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PAPER

# Balancing decarbonisation pathways: a comparative analysis of the effects of carbon pricing strategies on the decarbonisation of the EU energy system via a linked modelling approach

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**Keywords:** energy security, carbon pricing, agent-based modelling, integrated assessment model

## Abstract

Achieving the European Union's decarbonisation goals while safeguarding a reliable energy transition presents a complex policy challenge. This paper addresses this challenge through an integrated modelling approach that combines a system dynamics-based Integrated Assessment Model, *pymedeas*, with an agent-based model of the electricity market, *TaxvsETS* agent based model *(ABM)*. The two models are linked through a one-way transfer of information, whereby a realistic EU decarbonisation pathway derived from pymedeas2 is used to constrain the TaxvsETS ABM, allowing assessment of whether the faster decarbonisation achieved by carbon taxes (CTs) remains robust under a realistic emission trading scheme (ETS) cap and an equivalent carbon price. The linked framework combines decarbonisation pathway with firms' adaptive investment behaviours, enabling the comparison of alternative carbon pricing policies under empirically informed transition conditions. Results suggest that even when the ETS is calibrated using a realistic decarbonisation pathway derived from the integrated assessment model and compared under equivalent policy stringency, CTs continue to outperform emissions trading schemes in terms of decarbonisation speed, cumulative emissions reductions, and investment efficiency. However, broader governance and political economy considerations also influence the feasibility and equity of implementation. This study further demonstrates the value of hybrid modelling frameworks in supporting the evaluation of alternative carbon pricing policies within complex socio-technical systems.

## List of Abbreviations

| | |
|---|---|
| ABM | Agent based model |
| CT | Carbon tax |
| ETS | Emission trading scheme |
| FAIR | Findable, accessible, interoperable, and reusable |
| GDPpc | Gross domestic product per capita |
| GECO | Global energy and climate outlook |
| IAMs | Integrated assessment models |
| IEA | International energy agency |

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| | |
|---|---|
| MIX-CP | MIX carbon price |
| NZP | Net zero pathway |
| SD | Systems dynamic |

## 1. Introduction

Ensuring the European Union (EU) energy transition and security (Commission *et al* 2024a), (Commission 2024b) while achieving rapid decarbonisation represents one of the most complex and pressing challenges for contemporary policymakers. As the climate crisis intensifies and geopolitical disruptions reshape global energy systems, the transition to a low-carbon economy must be pursued in a manner that preserves the reliability, accessibility, and resilience of energy supply. Meeting these goals requires careful evaluation of the policies and instruments that can address systemic risks while driving structural change across the energy—economy system (Perissi and Jones 2022). Traditionally, energy security has been defined in terms of the uninterrupted availability of energy at affordable prices. However, the need for decarbonisation has expanded this definition, demanding that energy systems also include environmental sustainability (Perissi 2025). In this context, understanding how different decarbonisation policies influence the pace of the energy transition is an important component of broader energy policy. Indeed, the recent blackout on April 28, 2025[7], which affected nearly the entire Iberian Peninsula, underscores the complexities in this transition. Within seconds, approximately 15 gigawatts, around 60% of Spain's electricity demand, were lost, leading to widespread impacts across Spain and Portugal. Although the event has been linked to technical issues related to grid operation and system balancing, it highlights the importance of designing decarbonisation pathways that are accompanied by appropriate investments in energy infrastructure. While the present study does not model technical aspects of energy security, such as grid stability, storage, or electricity trade, this event provides the broader policy context motivating the analysis.

Among decarbonisation policies, carbon pricing mechanisms, namely CTs and emissions trading schemes (ETS), have been widely endorsed for their theoretical cost-effectiveness. These instruments are usually assessed within frameworks that assume rational, equilibrium-based responses by market actors, i.e. the energy firms. However, recent empirical and simulation-based analyses presented in Natalini *et al* (2026) have questioned the robustness of these assumptions in the context of non-linear, path-dependent, and dynamically evolving energy systems. The macro-level outcomes of carbon pricing policies are contingent on the heterogeneous behaviours of firms, innovation feedback, and policy-induced expectations, which cannot be adequately captured through static or equilibrium-based frameworks.

The ABM presented in Natalini *et al* (2026) embeds these innovations while testing the effectiveness of alternative carbon pricing policies on a stylised electricity market.

