Modeling the decarbonization trajectories of the Moroccan agri-food industry: a prospective analysis with OSeMOSYS

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Received 25/07/2026
Accepted 08/09/2026

Abstract

This study analyzes the decarbonization trajectories of the Moroccan agri-food industry by 2050 in a context of strengthening climate policies and increasing exposure to the European Union's Carbon Border Adjustment Mechanism (CBAM). A bottom-up energy optimization model based on OSeMOSYS was developed to evaluate four scenarios: baseline (BAU), deep decarbonization (DO), national strategy (SN) and carbon tax (TC). The results show that an 85% reduction in emissions is technically feasible through the electrification of thermal processes and the massive deployment of high-temperature heat pumps (heat pumps). This transition increases the cost of the system by about 15%, with a marginal abatement cost of €51/tCO_2. The CBAM's prospective analysis indicates a cumulative cost of around €422 million between 2025 and 2050. However, a carbon tax alone does not allow for a profound technological transformation. The success of the transition therefore requires a decarbonization of the electricity system and investment support mechanisms.

Keywords: Industrial decarbonization, Agri-food industry, Morocco, OSeMOSYS, Heat pumps, Carbon tax, Energy efficiency

INTRODUCTION

The Moroccan agri-food industry accounts for 11.6% of national industrial energy consumption and has historically depended on fossil-based electricity and petroleum fuels (Ibn Batouta *et al.*, 2025; UNSD, n.d.). The sector is facing a double pressure: national decarbonization targets aligned with international climate commitments, and increasing exposure to the European Union's CBAM, which could impose an annual bill of €14 to €20 million on exporting companies (Morchid *et al.*, 2024). This is emblematic of a broader challenge: hard-to-decarbonize industrial sectors in emerging economies, must navigate technological transformation, resource constraints, and international competitiveness (Plazas-Niño *et al.*, 2023).

The decarbonization of industrial heat remains a critical issue that is not sufficiently documented. Although it accounts for a significant share of final energy demand, it remains largely dependent on fossil fuels and receives less attention than electricity or transport. For the food industry, processes require heat at low and medium temperatures, which are difficult to electrify directly (Carmona-Martínez *et al.*, 2024). Massive electrification, the preferred solution in decarbonization analyses in developed economies, may prove less viable in emerging contexts where existing infrastructure, capital costs, and the availability of alternative technologies shape distinct trajectories (Plazas-Niño *et al.*, 2023).

Three major shortcomings justify this study. First, the literature on decarbonization in Morocco has focused on the electricity sector or the textile sector (Smouh *et al.*, 2022), neglecting a systemic analysis of the technological trajectories of the food industry. Second, few studies explicitly examine cost-emission trade-offs under international competitiveness constraints in emerging economies (Alam *et al.*, 2025). Third, the effectiveness of price instruments alone in inducing deep structural transformation remains debated. Recent analyses suggest that carbon taxes, while essential, are hampered by capital-intensive infrastructure inertia and technological uncertainties (Fragkos *et al.*, 2021; Gianoli and Bravo, 2020). A mix of policies integrating regulation, investment and technology is necessary (Cocker, 2025).

On the technological front, the literature identifies several levers for decarbonization. The hybrid approach combining carbon-free electricity, biogas, cogeneration and heat pumps is essential for the food industry (Gowreesunker *et al.*, 2018). Renewable heat solutions (concentrated solar, industrial heat pumps, geothermal energy) are crucial for non-electrifiable processes (Carmona-Martínez *et al.*, 2024; Silva *et al.*, 2020). For emerging economies, substitution with sustainable biomass or green hydrogen offers an alternative to massive electrification trajectories (Sovacool *et al.*, 2021). However, bioenergy raises critical questions of sustainability, availability of inputs, and competition for land use (Hafez *et al.*, 2024), while green hydrogen remains expensive and dependent on production cost trajectories (Fernandez *et al.*, 2025).

Methodologically, energy optimization models are essential tools for defining effective decarbonization trajectories. Platforms such as TIMES and OSeMOSYS allow for the analysis of optimal trajectories for the food industry (Gowreesunker *et al.*, 2018; Manuel *et al.*, 2022; Silva *et al.*, 2020). However, the application to specific sectors in emerging economies remains limited, particularly in North Africa (Plazas-Niño *et al.*, 2023).

Regarding climate policies, the introduction of CBAM creates a direct push for decarbonization and a catalytic opportunity for low-carbon investments (Fernandez *et*

https://doi.org/10.5281/zenodo.22837862

al., 2025; Morchid *et al*., 2024). However, exposure to CBAM depends not only on aligning national carbon prices with EU levels, but also on the actual reduction in the carbon intensities of exported products (Morchid *et al*., 2024). This dimension introduces a central question: to what extent is the economic signal induced by the CBAM sufficient to guide investment decisions in emerging economies?

Although the literature on industrial decarbonization is growing considerably, the claim that few studies simultaneously incorporate rigorous sectoral energy optimization modeling, explicit analysis of cost trajectories, and an assessment of the implications for economic competitiveness in emerging economies is scientifically sound. Current modelling frameworks often favour an ideal technical configuration without fully coupling these results to the realities of local markets or to strategic interactions between decision-makers (Tan *et al*., 2025). This fragmentation is particularly marked for the agro-industrial sectors in North Africa and the Middle East, where research has traditionally focused on overall energy efficiency or climate adaptation rather than on the deep decarbonization of process heat via integrated techno-economic models (Ciambellotti *et al*., 2024; Markussen *et al*., 2025). The case of Morocco illustrates this disconnect: while detailed roadmaps exist for cement and steel (Hasanbeigi and Springer, 2023), agribusiness still lacks *bottom-up* analyses capable of guiding technological investments while preserving competitiveness in the face of international regulations such as CBAM (Berahab and Dadush, 2021). Thus, the development of integrated approaches calibrated to the thermal and economic specificities of agribusiness is an imperative to fill this methodological and strategic gap.

