure, carbon-price differences and transition costs shift the corresponding evolutionary thresholds?** The contribution is threefold. First, the paper provides a Morocco-specific analytical extension of the government-exporter evolutionary game with an explicit CBAM-incidence mechanism. Second, it derives static equilibria, replicator dynamics, eigenvalue-based stability conditions, nullclines, a basin-separating trajectory condition and comparative statics. Third, it maps these analytical quantities to measurable inputs that can support subsequent empirical calibration using trade, emissions, energy-price and technology-cost data.

The analysis is theoretical and is presented as an applied environmental-systems model rather than a forecast. The numerical section uses normalised values only to verify the analytical mechanism. No claim is made that those values estimate Moroccan behavioural parameters.

2 Institutional context and research gap

2.1 CBAM incidence, emissions accounting and Morocco

CBAM is intended to narrow the carbon-cost differential between EU production and covered imports [1,2]. For the initial product scope, the charge depends on the relevant EU ETS price, the carbon price recognised as having been paid in the country of origin, and the embedded emissions attributed to the imported product. Amendola formalises this policy logic in a multi-regional input-output setting by first calculating covered emissions per unit of output and then converting them into production and trade price shocks [30]. That structure is important here because it suggests that the exporter-facing incentive should be represented as a carbon-price gap multiplied by an emissions term, not as an arbitrary fixed penalty.

For Morocco, direct exposure is concentrated. Fertilisers are the clearest current channel; cement, iron and steel, aluminium and emerging hydrogen value chains may also be relevant. The difference between the OECD's 2024 sector-based estimate of roughly 15% and the CESE's later estimate of about 3.7% under the current direct product scope [4,29]

reinforces two modelling choices. First, exposure should be indexed by sector or product rather than imposed as a national constant. Second, the model should distinguish current covered output from potential future coverage and indirect supply-chain effects.

Emissions measurement also matters. Under CBAM, actual verified emissions can affect the charge, while default values may be used when adequate information is unavailable. Amendola highlights the strategic and distributional importance of actual versus default emissions in CBAM modelling [30]. For Moroccan firms, this means that measurement, reporting and verification (MRV) is not merely an administrative cost. It can alter the emissions value used in the border calculation and therefore the effective price signal transmitted to the exporter.

2.2 Domestic decarbonisation and carbon pricing

Morocco's policy environment creates both opportunities and constraints. The OECD documents a low current coverage of explicit carbon pricing, high reliance on coal in electricity generation, ambitious renewable-energy targets and a policy objective of net zero by 2050 [25,29]. These characteristics make electricity decarbonisation, grid access and technology finance directly relevant to the transition cost faced by exporting firms. They also imply that an eventual domestic carbon price could interact with CBAM in two directions: it may increase a firm's domestic carbon payment while reducing the residual border charge to the extent that the payment is recognised under EU rules [1,2].

This interaction is economically distinct from a simple punitive tax. If domestic carbon-pricing revenue is retained in Morocco and partly recycled toward low-carbon investment, the policy can simultaneously alter the relative cost of high-carbon production, the residual CBAM burden and the financing of transition. A model that collapses all three effects into one penalty parameter cannot identify these channels cleanly.

2.3 Research gap

Morocco-specific CBAM studies have begun to quantify exposure. Morchid et al. estimate an initial annual carbon bill of roughly USD 20-34 million under their Morocco-focused input-output scenarios [11]. Fertiliser-market analysis also indicates that demand elasticities and product composition can substantially affect the incidence of CBAM on individual suppliers [12]. These approaches are valuable for quantifying outcomes, but they do not model repeated strategic adjustment between domestic policy and exporter technology choice.

Evolutionary game theory addresses that behavioural margin. Huang et al. identify the government and export firms as the central actors, formulate their payoffs and derive replicator equations that determine the evolutionary stable states [13]. Their framework establishes the strategic logic of active government intervention, subsidies, penalties and low-carbon transition costs. The present paper retains that two-actor logic but modifies the exporter payoff so that CBAM enters through a separately derived incidence term. This

creates testable comparative statics with respect to EU exposure, the carbon-price gap and the emissions differential.

3 Model formulation

3.1 Actors, strategies and state variables

The game contains two adaptive populations. The first is an adaptive policy process rather than a literal population of governments. Let $x \in [0,1]$ denote the probability or propensity that the Moroccan policy regime is in an **active** CBAM-response state A ; $1 - x$ denotes a **passive** state P . This interpretation is consistent with repeated policy updating across budgets, regulatory cycles and observed exporter responses. The second population is the set of CBAM-exposed Moroccan exporters. Let $y \in [0,1]$ denote the share using a **low-carbon** technology L and $1 - y$ the share using a **high-carbon** technology H .