At the same time, IAMs have emerged as pivotal tools in this context, offering a coherent analytical framework to explore decarbonisation pathways and assess long-term policy impacts (Weyant 2017). IAMs integrate insights from multiple disciplines, energy systems, macroeconomics, land use, and climate science to simulate how different policy choices can affect emissions trajectories, economic outcomes, and environmental sustainability. Originally developed to inform global climate negotiations (Schwanitz 2013, Tavoni *et al* 2015, Füssel 2010)IAMs are now increasingly applied at regional (Perissi and Jones 2024) and national scales (Perissi *et al* 2021), where they support the design of context-specific climate and energy policies (van Vuuren *et al* 2011). Mainstream IAMs are typically built around optimisation or equilibrium-based frameworks that prioritise cost-effectiveness, often under assumptions of continuous GDP growth (Perissi and Jones 2023), technological progress, and efficient markets. While these models have provided valuable policy insights, they tend to underrepresent ecological limits, biophysical constraints, and issues of social equity (Hickel *et al* 2021). To address these limitations, researchers have developed next-generation IAMs that internalise non-equilibrium dynamics, resource depletion, and planetary boundaries. The *pymedeas* model (Solé *et al* 2020) is one such example. It is an open-source, SD-based IAM designed to evaluate sustainable transitions while accounting for finite energy and material resources (Solé *et al* 2020). Unlike conventional IAMs, *pymedeas* prioritises the physical and biophysical feasibility of climate pathways by explicitly integrating factors such as biophysical constraints, ecological boundaries, and non-equilibrium dynamics, making it particularly well-suited for assessing realistic, constraint-aware transition strategies. The model has been applied to several case studies within the EU to support policy design consistent with sustainability goals and resource availability.

[7] www.entsoe.eu/publications/blackout/28-april-2025-iberian-blackout/

These sub-national applications of the *pymedeas* model (CREAF 2024) allow for the exploration of transition scenarios under conditions of resource scarcity, social inertia, and systemic risk.

Despite the advances embedded in ABMs and IAMs, very few modelling efforts have brought them together in an integrated framework. In this study, we link the ability of SD approaches to simulate interrelated dynamics of large-scale complex systems and capture general trends in key variables (Eidin *et al* 2024) combined with ABM's ability to capture emergent properties by generating the systems from the bottom up, i.e. via the interaction of individual agents' behaviours (Bonabeau 2002).

Several reviews and studies have explored the respective roles of these two modelling approaches in the field of energy simulation. For instance, Mundu *et al* (2024) provided a review of the literature on energy system simulation modelling, with a focus on ABM, SD, Discrete-Event Simulation and Integrated Energy Models, highlighting the individual role of these different methodologies in understanding, analysing, and optimising complex energy systems. Similarly, different authors provided instructions and methodologies to either integrate the SD and ABM approaches (Wang *et al* 2019) or translate SDs into ABMs (Ahmadi Achachlouei and Hilty 2015). However, to our knowledge, no study has yet combined a SD model of an energy system that includes biophysical limits with an ABM in electricity market simulation.

In addition, although environmental and ecological economics have extensively examined alternative carbon pricing policies, these are typically evaluated in terms of their theoretical efficiency rather than their performance under empirically informed transition pathways. Where empirical effectiveness has been investigated, findings remain mixed and context-dependent (Ohlendorf *et al* 2021). While Natalini *et al* (2026) compared these alternative carbon pricing policies using the TaxvsETS ABM in a stylised electricity market, the present study extends that work by linking the ABM with the SD-based pymedeas2 integrated assessment model (Solé *et al* 2020). This enables the comparison to be conducted under a realistic EU decarbonisation pathway, allowing us to assess whether the previously observed relative performance of CTs and ETS remains robust when the ABM is constrained by empirically informed system-level transition trajectories. The methodology used is designed as a linked approach using the output emissions of the IAM to constraint the ABM but allowing enough freedom to explore a broad spectrum of options. Hereafter, we follow by describing the modelling approach, presenting simulation results, discussing policy implications, to conclude with recommendations for future research.

## 2. Methodology

This study adopts a hybrid modelling framework that involves the one-way linkage of SD and ABM models to explore the dynamic interplay between top-down structural constraints and bottom-up behavioural responses in the context of energy system decarbonisation. This one way linkage enables the assessment of the feasibility, efficiency, and behavioural implications (in terms of investment decisions from energy companies) of different carbon pricing policies, specifically CTs and ETS, under real-world complexity of the electricity system and resource limitations. The two models (see appendix B for access links) operate in a complementary fashion: the SD model simulates the underlying trends in the EU energy system, embedding biophysical limitations (e.g. land available for renewable deployment, fossil fuel availability) while the ABM simulates a stylised electricity market, embedding dynamics related to electricity production, consumption and technological innovation, induced by alternative carbon pricing policy scenarios. In particular, we run *pymedeas* for the timeframe 1995–2050 with one of the baseline decarbonisation scenarios (NZP, see section 2.1.1) that simulates the transition of the EU energy system to decarbonisation. As discussed in the next section, *pymedeas* does not include price or innovation dynamics, therefore making the model complementary to the *TaxvsETS* ABM. From *pymedeas* we identify system-wide constraints (i.e. carbon budgeting and the decline curve of the emissions cap for the ETS) and implement them in the ABM, where they shape the behaviours of agents (i.e. energy companies), that, according to the scenario chosen (i.e. either CT or ETS) operate within these constraints, making decisions around technological investments and decarbonisation, which result in policy-induced dynamics. This procedure is discussed in depth in section 2.3.