This study fills these gaps by developing a *bottom-up* energy optimization model calibrated for the Moroccan agro-industrial sector, using OSeMOSYS. The model evaluates four contrasting scenarios: BAU (status quo), OD (Decarbonization Objective with 80% reduction), SN (National Strategy), and TC (Carbon Tax aligned with *the EU Emissions Trading System (EU ETS)).* The analysis answers four interconnected questions:

- Is deep decarbonization technically feasible and what are the optimal levers?
- Is a domestic carbon tax aligned enough with the EU ETS to induce structural transformation, or is a policy mix needed?
- What are the absolute and relative economic costs of deep decarbonization trajectories?
- To what extent is the CBAM a sufficient economic signal to guide investment decisions and decarbonization trajectories for the Moroccan agri-food sector?

The study contributes to the literature by providing contextualized analysis for an emerging economy, filling a geographical and structural gap in understanding industrial decarbonization trajectories. It informs debates on the optimal design of climate policies and offers insights applicable to other developing agribusiness sectors. It also includes a prospective assessment of the impact of the CBAM on sectoral competitiveness, making it possible to link technological trajectories to the emerging constraints of low-carbon international trade.

METHODOLOGY

Scientific positioning and conceptual framework

This study adopts a prospective techno-economic modelling approach to analyze the decarbonization trajectories of the Moroccan agro-industrial sector until 2050. The use of a *bottom-up* optimization model is part of the standard conceptual frameworks of energy sciences, allowing for the granularity of energy technologies, their costs and emissions while minimizing the total levelized cost of the system under climate constraints (Howells *et al*., 2011; Pye *et al*., 2021). This conceptual framework is particularly suited to the study of industrial transitions, where the diversity of technological options, their interdependencies and economic trade-offs play a decisive role in achieving long-term climate goals (Sovacool *et al*., 2021).

The *bottom-up* approach captures the sectoral and technological specificities of the Moroccan energy system, unlike top-down models that aggregate macroeconomic behaviors (Fragkos and Siskos, 2022). This granularity is essential for assessing decarbonization trajectories in an emerging economy context, where technological constraints, capital costs, and resource availability shape energy choices in ways distinct from developed economies (Plazas-Niño *et al*., 2023).

Definition of the reference energy system

The first methodological step is to define the reference energy system (RES) for the Moroccan agri-food industries. The RES is based on a complete mapping of the sector's energy flows, integrating thermal (heat and steam production), electrical and auxiliary uses. These elements are quantified on the basis of harmonised national data and available sectoral statistics. In line with the practices established in the Sector Energy Analysis (IEA, 2025), thermal uses dominate energy consumption, mainly powered by fossil fuels and electricity purchased from the grid.

The RES makes it possible to construct the basic Business-As-Usual (BAU) scenario, which is the comparative reference for all simulations. In this BAU scenario, all energy emissions from the industrial system are accounted for, including direct emissions from the combustion of fossil fuels, indirect emissions from electricity consumption, and upstream emissions from fuels and feedstocks, thus ensuring a comprehensive assessment of the sectoral carbon footprint (Intergovernmental Panel on Climate Change (IPCC, 2023)). This distinction between the exhaustive scope (BAU) and the scope restricted to controllable emissions (decarbonization scenarios) guarantees complete transparency on the levers that can actually be mobilized by manufacturers.

Technical and economic data and assumptions

The collection and harmonization of techno-economic data is the second methodological step. The parameters of the technologies available or potentially deployable in the sector (investment costs, fixed and variable costs, energy yields, lifetimes, emission factors) come from recognized international databases and institutional reports, in particular those of HCP (High Commission for Planning of Morocco, n.d.), FAO (Food and Agriculture Organization of the United Nations (FAO), 2024), NREL (NREL (National Renewable Energy Laboratory), n.d.), ensuring the robustness of the hypotheses. These institutional sources are preferred because they benefit from rigorous scientific validation and regular updating based on market data and observed technological trajectories.

Energy demand trajectories are considered exogenous and identical in all scenarios in order to isolate the effects of climate policies and carbon price signals, a common practice in long-term energy optimization models (Howells *et al.*, 2011; Pye *et al.*, 2021). This assumption means that the model does not optimize the level of industrial production itself, but only the energy technology mix that satisfies this demand at the minimum cost. However, it implies that the observed emission reductions are the result exclusively of technological choices and policies implemented, and not of a change in the production structure or final demand.

The carbon price assumptions applied in the Carbon Tax (CT) scenario are calibrated on the basis of the levels observed and projected in the European Emissions Trading System and institutional recommendations (European Union, 2015). These levels allow for a consistent examination of the potential impact of a price signal on technology choices and potential exposure to CBAM in the Moroccan context (Morchid *et al.*, 2024). The carbon price trajectory adopted follows an annual progression calibrated to reflect the European Union's commitments to climate neutrality by 2050.

Modeling and objective function

The third step concerns the implementation of the energy optimization model. The model used is the open-source framework OSeMOSYS, as described in the scientific reference literature (Howells *et al.*, 2011). OSeMOSYS is a linear optimization framework applied to the prospective analysis of national and sectoral energy systems, designed to solve multi-periodic energy planning problems (Pye *et al.*, 2021). In the present work, the model minimizes the total actualized cost (TAC) of the industrial system over the period 2025-2050, by integrating investment costs, operating costs, fuel costs and, depending on the scenarios, the costs related to a carbon price.

The objective function is formally expressed as:

$$\text{Min } TAC = \sum_t \frac{\sum_i (CAPEX_{i,t} + OPEX_{i,t} + FUEL_{i,t} + CARBON_{i,t})}{(1+r)^t}$$

where *CAPEX* is the investment costs, *OPEX* is the operational costs, *FUEL* is the fuel costs, *CARBON* is the carbon costs (if applicable), t is the simulation year, i is the technology considered, and r is the discount rate. Investment and technological deployment decisions are optimized under the constraint of annual satisfaction of energy demand.