An active response may combine MRV infrastructure, transition finance, access to renewable electricity, sectoral support, domestic carbon-pricing reform and cooperation with EU institutions. Low-carbon production denotes a technology bundle that reduces the product's CBAM-relevant embedded emissions relative to the incumbent high-carbon technology.

3.2 Sector-linked CBAM incidence

Let $s \in \mathcal{S}$ index CBAM-exposed sectors. For sector s , define the residual CBAM carbon-price gap as

$$\tau_s = \max\{0, p_{ETS}^{EU} - \rho_s p_s^{MA}\},$$

where p_{ETS}^{EU} is the relevant EU ETS-linked certificate price, p_s^{MA} is the carbon price effectively paid in Morocco for the covered emissions, $\rho_s \in [0,1]$ is the proportion recognised for CBAM crediting.

Let $e_{H,s}^C$ and $e_{L,s}^C$ denote the CBAM-relevant embedded emissions per unit of covered output under high- and low-carbon technologies. These values are understood as the emissions values actually used for CBAM purposes after the applicable verification/default-value rules. The technological emissions differential is

$$\Delta e_s = e_{H,s}^C - e_{L,s}^C > 0.$$

Let $\alpha_s \in [0,1]$ be the share of sectoral output commercially exposed to the EU market, $\phi_s \in [0,1]$ the fraction of the border cost transmitted back to the Moroccan exporter, and $q_s > 0$ the relevant covered export quantity or normalisation scale. The expected incremental CBAM incidence on high-carbon relative to low-carbon production in sector s is then

$$B_s = \alpha_s \phi_s q_s \tau_s \Delta e_s.$$

For a representative multi-sector exporter population, define

$$B = \sum_{s \in \mathcal{S}} w_s B_s, \quad w_s \geq 0, \quad \sum_{s \in \mathcal{S}} w_s = 1.$$

This specification mirrors the institutional logic of CBAM and the emissions-times-price treatment used in input-output modelling [30]. It also makes the Moroccan application explicit. Exposure enters through α_s , contractual incidence through ϕ_s , carbon-price differences through τ_s , and technology/MRV through Δe_s .

When $p_{ETS}^{EU} > \rho_s p_s^{MA}$, the direct comparative statics of sectoral incidence are

$$\frac{\partial B_s}{\partial p_{ETS}^{EU}} = \alpha_s \phi_s q_s \Delta e_s > 0,$$

$$\frac{\partial B_s}{\partial p_s^{MA}} = -\rho_s \alpha_s \phi_s q_s \Delta e_s \leq 0,$$

and

$$\frac{\partial B_s}{\partial \Delta e_s} = \alpha_s \phi_s q_s \tau_s > 0.$$

These derivatives describe the border-incidence component only. A domestic carbon price may also enter the separate domestic-policy cost parameter defined below, so its total effect on firms need not equal its effect on B_s alone.

3.3 Payoffs and assumptions

Table 1 defines the remaining payoff parameters. Monetary quantities can be interpreted per representative firm and period or as consistently normalised payoff units.

Table 1 Model parameters and interpretation

Symbol	Interpretation
R_G	Government strategic, environmental and competitiveness benefit when active policy coincides with low-carbon production
C_G	Public implementation and administrative cost of the active policy package
S	Direct subsidy or transition support received by a low-carbon firm under active policy
E	Additional export, market-access or green-production incentive generated by active policy
F	Domestic differential cost imposed on high-carbon production under active policy (penalty, compliance cost and/or carbon-pricing effect)
L_G	Government macroeconomic/environmental loss while firms remain high carbon
π_H	Baseline operating profit under the incumbent high-carbon technology before policy and CBAM incidence
$\Delta \pi_L$	Additional operating, market-access or reputational profit associated with low-carbon production
C_L	Incremental private transition cost of adopting low-carbon production
B	Expected incremental CBAM incidence on high-carbon relative to low-carbon production, defined above

The payoff matrix is

Table 2 Payoff matrix for the Morocco-CBAM game

Policy state	Firm technology	Government payoff	Firm payoff
Active (A)	Low carbon (L)	$R_G - C_G - E - S$	$\pi_H + \Delta\pi_L + E + S - C_L$
Active (A)	High carbon (H)	$F - C_G - L_G$	$\pi_H - F - B$
Passive (P)	Low carbon (L)	0	$\pi_H + \Delta\pi_L - C_L$
Passive (P)	High carbon (H)	$-L_G$	$\pi_H - B$

Four assumptions are explicit. First, B is a *differential* burden, so the low-carbon payoff is normalised relative to any residual CBAM charge that both technologies would pay. Second, B appears under both domestic policy states because CBAM is externally determined by EU rules. Third, F is domestic and appears only under active policy. If F contains a domestic carbon-price component, B must be calculated using the residual EU charge after any recognised credit, avoiding double counting. Fourth, L_G is incurred whenever firms remain high carbon and therefore cancels from the government's switching condition in this parsimonious specification.