### 2.1. System dynamics modelling with pymedeas2

*pymedeas*, developed as part of the EU-funded Horizon 2020 MEDEAS project, is an open-source IAM designed to simulate long-term transitions of the energy-economy-environment system under biophysical and policy constraints. The model is developed with a system dynamics approach and includes a post-Keynesian macroeconomic module, allowing for a non-equilibrium, demand-driven representation of the

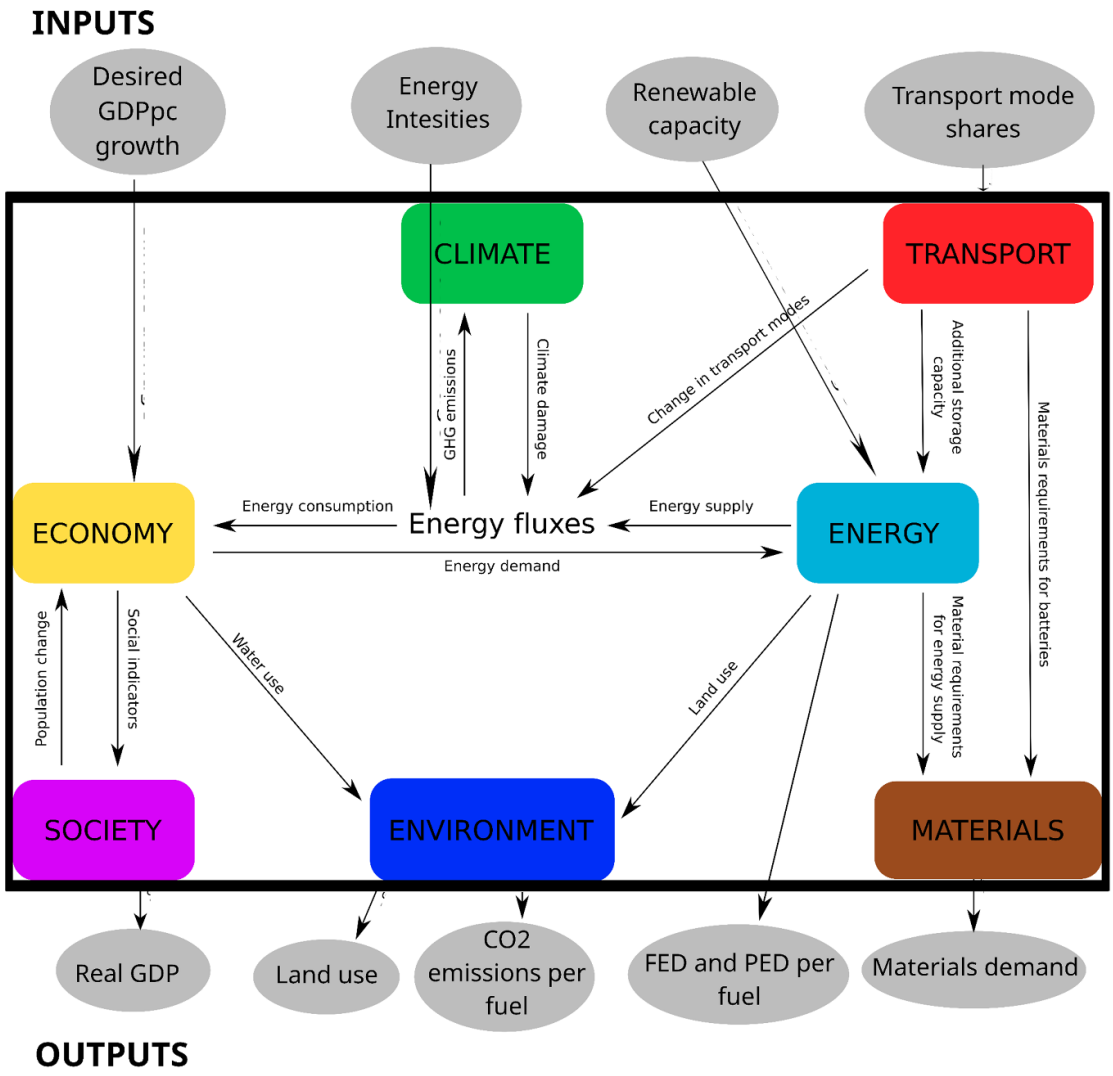


**Figure 1.** Flux of information between the 7 modules of pymedeas2.

economy in which energy availability (including production constraints) acts as a limiting factor rather than a passive input.

The most recent version, *pymedeas2* (Samsó *et al* 2025) (figure 1) includes a modular structure that facilitates the inclusion of new sectors and policy levers. The core modules of the model are the Economy, Energy, Environment, Land Use, Materials, Society, and Transport. These interact dynamically over time, incorporating feedbacks such as energy system inertia, emissions and climate change impacts, and technological deployment rates. The model timeframe is from today to 2050, with time steps that represent 11 d, with high sectoral detail, aligned with national accounts.