The assumption of perfect economic rationality and full anticipation of future costs, commonly used in the literature on intertemporal energy models (Chang *et al.*, 2021; Pye *et al.*, 2021), is adopted to allow the identification of optimal trajectories. This assumption facilitates comparative scenario analysis, although it tends to underestimate the institutional and behavioral frictions that can affect real-world investments (Löschel *et al.*, 2010). This limitation is explicitly acknowledged in the discussion of the results.

The results obtained should be interpreted as optimal techno-economic trajectories resulting from an energy

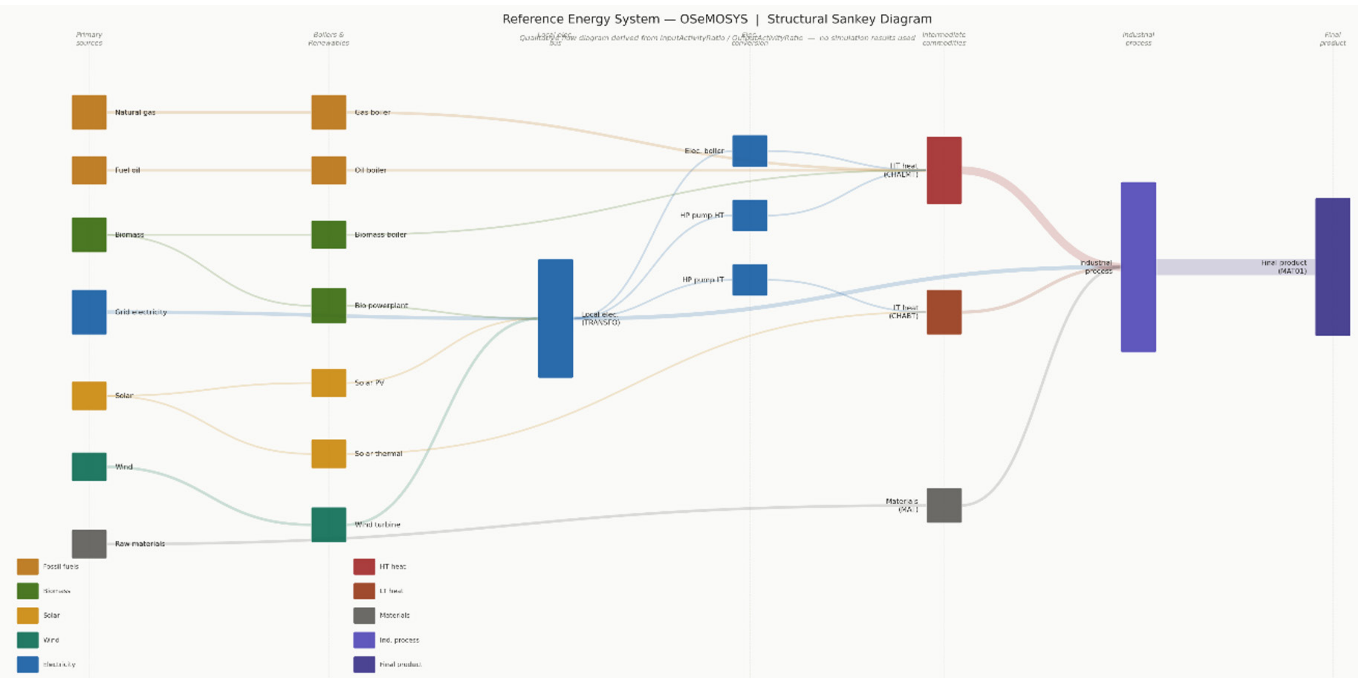

Figure 1: Moroccan agri-food sector Reference Energy System

planning model, and not as direct forecasts of the investment decisions of industrial players. The objective is to identify the most theoretically efficient technological configurations to achieve different levels of decarbonization.

Scenario construction

The fourth step concerns the construction of climate and economic policy scenarios. Four contrasting trajectories have been defined, all based on the same techno-economic structure and the same demand assumptions, allowing a rigorous comparison of political impacts (Table 1).

Analytic metrics

The comparative analysis of the scenarios is based on a set of evaluation indicators selected in line with the objectives of the study and the practices of the literature (Pye *et al.*, 2021). Annual and cumulative emissions are used to assess climate performance and estimate the required mitigation effort. The technology mix and installed capacity by 2050 provide information on the structural transformations of the energy system and the technological viability of the simulated trajectories.

The total discounted costs are used to measure the economic sustainability of the simulated trajectories. Carbon intensity per unit of energy or production offers a relevant measure for competitiveness analysis, particularly with regard to CBAM (Morchid *et al.*, 2024). These indicators make it possible to quantify the trade-offs between emission reductions, technological transformation and economic costs, while identifying the most effective technological solutions in the Moroccan context.

In addition to these indicators, the study also uses the Marginal *Abatement Cost* (MAC). This indicator measures the economic cost associated with reducing an additional tonne of carbon dioxide compared to the baseline scenario. It makes it possible to assess the economic efficiency of decarbonization trajectories and to identify technological strategies to reduce emissions at the lowest cost. The simplified wording used in this study is as follows:

$$MAC = \frac{C_{scenario} - C_{BAU}}{E_{BAU} - E_{scenario}}$$

where:

MAC: marginal cost of carbon abatement (€/tCO_2);

$C_{scenario}$: Levelized total cost of the system in the scenario under study;

C_{BAU}: Levelized total cost of the system in the baseline scenario;

E_{BAU}: Total emissions in the Reference Case;

$E_{scenario}$: total emissions in the scenario considered.

The MAC is estimated by comparing the total system costs and associated emissions between a climate policy scenario and the Business-As-Usual (BAU) baseline scenario. This indicator estimates the economic cost associated with each tonne of CO_2 avoided and compares this cost to potential carbon pricing levels.