3.4 Static Nash equilibria

The active/low-carbon state (A, L) is a Nash equilibrium if neither actor gains from unilateral deviation. The government's condition is

$$R_G \geq C_G + E + S,$$

while the firm's condition is

$$C_L \leq \Delta\pi_L + E + S + F + B.$$

The remaining pure-strategy conditions are shown in Table 3.

Table 3 Pure-strategy Nash equilibrium conditions

Equilibrium	Government condition	Firm condition	Interpretation
(A, L)	$R_G \geq C_G + E + S$	$C_L \leq \Delta\pi_L + E + S + F + B$	Active transition equilibrium
(A, H)	$F \geq C_G$	$C_L \geq \Delta\pi_L + E + S + F + B$	Government acts but firms remain high carbon
(P, L)	$R_G \leq C_G + E + S$	$C_L \leq \Delta\pi_L + B$	Firm-led transition
(P, H)	$F \leq C_G$	$C_L \geq \Delta\pi_L + B$	Policy and technology inertia

For mixed strategies, each population is indifferent at the interior thresholds

$$x^* = \frac{C_L - \Delta\pi_L - B}{E + S + F},$$

$$y^* = \frac{C_G - F}{R_G - E - S - F},$$

provided the denominators are non-zero and the resulting values lie in $(0,1)$.

4 Evolutionary dynamics and formal stability analysis

4.1 Replicator equations

Following the standard replicator principle used in evolutionary games [13,22,23], the growth rate of a strategy equals its current share multiplied by its payoff advantage. Let U_A and U_P be the government's expected payoffs. From Table 2,

$$\begin{aligned} U_A &= y(R_G - C_G - E - S) + (1 - y)(F - C_G - L_G), \\ U_P &= -(1 - y)L_G, \end{aligned}$$

and hence

$$U_A - U_P = y(R_G - E - S - F) + F - C_G.$$

Therefore,

$$\dot{x} = x(1 - x)[y(R_G - E - S - F) + F - C_G].$$

For firms, let V_L and V_H denote expected payoffs from low- and high-carbon technologies. Their difference is

$$V_L - V_H = x(E + S + F) + \Delta\pi_L + B - C_L,$$

so

$$\dot{y} = y(1 - y)[x(E + S + F) + \Delta\pi_L + B - C_L].$$

For compactness define

$$\begin{aligned} A &= R_G - E - S - F, & c &= F - C_G, \\ K &= E + S + F > 0, & d &= \Delta\pi_L + B - C_L. \end{aligned}$$

The dynamic system becomes

$$\begin{aligned} \dot{x} &= x(1 - x)(Ay + c), \\ \dot{y} &= y(1 - y)(Kx + d). \end{aligned}$$

The nullclines inside the unit square are therefore

$$y^* = -\frac{c}{A} = \frac{C_G - F}{R_G - E - S - F}, \quad x^* = -\frac{d}{K} = \frac{C_L - \Delta\pi_L - B}{E + S + F}.$$

4.2 Feasibility and coordination regime

The economically relevant bistable case is a coordination regime in which $A > 0$ and the interior nullclines lie in $(0,1)^2$. Since $K > 0$, the interior equilibrium exists in this regime if and only if

$$F < C_G < R_G - E - S,$$

and

$$\Delta\pi_L + B < C_L < \Delta\pi_L + B + E + S + F.$$

The first inequality means that active policy is not worthwhile when firms remain high carbon, but becomes worthwhile once low-carbon adoption is sufficiently widespread. The second means that firms do not decarbonise autonomously, yet will do so once policy support and avoided high-carbon costs are sufficiently strong.