*pymedeas2* supports scenario exploration, allowing users to define trajectories for key variables such as population, energy efficiency, renewable energy installation rates, electrification of end uses, energy trades, and climate mitigation policies. Environmental impacts include $CO_2$ emissions, land use change, and material use. Physical constraints, such as renewable resource techno-ecological potentials, land availability, and fossil fuel limitations, are explicitly modelled to test the feasibility of climate pathways under realistic limitations (MEDEAS 2020).

Thanks to its open-source nature and modular structure, *pymedeas2* has been applied to both EU and national case studies. The model operates across three nested geographical levels, global (Solé *et al* 2020), regional (e.g. Europe) (Samsó *et al* 2020) and subregional/national (e.g. Catalonia, Comitè d'Experts sobre el Canvi Climàtic (CECC) de Catalunya 2025) where each upper-level simulation provides boundary conditions for the level below. This hierarchical structure makes *pymedeas2* particularly suitable for assessing policy strategies aimed at climate neutrality and sustainability, enabling integrated

analysis of biophysical constraints, energy transitions, and socioeconomic transformations across economic sectors (figure 1).

The model is open-source[8] and implemented in Python, which enhances its transparency, flexibility, and interoperability with other modelling frameworks. This design aligns with FAIR data and software principles foster reproducibility and wider adoption within the IAMs community. It also enables coupling with external models, including biophysical, land use, or climate impact modules for more comprehensive sustainability assessments.

Furthermore, *pymedeas2* could be integrated with ABMs, allowing for the exploration of behavioural and institutional dynamics, such as the role of energy companies in investment decisions, technology adoption, or response to policy incentives. This interdisciplinary potential strengthens its capacity to simulate complex socio-technical transitions under ecological constraints.

*2.1.1. Scenarios implementation in pymedeas2: The NZP*

For this study, we used the *pymedeas2* NZP scenario for the EU. This was originally developed to assess the feasibility and implications of achieving climate neutrality by 2050, in line with the targets set by the European Climate Law (European Parliament and Council of the European Union 2021) and the European Green Deal (European Commission 2021a). This scenario integrates the EU's climate and energy objectives, including a 55% reduction in greenhouse gas emissions by 2030, with technological, economic, and biophysical constraints to simulate a coherent decarbonisation trajectory of the EU energy system. The NZP builds on major policy frameworks such as the Fit for 55 package (Schlacke *et al* 2022), The Circular Economy Action Plan (European Commission 2020b), The Farm to Fork Strategy (European Commision 2020a), and the European Taxonomy for Sustainable Investment (European Parliament and Council of the European Union 2020), using their quantified targets as input parameters.

In the design of the NZP, the MIX-CP scenario developed by the European Commission (European Commission 2021b), is used as a core reference for various parameters. The MIX-CP scenario, modelled using the PRIMES energy system model (E3-Modelling 2018), represents a central pathway for delivering the European Green Deal under the Fit for 55 legislative framework and was the most compatible with the policies that we then tested with the *TaxvsETS* ABM. It assumes a mix of regulatory and carbon pricing instruments across sectors and includes detailed projections for the transport sector, energy mix, electrification trends, and final energy consumption. In this work, sectoral targets such as electrification levels, transport modal shares, and emissions reductions are aligned with MIX-CP values to ensure consistency with officially endorsed policy pathways (European Commision 2024).

The NZP emphasises a strong deployment of renewable energy sources and widespread electrification of final energy uses. In sectors where electrification is not feasible, such as long- distance transport and some industrial processes, alternative solutions include hydrogen (Perissi and Bilous 2026) hydrogen-based fuels, and bioenergy. Fossil fuels are gradually being phased out but continue to be used in limited applications, including non-combustion industrial uses and heavy-duty transport.

Inspired by the EU Joint Research Centre's GECO 2021 (European Commision and Joint Research Centre 2021), the scenario incorporates an average annual energy intensity (energy use per unit of economic output) reduction of 3.1%, making efficiency one of its key decarbonisation levers.

The NZP scenario is structured along eight thematic policy axes. To ensure internal consistency and coherence with existing European and international frameworks, diverse data sources have been harmonised, ranging from EU policy documents and energy outlooks to scientific literature and techno-economic projections. The scenario is structured and defined as follows:

- Input population and GDPpc growth: Encompasses demographic trends and macroeconomic assumptions, including population and GDP per capita. Population estimates are based on the updated EUROPOP2019 projections (Eurostat 2024) while GDPpc growth from 2022 to 2050 follows the GECO2021 projections.
- Renewables: Establishes five-year deployment targets for solar photovoltaic, onshore and offshore wind, biomass, hydro, and combined solar panel technologies. These targets are derived from the MIX-CP scenario.