Table 1: Summary of modeling scenarios

Scenario	General Description	Type of climate instrument	Emission constraints	Specific Assumptions
BAU (Business As Usual)	Reference scenario describing the evolution of the industrial energy system in the absence of new climate policies. It extends the current trends in the energy mix and technological practices.	No new instruments	No additional constraints	Maintaining existing policies and the current energy mix while always looking for the minimum cost.
OD (Decarbonization Objective)	Scenario imposing a strong trajectory for reducing controllable emissions in order to achieve ambitious long-term climate objectives (Pastore *et al*., 2025).	Regulation by emission ceilings	-80% in 2050 compared to BAU	Exogenous decarbonization of the national electricity mix and implementation of annual emission caps in the model. Technologies are selected endogenously according to the minimum cost (Intergovernmental Panel on Climate Change (IPCC), 2023).
SN (National Strategy)	Scenario reflecting Morocco's national energy and climate commitments.	Mixed public policy without carbon tax	Partial reduction of emissions	Exogenous decarbonization of the national electricity mix and application of the guidelines of the national energy strategy. Alignment with commitments communicated to the United Nations Framework Convention on Climate Change (Ministry of Energy, Mines and Environment, Department of Environment, 2021).
TC (Carbon Tax)	Scenario testing the impact of a carbon price signal coupled with national strategies on the technological decisions of the industrial energy system (Fragkos *et al*., 2021; Morchid *et al*., 2024).	Price Instrument	No emissions cap	Applying an increasing carbon price to dispatchable emissions. The reductions result from the endogenous economic trade-offs of the model.

Integration of the CBAM mechanism and calculation framework

The CBAM aims to ensure an equivalent carbon price between domestic products and imports, in line with the European Emissions Trading System (EU ETS).

In its general formulation, the cost of CBAM can be expressed as follows:

$$C_{CBAM} = E_{prod} \times P_{CO2} - C_{carbon,origin}$$

where E_{prod} designates the emissions incorporated in the exported product, P_{CO2} the carbon price on the European market, and C_{carbon}, origin the carbon cost that may have been paid in the country of origin. In the absence of an explicit carbon pricing mechanism in Morocco, the latter term is assumed to be zero.

The analysis focuses exclusively on Moroccan exports of processed agri-food products to the European Union, estimated at 0.6 million tons per year over the period 2025-2050 (International Trade Centre (ITC), n.d.). Fresh products are excluded in order to ensure consistency with the industrial perimeter covered by the OSeMOSYS energy model.

The carbon intensity of the Moroccan agri-food sector is derived directly from the results of the model. For each year *t*, it is defined as:

$$CI_{MA,t} = \frac{E_{MA,t}}{Q_{MA,t}}$$

where $E_{MA,t}$ represents the total emissions of the sector ($ktCO_2$) and $Q_{MA,t}$ the total physical production (Mt). This formulation ensures consistency between the simulated energy trajectories and the estimated carbon cost.

Emissions associated with exports are then calculated as:

$$E_{export,t} = C_{IMA,t} \times Q_{export}$$

where Q_{export}=0,6 Mt/an.

The reference carbon intensity of the European agri-food sector is set at:

$$CI_{UE} = 0{,}129tCO2/t$$

This value, calculated from European sectoral data (FoodDrinkEurope, 2021; Giner *et al.*, 2019), is assumed to be constant over the period. This assumption is a conservative approximation, as it does not incorporate the decarbonization progress expected on the European side.

Two formulations of the cost of CBAM are considered.

The first, called absolute, is given by:

$$CBAM_{abs,t} = CI_{MA,t} \times Q_{export} \times P_{CO2,t}$$

The second, called differential, is defined as:

$$CBAM_{rel,t} = (CI_{MA,t} - CI_{UE}) \times Q_{export} \times P_{CO2,t}$$

This second formulation is retained in the analysis, as it directly reflects the carbon intensity gap between Morocco and the European Union, and thus constitutes a measure of the competitive disadvantage associated with Moroccan exports. By design, if $CI_{MA,t} \leq CI_{UE}$, the cost of the CBAM is zero.

The $P_{CO2,t}$ carbon price follows an increasing exogenous trajectory over the period studied:

$$P_{CO2,t} \in [60,160]€/tCO2 \;\; (2025 \rightarrow 2050)$$

Finally, several limitations must be highlighted. The analysis is based on an aggregate average carbon intensity for the entire agri-food sector, without distinction between sub-sectors. In addition, only direct and indirect energy emissions (Scope 1 and Scope 2) are taken into account, in line with the scope of the CBAM. Emissions from industrial processes, logistics or the cold chain are not explicitly included. Finally, the application of the CBAM to the agri-food sector is based on a forward-looking approach, in anticipation of its extension to new sectors exposed to the risk of carbon leakage.

Methodological limitations

Like any energy optimization model, the approach is based on simplifying assumptions. The absence of explicit macroeconomic feedbacks implies that investment costs and fuel prices are considered exogenous, with no interaction with economic growth or inflation (Löschel *et al.*, 2010). The homogeneity of economic agents assumes that all manufacturers in the sector react identically to price signals and climatic constraints, while the heterogeneity of firms, their financial capacities and their technological constraints vary considerably (Buettner *et al.*, 2025).

The absence of explicit institutional barriers to technology adoption implies that the model does not capture frictions related to delays in technology diffusion, risks perceived by investors, or market failures (Löschel *et al.*, 2010). These limitations, although implicitly acknowledged in the literature (Howells *et al.*, 2011; Pye *et al.*, 2021), should be taken into account in the interpretation of the results and in the extrapolation of the conclusions to real operational contexts.