4.3 Jacobian, eigenvalues and corner stability

The Jacobian of the system is

$$J(x, y) = \begin{pmatrix} (1 - 2x)(Ay + c) & x(1 - x)A \\ y(1 - y)K & (1 - 2y)(Kx + d) \end{pmatrix}.$$

At the four corner equilibria, the eigenvalues are particularly transparent:

$$E_0 = (0,0): \quad \lambda_1 = c, \quad \lambda_2 = d,$$

$$E_1 = (0,1): \quad \lambda_1 = A + c, \quad \lambda_2 = -d,$$

$$E_2 = (1,0): \quad \lambda_1 = -c, \quad \lambda_2 = K + d,$$

$$E_3 = (1,1): \quad \lambda_1 = -(A + c), \quad \lambda_2 = -(K + d).$$

Substitution yields the economic stability conditions in Table 4.

Table 4 Local stability of the corner equilibria

Equilibrium	Stability conditions	Economic interpretation
$E_0 = (0,0)$	$F < C_G$ and $C_L > \Delta\pi_L + B$	Passive/high-carbon trap
$E_1 = (0,1)$	$R_G < C_G + E + S$ and $C_L < \Delta\pi_L + B$	Firm-led low-carbon state
$E_2 = (1,0)$	$F > C_G$ and $C_L > \Delta\pi_L + E + S + F + B$	Active-policy/high-carbon state
$E_3 = (1,1)$	$R_G > C_G + E + S$ and $C_L < \Delta\pi_L + E + S + F + B$	Active/low-carbon state

Proposition 1. If $A > 0$, $K > 0$ and the interior-equilibrium feasibility conditions above hold, then E_0 and E_3 are locally asymptotically stable, E_1 and E_2 are unstable, and the interior equilibrium $E_4 = (x^*, y^*)$ is a saddle.

Proof. Under the feasibility conditions, $c < 0$, $d < 0$, $A + c > 0$ and $K + d > 0$. Thus both eigenvalues are negative at E_0 and E_3 , whereas both are positive at E_1 and E_2 . At E_4 , the diagonal elements of J are zero and

$$J(E_4) = \begin{pmatrix} 0 & x^*(1 - x^*)A \\ y^*(1 - y^*)K & 0 \end{pmatrix},$$

so

$$\lambda_{\pm} = \pm \sqrt{x^*(1-x^*)y^*(1-y^*)AK}.$$

Because $A > 0$ and $K > 0$, the eigenvalues have opposite signs. E_4 is therefore a saddle.

The proposition formalises path dependence: the desirable outcome is locally stable, but it is not globally guaranteed. Initial policy commitment and initial firm adoption determine which basin of attraction the system enters.

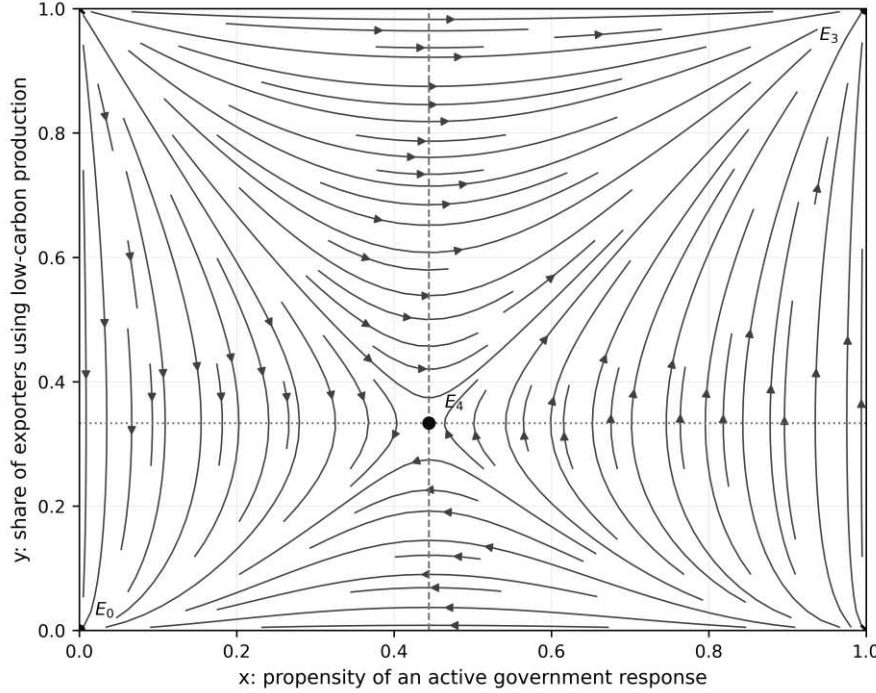


Fig. 1 Phase portrait for the illustrative Morocco-CBAM evolutionary game under the baseline normalised scenario