[8] https://github.com/Earth-and-Energy-Systems-Lab/pymedeas2

- Fossil fuels: Introduces phase-out policies, limiting residual fossil fuel use to non-energy applications and hard-to-abate sectors. Policies targeting the elimination of oil use for heating and electricity generation are to be fully implemented by 2040 at the latest, according to the IEA net zero emissions (IEA-NZE) (IEA 2021a).
- Transport: Simulates the decarbonisation of the transport sector through electrification, modal shifts, and the deployment of hydrogen-based fuels. The evolution of transport demand and modal shares is informed by the MIX-CP scenario.
- Energy intensities: Applies annual improvements (up to 3.1%) based on GECO 2021[9] to represent efficiency gains and the electrification of the final energy demand.
- Climate and environment: End-of-life recycling rates of critical materials are assumed to be those of the world, EOL-RR in 2050 are projected from (UNEP International Resource Panel2011) (Henckens 2021). Afforestation programmes and process emissions reductions are also defined.
- Energy imports: accounts for dependencies and diversification in primary energy sourcing. The estimations are made using the lowest values between the Announced Pledges and Sustainable Development scenarios by the IEA (IEA 2021b).
- Land use: Incorporates constraints on land availability for renewable energy infrastructure by applying surface efficiency metrics (W $m^{-2}$) for each technology. It also accounts for projected improvements in renewable energy efficiency, ensuring a realistic assessment of spatial requirements over time.

This scenario provided the best compatibility with the ABM presented in the next section.

### 2.2. Agent-based modelling of carbon pricing policies

#### *2.2.1. The Tax-vs-ETS ABM*

To complement the systems-level analysis, we use the *TaxvsETS* ABM (Natalini *et al* 2025a), an ABM designed to simulate investment behaviour and technological transitions in a competitive electricity market under different carbon pricing regimes. The ABM simulates a stylised competitive, closed electricity market and captures the endogenous dynamics of electricity-generating firms that differ in capital, strategic behaviour, technology preferences, and expectations about policy evolution. The model's key contribution is the endogenous innovation built into the technological advancements of the energy technologies and is aimed at comparing the effectiveness of alternative decarbonisation policies, namely CT and ETS. A full description of the model, tests and limitations is available in Natalini *et al* (2026), however we report key elements here to ensure the completeness of this paper.

The model considers three scenarios, testing the effect of alternative carbon pricing policies on the decarbonisation of the stylised electricity sector: a business-as-usual (or No-Policy) baseline, a CT, and an ETS. A set of firms (i.e. the agents in the model) is initialised with 'behaviours' to choose between coal, gas, wind, and solar technologies based on profit expectations, which are influenced by projected electricity prices, technology costs, fuel prices, carbon prices, and capital availability. Innovation is modelled endogenously via Wright's law, relating technology costs to cumulative deployment. Electricity prices emerge from a merit-order mechanism, and permit prices in the ETS scenario are determined by firms' willingness to pay, available emissions caps and sanctions that firms incur. Energy technology installations are also represented in a stylised way, with energy installed in 'batches' as opposed to power plants. This means that companies can invest to build plants of variable sizes according to the amount of energy they want to produce with each technology as resulting from the model dynamics. The model was developed for a UK-based study, therefore economic variables are presented in pounds.

Unlike equilibrium models, an ABM approach allows for path dependence (Brown *et al* 2005), system emergence and investment hysteresis (Bassi and Lang 2016). The model is implemented in NetLogo v6.3.0 (Wilensky 1999). Despite the model representing a stylised, synthetic electricity system, the developers attempted to implement empirical data for key dynamics where available.

The model is partially empirically grounded, with key technological, economic, and policy parameters informed by empirical data and the literature. Full details of the model parameterisation and calibration are available in (Natalini *et al* 2026).

In the model, agents (energy companies) make yearly decisions around which technologies to invest in and the size of the investment. Companies are assumed to want to grow their market share by 10%

[9] https://joint-research-centre.ec.europa.eu/projects-and-activities/global-energy-and-climate-outlook/past-geco-editions/geco-2021_en

yearly and in the process they implement a series of behaviours, which are defined by parameters set in the model's user interface (the parameters used in the initialisation of the model are available in appendix A):

- Market leadership (aggressivevsneutral)—companies can either be 'aggressive,' i.e. want to increase their capacity to generate energy by more than 10%, or 'neutral,' i.e. want to increase their share of the market by 10%
- Preferred energy source (fossilvsrenewables-preference)—this weighting factor assigns companies a preference for either fossil-fuels-generating-technologies or renewable technologies
- ETS permits (ambitiousvnot-ambitious)—companies can expect future permit prices to be lower (−3%) or higher (+10%) than the previous year

Most indicators and parameters have been introduced in the model with some variability to avoid deterministic simulations.