The perfect foresight *hypothesis*, although standard in energy planning models, implies a perfect knowledge of future costs and an unrealistic ability to anticipate. Sensitivity analyses and alternative scenarios make it possible to test the robustness of the results in the face of this hypothesis (Pye *et al.*, 2021).

Finally, the restriction of the scope of controllable emissions in decarbonization scenarios, although methodologically justified, implies that certain upstream emissions (production of raw materials, transport of fuels) are not explicitly optimized. This approach reflects the levers that can actually be mobilized by manufacturers at the scale of their facilities, but it may underestimate the sector's total emissions.

RESULTS AND ANALYSIS

Climate performance

CO_2 emission trajectories differ greatly depending on the climate instruments considered (Figure 2). Cumulative emissions reach 61 162 ktCO_2 in the BAU scenario. They are reduced to 31 897 ktCO_2 in the OD scenario (-48%) and to 38 910 ktCO_2 in the SN scenario. On the other hand, the TC scenario follows a similar trajectory to the BAU, showing that a carbon tax alone is not enough to induce a significant decarbonization of the sector.

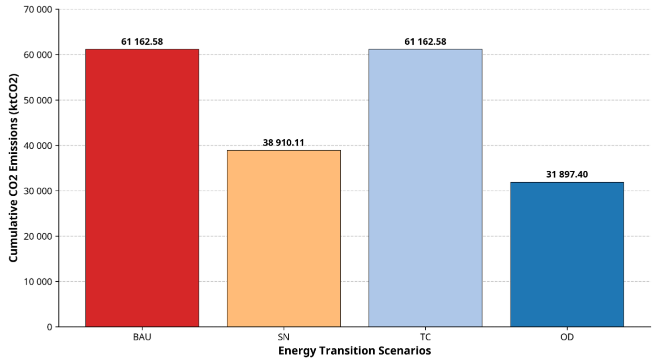

Figure 2: Cumulative emissions by scenario (2025-2050)

The evolution of annual emissions confirms the contrasting effectiveness of decarbonization levers (Figure 3). The OD and SN scenarios gradually reduce emissions compared to the BAU, with respective decreases of 20% and 17% from 2030. In 2050, OD reaches 408 ktCO_2 (-85%) and SN 1246 ktCO_2 (-54%), compared to 2688 ktCO_2 for BAU. The TC scenario remains virtually unchanged, confirming the low effectiveness of an isolated carbon tax.

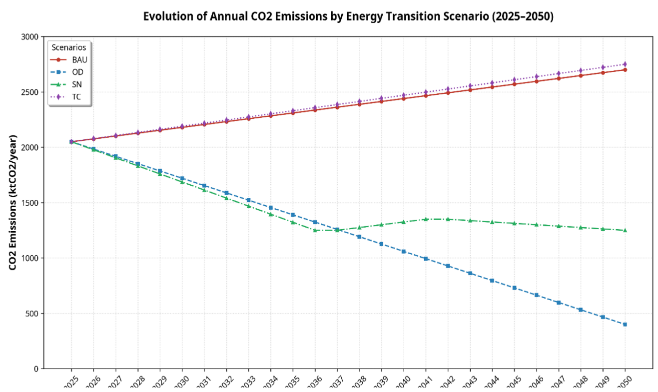

Figure 3: Annual emissions 2025-2050

The emission differences are the result of a differentiated transformation of the heat production system and the energy mix (Figure 4 and Figure 5). The carbon intensity remains stable in the BAU scenario (245.7 ktCO_2/Mt), while it decreases to 37.3 ktCO_2/Mt in the OD scenario and to 113.9 ktCO_2/Mt in the SN scenario in 2050. The convergence of the TC and BAU scenarios shows the low effectiveness of an isolated carbon tax to sustainably transform the sector.

Structure of the energy transition

The differences in emissions can be explained by the evolution of the heating system and the energy mix. The BAU scenario remains dominated by heavy fuel oil, whose capacity increases from 586.5 to 774.8 MW, while the TC scenario reproduces the same energy structure. This similarity confirms the ineffectiveness of the carbon price signal in bringing about a significant technological transition.