4.4 Trajectory invariant and basin boundary

Inside the open unit square, division of the two replicator equations gives

$$\frac{dy}{dx} = \frac{y(1-y)(Kx+d)}{x(1-x)(Ay+c)}.$$

Separating variables and integrating yields the trajectory invariant

$$\mathcal{H}(x, y) = c \ln y - (A + c) \ln(1 - y) - d \ln x + (K + d) \ln(1 - x) = \mathcal{C}.$$

In the bistable coordination regime, the stable manifold of the interior saddle is the level set

$$\mathcal{H}(x, y) = \mathcal{H}(x^*, y^*).$$

This curve is the analytical basin boundary between trajectories converging to E_0 and those converging to E_3 . It provides a more precise interpretation of policy sequencing than a phase portrait alone: an early policy or technology intervention matters when it moves the state across this boundary.

4.5 Comparative statics

The firm switching threshold can be written as

$$x^* = \frac{N}{K}, \quad N = C_L - \Delta\pi_L - B.$$

For an interior threshold $N > 0$,

$$\begin{aligned} \frac{\partial x^*}{\partial B} &= -\frac{1}{K} < 0, & \frac{\partial x^*}{\partial C_L} &= \frac{1}{K} > 0, \\ \frac{\partial x^*}{\partial \Delta\pi_L} &= -\frac{1}{K} < 0, \end{aligned}$$

and

$$\frac{\partial x^*}{\partial E} = \frac{\partial x^*}{\partial S} = \frac{\partial x^*}{\partial F} = -\frac{N}{K^2} = -\frac{x^*}{K} < 0.$$

Thus a larger residual CBAM incidence, greater low-carbon profitability, stronger support or a stronger domestic high-carbon cost all reduce the policy-activity threshold at which firms switch toward low-carbon production; larger transition cost increases it.

Combining the sector-incidence equation with the threshold gives, whenever the residual carbon-price gap is positive,

$$\frac{\partial x^*}{\partial p_{ETS}^{EU}} = -\frac{1}{K} \sum_{s \in \mathcal{S}} w_s \alpha_s \phi_s q_s \Delta e_s < 0,$$

while the direct border-incidence effect of a recognised Moroccan carbon price is

$$\left. \frac{\partial x^*}{\partial p_s^{MA}} \right|_{F \text{ fixed}} = \frac{w_s \rho_s \alpha_s \phi_s q_s \Delta e_s}{K} > 0.$$

The second derivative is intentionally conditional on holding F fixed. In practice, a Moroccan carbon price may simultaneously increase F and reduce B_s , so its total effect on x^* is policy-design dependent. This is precisely why domestic carbon pricing should not be represented as a single undifferentiated penalty.

A useful limiting condition is

$$B \geq C_L - \Delta\pi_L.$$

When it holds, $x^* \leq 0$ and low-carbon production is privately advantageous even without an additional active policy package. This is a firm-led transition region, not necessarily a welfare-improving outcome, because a large B can also reduce export margins and demand.

5 Illustrative numerical verification

5.1 Baseline normalised case

The numerical exercise verifies the analytical structure; it does not calibrate Morocco. To avoid importing behavioural parameters from another country, the values are normalised and selected only to place the system in the coordination regime:

$$R_G = 15, \quad C_G = 6, \quad S = 3, \quad E = 2, \quad F = 4, \\ \Delta\pi_L = 4, \quad C_L = 10, \quad B = 2.$$

These imply

$$A = 6, \quad c = -2, \quad K = 9, \quad d = -4,$$

and therefore

$$x^* = \frac{4}{9} = 0.444, \quad y^* = \frac{2}{6} = 0.333.$$

At E_0 , the eigenvalues are $(-2, -4)$; at E_3 , they are $(-4, -5)$. Both corners are locally stable. At the interior equilibrium,

$$\lambda_{\pm} = \pm \sqrt{\left(\frac{4}{9}\right)\left(\frac{5}{9}\right)\left(\frac{1}{3}\right)\left(\frac{2}{3}\right)(6)(9)} \approx \pm 1.72,$$

confirming that E_4 is a saddle. The phase portrait in Fig. 1 is therefore consistent with the analytical classification rather than being used as evidence in place of it.

5.2 Sensitivity to CBAM incidence

Holding the other normalised parameters fixed, variation in B changes x^* linearly while leaving y^* unchanged because B enters the firm payoff directly.