The key assumptions introduced in the model include the projected trend in the electricity demand of the sector, the way innovation is embedded in the model and the general functioning of the electricity market. For simplification purposes, electricity demand is represented as an exogenous demand trajectory that grows at a constant annual rate of 5%[10].

The stylised electricity market represented in the model lines up the energy units from all technologies from all companies, sorting them from cheaper to more expensive in terms of generation costs, with cheapest units used first until demand is met. The cost of the last unit used sets the electricity price on the market and is paid to all companies whose technologies have contributed to electricity generation.

Firms maximise expected profits by selecting investment portfolios based on anticipated revenues, technology costs, carbon pricing, and behavioural preferences, subject to capital constraints. Generation costs account for fuel, depreciation, and carbon pricing. A complete description of the investment algorithm, cost calculations, and profit dynamics is available in (Natalini *et al* 2026).

A thorough sensitivity analysis was conducted on key behavioural parameters to assess the robustness of the model and the variability of outcomes. In particular, this involved key variables that are input by the user interface of the model and some of the key assumptions introduced in the model. The results of the sensitivity analysis are reported in full in Natalini *et al* (2026).

The model showed sensitivity to the parameter 'aggressivevsneutral,' which defines how much new capacity companies invest in each year. When this parameter is below 0.8, results show that not enough capacity is built year-on-year to satisfy the increase in demand.

The model also showed sensitivity to the learning curves sourced from Mercure *et al* (2014), which was tested by introducing exogenous innovation through linear trendlines, which showed that both ETS and Tax scenarios would lead to a decarbonised electricity sector much more quickly with exogenous trendlines compared with endogenous innovation built into the model, which is positive as it implies that the model performs as expected in terms of endogenisation of innovation.

Finally, the model also showed sensitivity to the ETS cap reduction rate, which shows that this factor is important in the determination of the results, and justifies the rationale for the use of this variable in the connection of *pymedeas2* and the ABM in this paper.

Based on the results from the sensitivity analysis, and to maintain consistency with the simulations presented in Natalini *et al* (2026) the values for the key parameters used for the production of the results presented here were (see appendix 1 for the data used for the initialisation):

- Aggressivevsneutral [1.0]
- ambitiousvnot-ambitious [0.8]
- fossilvsrenewables-preference [0.8]
- avg-unit-cost-techvstot [0.8]

*2.2.2. Scenario implementation: how the alternative policy scenarios have been implemented in the TaxvsETS ABM*

The implementation of the CT and ETS scenarios is described in detail in Natalini *et al* (2026). Here, we summarise only the key mechanisms relevant to the present study.

[10] This stylized assumption is inherited from the original TaxvsETS ABM and is retained here to preserve consistency with the published model. It is not intended to represent a forecast of future EU electricity demand, but to maintain a dynamic investment environment in which the effects of alternative carbon pricing policies on technology choice and decarbonization pathways can be systematically compared.

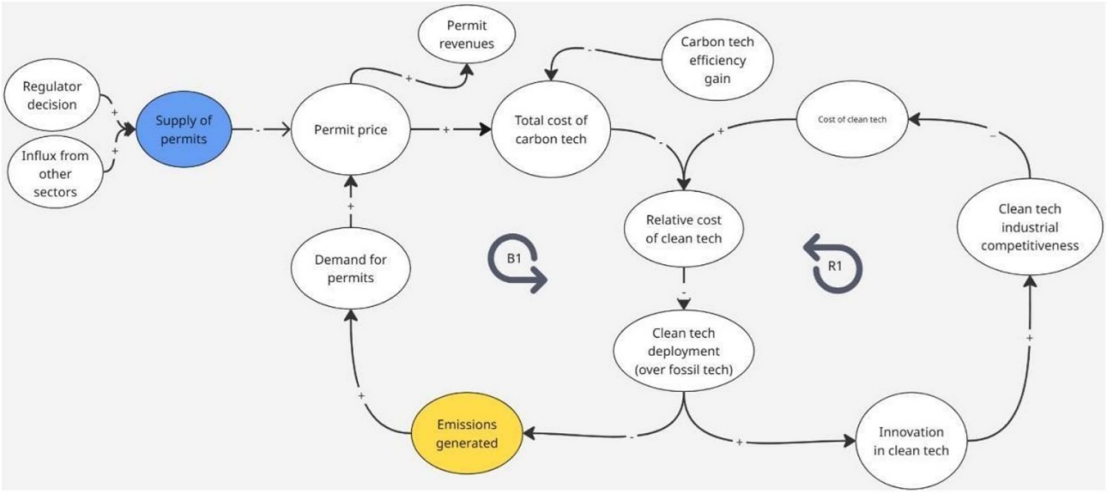


**Figure 2.** Systems map of a cap-and-trade scheme. In the figure, a positive feedback (+) indicates a positive mathematical relationship between two variables, whereas a negative feedback (−) indicates a negative mathematical relationship. Variables shown in blue represent intervention points, while those in yellow represent output variables. Adapted from Natalini *et al* 2026. CC BY 4.0.