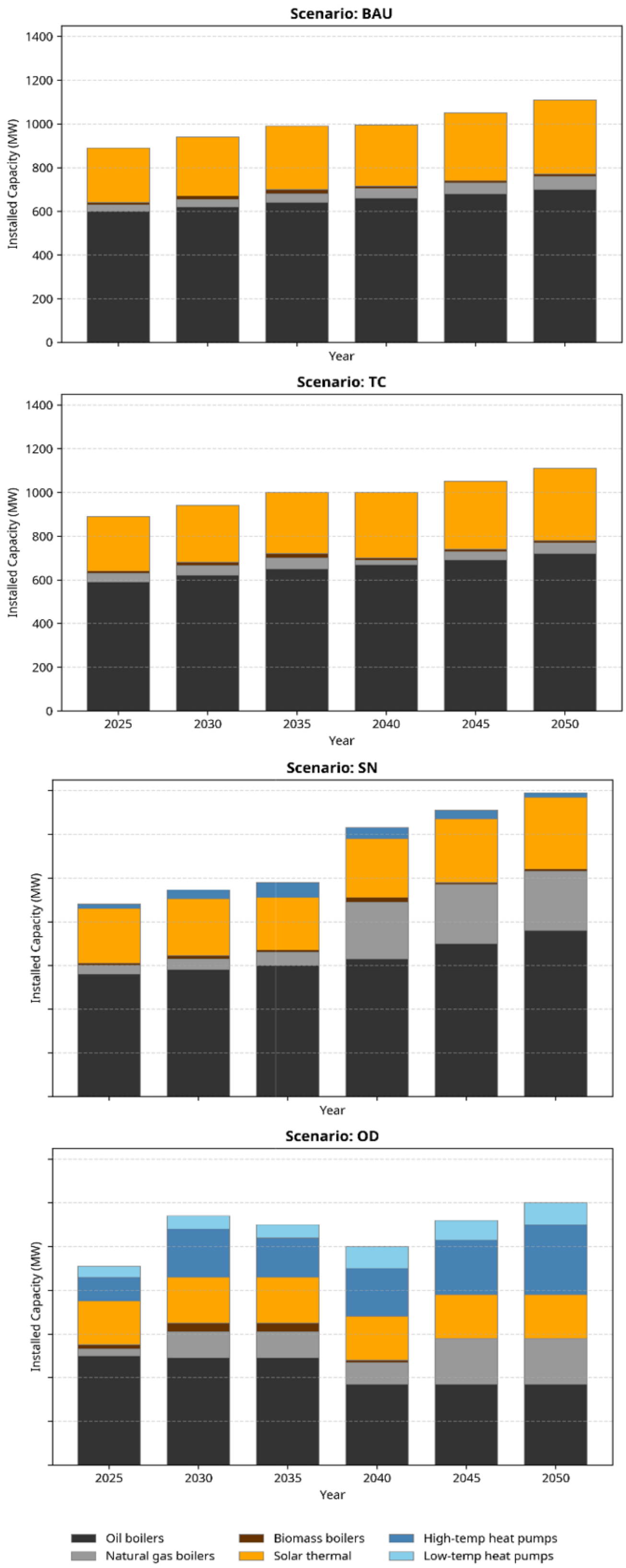

Figure 4: Process heat technologies installed

In contrast, the decarbonization objective (DO) scenario represents a major technological breakthrough focused on thermodynamic efficiency. This scenario is distinguished by a massive deployment of heat pumps, whose cumulative capacity reaches 435.6 MW in 2050 (321.2 MW in high temperature and 114.4 MW in low temperature). This technological shift is leading to an electrification of the consumption mix, the share of which rises from 52% in 2025 to a level of 80% in 2050. At the same time, fossil fuels have been virtually crowded out, with their share falling from 35% to just 8% by the end of the period, while natural gas will be phased out altogether by 2045.

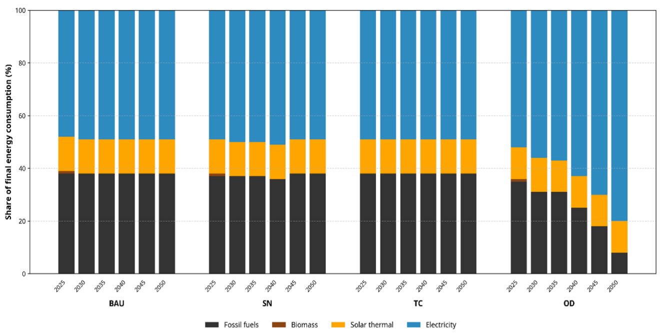

Figure 5: Energy mix transformation (%)

Solar thermal remains stable at around 13% of the final mix, while biomass disappears by 2030, displaced by electric and solar solutions.

System costs and economic trade-offs

The decarbonization of the industrial energy system is accompanied by an increase in levelized costs (Figure 6). The levelized cost of the system increases from €10 billion in the BAU scenario to €11.5 billion in the OD scenario (+15%). The SN scenario limits this additional cost to 3% (€10.2 billion), while the TC scenario reaches €16.9 billion (+69%), under the effect of the carbon burden rather than decarbonization investments.

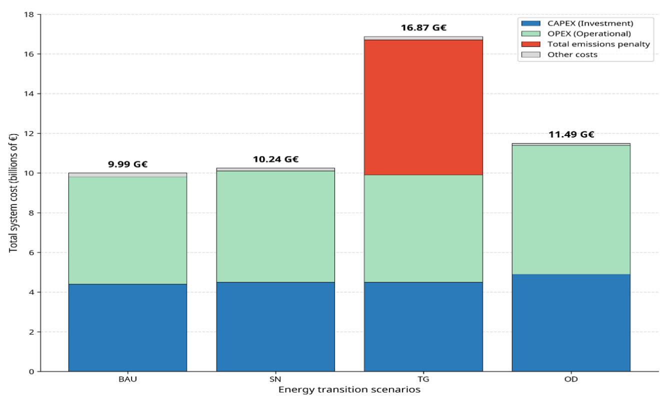

Figure 6: Total Energy System Cost (CAPEX / OPEX)

CAPEX increased from €4.4 billion in the BAU to €4.9 billion in the OD scenario, while electricity investments remained broadly stable between scenarios. The additional cost of the DO therefore comes mainly from the integration of the system. OPEX also increased, from €5.4 billion to €6.6 billion, due to the increased use of electric heat pumps.

Economic efficiency indicators show diminishing returns to decarbonization (Figure 7). The marginal abatement cost increases from €11.3/tCO_2 in the SN scenario to €51.1/

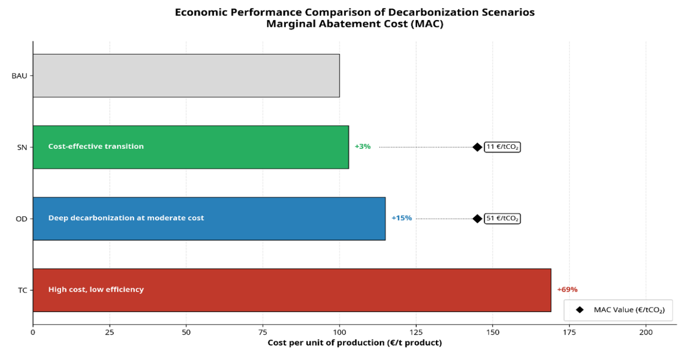

Figure 7: Marginal abatement cost

tCO_2 in the OD scenario, reflecting the increasing cost of the deepest emission reductions. In 2050, the cost of production will increase from €40.1/t in BAU to €46.2/t in DO (+15%). The CT scenario reaches €67.8/t, demonstrating that a carbon tax without technological change strongly penalizes competitiveness without reducing emissions. These results show that the SN scenario is the best cost-effectiveness trade-off, while deep decarbonization requires complementary support policies beyond the price signal alone.