Table 5 Sensitivity of the firm switching threshold to CBAM incidence

B	$x^* = (C_L - \Delta\pi_L - B) / (E + S + F)$	Interpretation
0	0.667	Strong government activity is required for private low-carbon adoption
2	0.444	Baseline coordination case
4	0.222	Border-cost differentiation materially strengthens the transition incentive
6	0.000	Low-carbon production is privately preferred even at $x = 0$

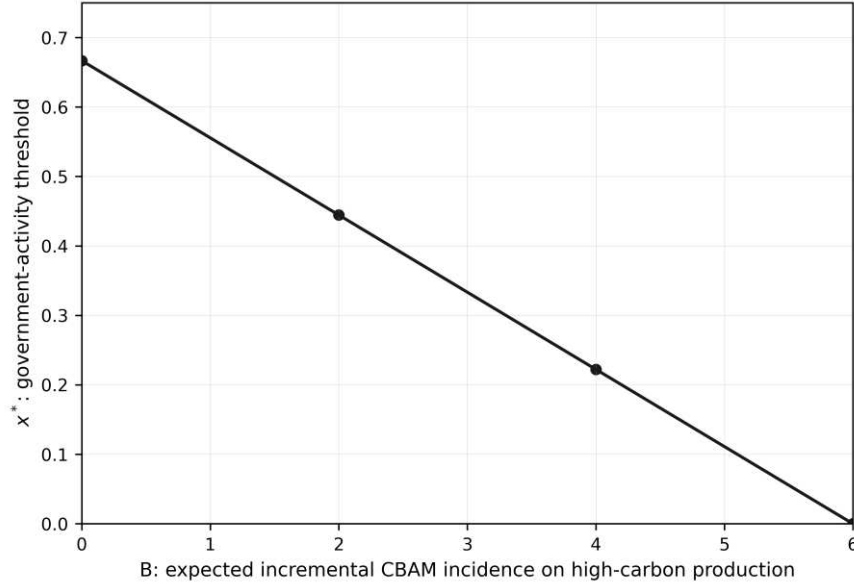


Fig. 2 Effect of expected CBAM incidence on the government-activity threshold for low-carbon adoption

At the baseline, the local derivatives are

$$\frac{\partial x^*}{\partial B} = -\frac{1}{9} = -0.111, \quad \frac{\partial x^*}{\partial C_L} = \frac{1}{9} = 0.111,$$

and

$$\frac{\partial x^*}{\partial E} = \frac{\partial x^*}{\partial S} = \frac{\partial x^*}{\partial F} = -\frac{4}{81} \approx -0.049.$$

The normalised elasticity of the switching threshold with respect to CBAM incidence is

$$\varepsilon_{x^*,B} = \frac{\partial x^*}{\partial B} \frac{B}{x^*} = -\frac{B}{C_L - \Delta\pi_L - B} = -0.50.$$

The corresponding elasticity with respect to transition cost is

$$\varepsilon_{x^*,C_L} = \frac{C_L}{C_L - \Delta\pi_L - B} = 2.50.$$

These values are not empirical estimates. They simply show, within the chosen normalisation, that the switching threshold is more sensitive to the assumed transition cost than to the assumed CBAM incidence. This supports the paper's policy emphasis on reducing C_L rather than relying on an external border cost to force adjustment.

6 Discussion and policy implications

6.1 What the model adds to the Morocco-CBAM debate

The model reconciles two observations that can otherwise appear contradictory. First, current direct CBAM exposure is relatively narrow at the aggregate export level [4].

Second, the incentive can still be strong for the specific firms and product lines that are covered, especially where embedded emissions are high and EU sales are commercially important. This is why an economy-wide measure of exposed exports is not enough to infer firm-level behaviour.

The explicit B term also prevents the border mechanism from disappearing into a generic environmental-policy game. A domestic penalty F is controlled by the Moroccan policy maker; the border incidence B is generated externally through EU rules, carbon prices, embedded emissions and commercial pass-through. These variables can move in different directions. For example, a credible Moroccan carbon price could raise a domestic firm's explicit carbon payment while reducing the net CBAM amount if the payment is recognised under EU rules [2]. If the domestic revenue is recycled toward transition investment, the same reform could also reduce C_L . A one-parameter "carbon tax" treatment would miss these channels.

The framework also clarifies why MRV is economically important. The emissions values $e_{H,s}^C$ and $e_{L,s}^C$ are the values used for CBAM purposes, not purely engineering estimates. Where verification allows a producer to demonstrate emissions below an applicable default, the measured border charge can change materially [30]. MRV therefore affects both compliance quality and the economically relevant B_s faced by the exporter.