Figure 2 illustrates the system dynamics underlying the ETS scenario. The model includes a reinforcing learning-by-doing feedback (R1), whereby increasing deployment of clean technologies reduces their costs, further improving their competitiveness and stimulating additional deployment. At the same time, the ETS introduces balancing feedback (B1): as emissions decline, the demand for emission permits decreases, lowering permit prices and consequently reducing the incentive for further decarbonisation. This self-regulating mechanism is a key characteristic of cap-and-trade systems and forms the basis for comparison with the CT scenario.

Within the model, firms compete for emission permits based on their willingness to pay, which depends on expected profitability and carbon costs. Permit prices emerge endogenously from market demand and are constrained by the emissions cap and the penalty for non-compliance. The detailed permit allocation mechanism and pricing algorithm are described in Natalini *et al* (2026). Figure 3 presents the CT scenario. Unlike the ETS, the CT applies a fixed carbon price and therefore does not generate the balancing feedback associated with permit trading. The learning-by-doing mechanism remains the primary driver of technological change, allowing the carbon price signal to operate without endogenous weakening.

In the simulations, the CT is represented as a constant tax applied to firms' emissions. To ensure comparability between the two policy instruments, the tax level is calibrated using the average ETS premium obtained from the benchmark simulations, as described in section 3.

### 2.3. One-way integration of pymedeas2 and TaxvsETS ABM

The integration of models developed with different modelling approaches can be tackled in different ways (IEEE Electronics Packaging Society 2015):

1. One-way integration (or one-way coupling), where one model's outputs (e.g. values for specific variables) are used as input in another model.
2. Two-way integration (or two-way coupling), where one model's outputs are used as input in another model and outputs from that model are used as input in the first model.
3. Full integration (or hybrid/co-simulation).

In this paper, we implement a one-way linkage approach using outputs from the SD-based *pymedeas2* model to constrain the ABM simulations as a natural first step in the progressive development of a fully coupled modelling framework. This initial one-way coupling allows us to assess the behavioural coherence and performance of the integrated system under realistic boundary conditions. Once validated, this provides a solid foundation for future work involving two-way coupling, where feedback from agent behaviour can dynamically inform system-level constraints. At the moment, this study is focused on demonstrating the robustness and policy relevance of the one-way coupling.

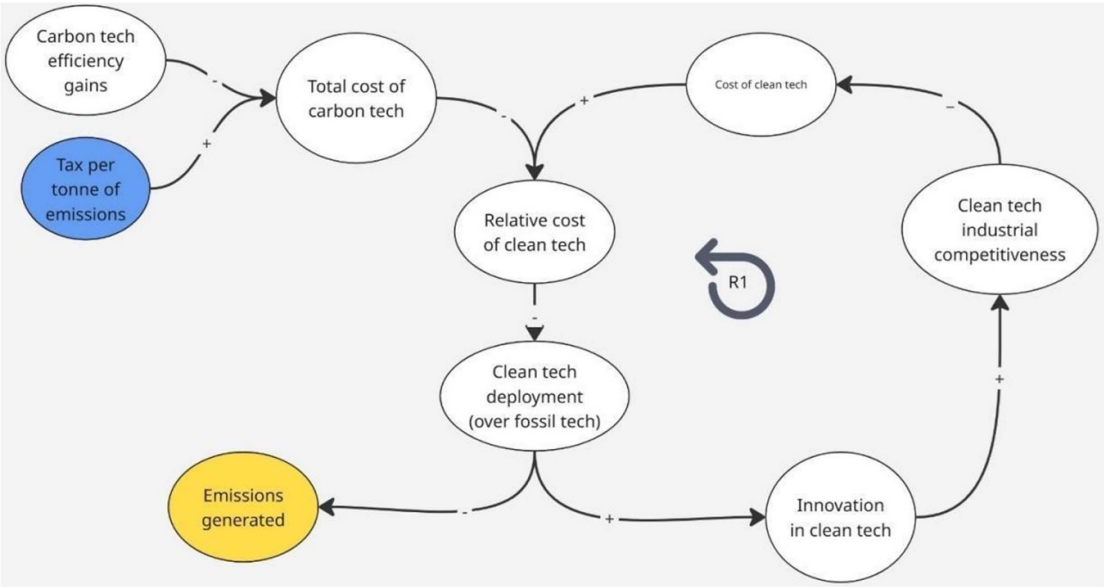


**Figure 3.** Systems map of the CT scenario as implemented in the ABM. In the figure, a positive feedback '+' highlights a positive mathematical relationship between two variables, as opposed to a negative relationship, highlighted with a '–.' In the diagram, variables in blue are intervention points, and in yellow are the outputs. Adapted from Natalini *et al* 2026. CC BY 4.0.