Integration of the CBAM mechanism

The CBAM has been applied to Moroccan exports of processed agri-food products to the European Union, estimated at 0.6 million tonnes per year over the period 2025-2050. The carbon intensity of the Moroccan agri-food sector, based on the OSeMOSYS model, is estimated at 0.245 tCO_2 per tonne produced, compared to 0.129 tCO_2 per tonne for the European agri-food sector. This difference of 0.116 tCO_2 per tonne implies direct exposure of Morocco to CBAM in its differential form.

The results indicate a gradual increase in the carbon cost over the entire period. The annual absolute cost, corresponding to the total valuation of emissions associated with exports, increases from around €9 million in 2025 to €23.6 million in 2050. The incremental cost, which reflects only the difference in carbon intensity between Morocco and the European Union, varies from €4.3 million to €11.2 million over the same period.

Over the entire 2025-2050 horizon, the cumulative cost of the CBAM is estimated at €422 million (Figure 8). At the same time, the transition to a decarbonization scenario for the agri-food sector entails an estimated 15% additional investment cost, i.e. around €1.4 billion over the period under consideration.

The ratio between these two quantities indicates that the cumulative cost of CBAM represents about 30% of the additional cost associated with the complete decarbonization of the sector.

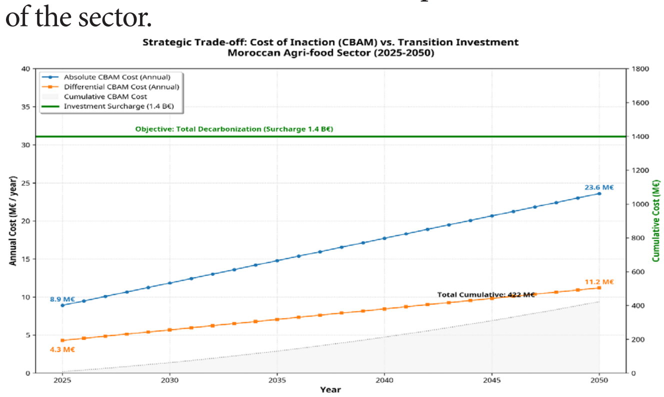

Figure 8: Effect of CBAM

DISCUSSION

This study explored the decarbonization trajectories of Morocco's agribusiness sector by 2050, revealing that achieving ambitious climate goals relies on deep structural transformation rather than marginal adjustments. Our results demonstrate that an 85% reduction in annual emissions is technically feasible in the optimal decarbonization (DO) scenario, bringing emissions to a residual level of 408.6 $ktCO_2$.

The MAC analysis provides additional insight that is essential to the interpretation of the results. The results show that it is increasingly expensive to decarbonize as we get closer to the goal. In reality, this will result in the fact that only measures whose MAC is lower than the carbon price are likely to be adopted spontaneously by economic actors. It is deduced that the carbon price only triggers the least costly abatement options, leaving aside a significant part of the reduction potential. This analysis therefore suggests that the deep decarbonization of the sector cannot be achieved by price signals alone.

These results must also be compared to the decarbonization climate policies of emerging countries.

Heat pumps have been identified as a pillar of decarbonization, unlike boiler electrification. This finding aligns with the decarbonization trajectories observed in other emerging economies such as South Africa, where electrification is identified as the most effective pathway for agro-processing sub-sectors (Joshi *et al.*, 2025; Steed *et al.*, 2025). The use of heat pumps makes it possible to meet process heat needs while optimizing the cost-effectiveness of decarbonization (Ciambellotti *et al.*, 2024; Giuli *et al.*, 2026; Markussen *et al.*, 2025). However, this strategy is only climate-virtuous if it is accompanied by a deep decarbonization of the national electricity mix, in accordance with the commitments of Morocco's Nationally Determined Contribution (NDC) (Ministry of Energy, Mines and Environment, Department of the Environment, 2021).

This dependence underlines that the environmental gains associated with electrification remain conditional on an effective decarbonization of the national electricity system, without which a portion of emissions is simply displaced rather than actually reduced.

International comparison highlights notable singularities. Industrial solar thermal, with a stable capacity representing about 13% of the final mix, is emerging as a basic solution. This dynamic is comparable to that of Mexico and India, where SHIP has become competitive for agribusiness thanks to exceptional sunshine (Best *et al.*, 2013; Suresh and Rao, 2017).

Conversely, the Moroccan model diverges radically from the Brazilian model. While Brazil is betting heavily on biomass and biogaz to decarbonize its industry (dos Santos *et al.*, 2025; Pelkmans *et al.*, 2024; Abouelnaga, 2025), our results show a total disappearance of this resource by 2030 in Morocco. This divergence can be explained by the specific barriers of the Moroccan industrial hub, in particular the scarcity of sustainable biomass and the priority given to the electricity-solar binomial (Ibn Batouta *et al.*, 2025; Smouh *et al.*, 2022).

These technological choices reflect a structural transformation of the production system, involving a profound reconfiguration of energy uses, industrial processes and value chains in the agri-food sector.