6.2 Transition costs are the central domestic lever

The strongest domestic lever in the model is C_L . Lowering transition costs expands the range of states in which low-carbon production is attractive and reduces x_{int} . For Morocco, this supports policies that improve access to renewable electricity, energy-efficiency finance, industrial electrification, cleaner process technology and low-carbon feedstocks. In fertilisers, green ammonia is particularly relevant because ammonia is both a major input and a significant source of embedded emissions.

Targeted instruments are preferable to blanket support. The current direct CBAM exposure is concentrated [4], and transition technologies differ substantially across fertilisers, cement, steel and aluminium. Subsidies should therefore be linked to verifiable emissions reductions, additional investment and a credible counterfactual rather than granted simply because a firm exports to the EU. This also limits the public-cost term $C_G + E + S$, which must remain below the strategic benefit R_G for the active equilibrium to be sustainable.

OCP's announced investment programme shows that firm-led transition is not hypothetical. Its 2023-2027 green investment programme is valued at MAD 130 billion and targets carbon neutrality before 2040 [6]. In model terms, large incumbents may already possess sufficiently high $\Delta\pi_L$, sufficiently low financing constraints, or sufficiently high expected B to move toward low-carbon production with limited marginal subsidy. Smaller suppliers may face a very different C_L , strengthening the case for differentiated support.

6.3 Carbon pricing should be analysed as a fiscal-and-trade instrument

Morocco's carbon tax remains under consideration [5]. The model does not identify an optimal tax rate, but it does show why the policy should be evaluated jointly with CBAM. A domestic carbon price can raise the opportunity cost of high-carbon production, corresponding partly to F , and if recognised under CBAM can reduce the net border component of B . It can also generate domestic fiscal revenue that may be recycled into S or into infrastructure that lowers C_L .

These channels pull in different directions for firms' cash flow and for government welfare. A gradual approach can therefore be justified on analytical rather than purely political grounds: the rate, sectoral coverage, revenue recycling, treatment of trade-exposed firms and compatibility with EU crediting rules should be designed together. The goal is not merely to replace a payment at the EU border with a payment at home; it is to create a domestic incentive structure that finances lower emissions and preserves export competitiveness.

6.4 MRV and Morocco-EU cooperation

The border burden depends on the credibility of embedded-emissions information. Morocco can reduce avoidable compliance and information costs by strengthening firm-level carbon accounting, accredited verification, digital reporting and sector-specific emission factors. The European Commission's CBAM guidance for fertilisers provides detailed reporting and emissions-calculation requirements that can be used as a basis for technical alignment [24].

International cooperation can affect several model parameters simultaneously. Technical assistance and shared standards can lower C_G ; technology transfer and concessional finance can lower C_L ; recognition of robust emissions data can reduce avoidable elements of B ; and stable access to low-carbon EU markets can raise $\Delta\pi_L$ or E . This is one reason why Morocco-EU cooperation is not a separate diplomatic add-on to the model. It changes the payoffs that determine the evolutionary path. This broader role of international carbon-pricing coordination is also emphasized in the economic-modelling literature [26].

6.5 Policy priorities implied by the thresholds

Table 6 maps the model's thresholds to policy actions. The point is not that every parameter should be maximised. Some instruments are costly, and excessive subsidy can make $R_G < C_G + E + S$, undermining the government's own incentive to sustain an active response. Policy design should instead seek the lowest-cost combination that places the system inside the stability region of E_3 .

Table 6 Policy levers and their connection to the model

Policy lever	Main channel	parameter	Model implication
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Policy lever	Main channel	parameter	Model implication
Renewable energy, efficiency finance, green-ammonia infrastructure	Lower C_L		Makes low-carbon adoption profitable at lower government activity
Verified low-carbon standards, green procurement, long-term offtake	Raise $\Delta\pi_L$ or E		Increases the private return to transition
Targeted, performance-based subsidies	Raise S , but also public cost		Can accelerate adoption if additionality is high; excessive support can weaken government sustainability condition
Credible domestic penalties/carbon pricing	Raise F ; potentially lower net B if EU credit applies		Discourages high-carbon production but must be coordinated with trade and revenue-recycling effects
MRV and accredited verification	Reduce avoidable B and C_G over time		Protects firms from unnecessary border incidence and lowers administrative friction
Morocco-EU technical and financial cooperation	Lower C_G, C_L ; raise E		Expands the stability region of the active/low-carbon equilibrium

7 Limitations and directions for empirical calibration

The model is intentionally parsimonious and its analytical precision should not be confused with empirical precision.

First, the numerical exercise is not a Morocco calibration. A sector-level calibration of B_s requires covered export quantities q_s , EU exposure α_s , pass-through estimates ϕ_s , CBAM-relevant emissions $e_{j,s}^C$, EU ETS/CBAM prices and the recognised Moroccan carbon price. Calibration of the remaining payoff terms requires technology-investment costs, energy prices, low-carbon operating benefits, subsidy expenditure and the fiscal/administrative cost of policy implementation.

Second, the pass-through coefficient ϕ_s compresses demand and bargaining responses into one reduced-form parameter. Amendola's MRIO framework explicitly propagates price shocks through final demand and intermediate-input substitution [30], while fertiliser-specific work estimates product-level demand responses [12]. A future hybrid model could replace ϕ_s with an import-demand or input-output block and feed the resulting sectoral incidence back into the evolutionary game.

Third, the exporter population remains aggregated within each strategic type. Firms differ in energy contracts, technology vintage, access to finance, emissions intensity and bargaining power. A heterogeneous-agent extension could model C_L , $\Delta\pi_L$ and ϕ_s as distributions rather than constants.

Fourth, the policy variable x is an adaptive propensity, not a literal fraction of Moroccan governments. This interpretation is analytically useful for replicator dynamics, but a richer institutional model could distinguish fiscal authorities, energy regulators, industrial-policy agencies and the EU importer as separate strategic actors.

Fifth, the deterministic system abstracts from uncertainty in EU ETS prices, exchange rates, technology costs, verification outcomes and future CBAM scope. Stochastic replicator dynamics, real-options methods or scenario-based uncertainty analysis would be natural extensions. The model structure also lends itself to a design-of-experiments approach in which parameter ranges are sampled systematically and the stability region of E_3 is evaluated rather than relying on a single illustrative parameter vector.

These limitations define the intended use of the current model. It identifies mechanisms, thresholds and measurable calibration targets. Forecasting trade, emissions or welfare effects requires an empirical extension.

8 Conclusion

CBAM makes the interaction between carbon intensity and EU market access more explicit for covered products. In Morocco, aggregate exposure estimates vary with sectoral classification and product scope, but the economically important point is that exposure is highly concentrated. A representative-firm model therefore needs to recover the border incentive from sector-level quantities rather than treat CBAM as a uniform national tax shock.

This study extends the government-exporter evolutionary game in two ways. First, it derives the incremental border incidence as $B_s = \alpha_s \phi_s q_s \tau_s \Delta e_s$ and aggregates it across exposed sectors. Second, it provides a complete stability characterization of the resulting two-dimensional replicator system, including corner eigenvalues, interior-feasibility conditions and an analytical trajectory invariant that defines the basin boundary in the coordination regime.

The principal result is conditional rather than deterministic. The active-policy/low-carbon equilibrium is locally stable when the public return to intervention exceeds implementation and incentive costs and when private transition cost is below the combined value of low-carbon gains, support, domestic high-carbon costs and avoided CBAM incidence. A larger residual border burden lowers the firm switching threshold, but this is not a welfare argument for a larger CBAM charge. Morocco's direct policy leverage is instead to lower C_L , strengthen credible MRV, improve the low-carbon return $\Delta \pi_L$, and coordinate carbon pricing so that domestic incentives and CBAM crediting are treated consistently.

The framework is designed for empirical extension. Combining product-level Morocco-EU trade with verified embedded emissions, EU ETS prices, technology costs and pass-through estimates would permit sector-specific values of B_s and the other payoff parameters. The resulting calibrated model could then be used to compare decarbonisation packages by their ability to move exporters across the basin boundary while also accounting for fiscal cost, trade effects and emissions reductions.

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Author contributions

Tarek DRISSI BOUZAID: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing – original draft, Writing – review & editing, Project administration. **Faouzi DAOUI**: Methodology, Software, Validation, Supervision, Writing – review & editing. **Said TOUNSI**: Methodology, Formal analysis, Investigation, Resources, Data Curation, Validation, Writing – review & editing. **El hassane MANOUZE**: Methodology, Validation, Supervision, Writing – review & editing. **Sara MOUJTAHID and Mohamed IDALFAHIM**: Supervision, Software, Writing – review & editing.

Data availability No new empirical dataset was generated for this theoretical study. The normalised values used in the illustrative scenario are reported in Section 5. All contextual statistics and policy information are drawn from the publicly available sources cited in the reference list.

Declarations

Ethics approval

Not applicable. This study did not involve human participants or animals.

Consent to participate

Not applicable. No participants were involved in this study.

Consent for publication

Not applicable.

Competing interest

The authors declare that they have no competing interest relevant to the content of this article.

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