Achieving the objectives of the OD scenario comes up against a set of multidimensional barriers, specific to the Moroccan industrial fabric. The empirical study conducted in the country's largest industrial hub (Ibn Batouta *et al.*, 2025) highlights that, despite a positive perception of energy efficiency, companies face critical obstacles:

- **Financial barriers and cost of capital:** The shift from a system based on OPEX (purchase of fossil fuels) to a system dominated by CAPEX (investment in heat pumps and solar thermal) is hampered by limited access to green finance at competitive rates. For agri-food SMEs, the high initial cost of thermal electrification technologies remains the main barrier, making disruptive investments less attractive than incremental solutions (Hasanbeigi and Springer, 2023; Ibn Batouta *et al.*, 2025). In this context, the results relating to the CBAM provide additional insights. Despite a gradual increase in the carbon price, the cumulative cost of the mechanism over the period remains limited compared to the investments needed to fully decarbonize the sector. This gap suggests that the price signal induced by the CBAM, although growing, remains insufficient to trigger large-scale technological transformations on its own. This is why decarbonization requires complementary policies targeting high-cost technologies, including through investment support or risk reduction mechanisms.
- **Technological inertia and "Carbon Lock-in":** The Moroccan agro-industrial sector is characterized by a fleet of oil and gas boilers that is relatively recent or has a long residual life. This technological inertia, coupled with local technical expertise still focused on conventional thermal systems, limits the rapid adoption of heat pumps as observed in Europe and in the Moroccan textile industry (Giuli *et al.*, 2026; Smouh *et al.*, 2022).
- **Power infrastructure challenges:** Massive electrification (80% of the mix in the OD scenario) is putting unprecedented pressure on the national power grid. As highlighted in the roadmaps for cement and steel in Morocco (Hasanbeigi and Springer, 2023), industrial decarbonization depends on ONEE's ability to guarantee electricity that is not only decarbonized, but also stable and at a competitive cost compared to heavy fuel oil, whose prices are historically low or indirectly subsidized (OECD, 2025).
- **Regulatory framework and incentives:** The ineffectiveness of the TC scenario in our results confirms that effective carbon tax rates in Morocco are currently too low to trigger technological substitution (OECD, 2025). The lack of direct support mechanisms for CAPEX, such as carbon contracts for difference (CCfD) or targeted tax incentives for thermal electrification, keeps the sector on a fossil fuel dependence trajectory (Cocker, 2025; Bozier *et al.*, 2022).

These barriers explain why, despite exceptional renewable energy potential, the transition remains timid in the National Strategy (NS) scenario. Removing these barriers requires close coordination between industrial policy and energy strategy, in order to transform these obstacles into opportunities to compete in the face of the growing demands of the European market (CBAM) (Morchid *et al.*, 2024; Berahab and Dadush, 2021). The relative ineffectiveness of the carbon tax (CT) scenario, which generates €6.9 billion in penalties without reducing emissions, highlights the limits of carbon pricing alone in emerging countries (OECD, 2025). However, the results also suggest that the moderate intensity of the economic signal, whether from a carbon tax or the CBAM, is not in itself a sufficient lever to guide large-scale investment choices. In particular, the comparison between the cumulative cost of the CBAM, estimated at around €422 million over the period studied, and the additional cost of decarbonization, estimated at almost €1.4 billion, shows that the mechanism covers only a limited fraction of the required investments. This differential underlines that, from a strictly economic point of view, the CBAM acts more as a guiding signal than as a real engine of transition.

In this context, agri-food companies are faced with a strategic trade-off between several options: absorbing the cost of the CBAM, using carbon credit markets to offset their emissions, or making structural investments in decarbonization. In the short term, offsetting solutions may appear economically attractive, especially when the cost of carbon remains moderate. However, they do not reduce structural exposure to climate policies, unlike investments in energy efficiency and process electrification. In addition, the use of international carbon markets remains subject to significant uncertainties in terms of price, availability and environmental integrity of credits, which limits their role as a sustainable solution. From this perspective, the CBAM appears less as an immediate financial constraint than as a strategic signal announcing a gradual transformation of the rules of competitiveness on international markets.

The introduction of the CBAM analysis thus makes it possible to answer the third structuring question of this study, relating to the economic impact of decarbonization on the international competitiveness of the sector. The results show that, despite a significant carbon intensity differential with the European Union, the induced economic signal remains insufficient to constitute a trigger for the transition on its own.

CONCLUSION

This study used the *bottom-up* energy optimization model OSeMOSYS to assess the decarbonization trajectories of the Moroccan agri-food industry by 2050. The analysis of four contrasting scenarios (BAU, OD, SN, TC) highlights several structuring lessons for the industrial energy transition in the context of an emerging economy.

First, deep decarbonization of the sector appears technically feasible, with an emission reduction of up to 85% in the OD scenario. This transformation is based on a massive electrification of thermal processes through the deployment of heat pumps. However, the performance of this trajectory remains conditional on the parallel decarbonization of the national electricity mix.

Second, the results confirm the limitations of an isolated price signal. The carbon tax scenario shows that pricing aligned with European levels is not enough to trigger a structural transformation in the presence of financial and technological barriers. The analysis of the marginal abatement cost highlights a high heterogeneity of abatement costs, implying that only the first actions are economically competitive, while the deepest reductions require significant investments. This underlines the need for a policy mix combining price signalling and investment support instruments.

Thirdly, the prospective integration of the CBAM reveals a real but moderate exposure of the Moroccan agri-food sector. The cumulative cost of the mechanism over the period 2025-2050, estimated at around €422 million, remains lower than the additional cost of fully decarbonizing the sector (around €1.4 billion). This differential indicates that the CBAM is more of an economic incentive than a sufficient lever to finance the transition, while introducing a trade-off for companies between investment, payment of the carbon cost or strategic adjustment.

Finally, the results show that the transition cannot be based solely on individual decisions. While some solutions can be implemented at the company level, others require sectoral coordination and public intervention, particularly for the development of large-scale energy infrastructure and access to competitive decarbonized energy.

In conclusion, while the electrification of thermal uses is the dominant technical path to carbon neutrality, its implementation will depend on the ability to articulate public policies, industrial strategies and international competitiveness constraints. At the operational level, policies must prioritize reducing the cost of capital of low-carbon technologies, accelerating the decarbonization of the electricity system and supporting the development of shared infrastructure. For companies, the transition involves a gradual trade-off between investing in the most cost-effective solutions and exposure to the cost of carbon. In this context, the CBAM acts less as a constraint than as a structuring signal, calling for a coordinated transformation of the sector.

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