This approach enhances *pymedeas2* results by providing an additional focus on the different policies that can lead to the decarbonisation of the EU energy system. *pymedeas2*, in turn, enhances the results from *TaxvsETS* ABM by leveraging the detailed information and specificity provided by the MEDEAS SD simulation framework. This integration allows the models to provide more comprehensive recommendations regarding the possible future decarbonisation scenarios available to the EU energy systems and the performance of alternative policies in achieving decarbonisation.

The variable that acted as a conduit between the two models is the cumulative emissions from the energy sector in *pymedeas2*. This is represented by three variables, i.e. *$CO_2$ emissions oil[electricity]*, *$CO_2$ emissions gas[electricity]*, *$CO_2$ emissions coal[electricity]*. The trend in emissions from the energy sector leading to the decarbonisation of the EU energy sector was analysed and used as input in the ABM, first setting the reduction rate of the cap for the ETS scenario (i.e. the variable *ets-cap-reduction* in the *TaxvsETS* ABM), which subsequently set the level of the CT (see following section for details on the procedure).

To assess the impact of emissions reductions on policy effectiveness, we first calculated the average percentage reduction from data provided by *pymedeas2* simulations, obtaining a mean emissions decrease of 2.25%. This value was then used to reduce the cap in the ABM model.

## 3. Results

To bridge the analysis between *pymedeas2* and the *TaxvsETS* ABM's energy simulations and behavioural policy modelling, we first analysed the emissions trajectories generated by the *pymedeas2* model (figure 4). These provide essential input for the ABM.

Figure 4 presents the evolution of $CO_2$ emissions from electricity generation in the EU under the NZP scenario, with emissions disaggregated by fossil fuel source: coal, gas, and oil. These trajectories reflect the underlying technological, regulatory, and macroeconomic constraints integrated into the scenario. Coal-based emissions, historically the highest, show a marked and sustained decline starting around 2010, with sharp reductions after 2020. This is consistent with the NZP's phase-out policies and the overarching objective of eliminating coal from the electricity mix by 2050, as outlined in the IEA NZEs roadmap. Emissions from natural gas rise modestly until the early 2010s and then stabilise, with only a slow downward trend through 2050. This indicates the continuing, though diminishing, role of gas as a transitional fuel, gradually being replaced by renewables, bioenergy, and hydrogen under the MIX-CP policy framework. Oil-related emissions, comparatively low throughout the period, decline steadily and approach zero before 2040, in line with targets for phasing out oil use in electricity generation.

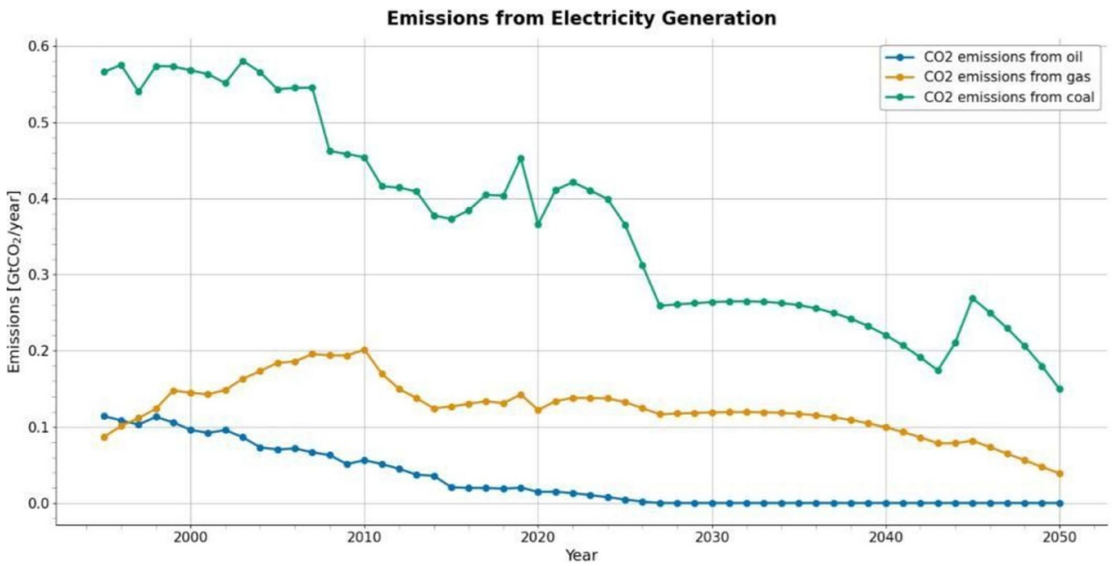


**Figure 4.** Emissions trends from NZP scenarios split by energy resources.

The overall trend illustrates a progressive decarbonisation of the power sector, with fossil fuels being largely displaced by renewable energy sources and efficiency gains, including an average 3.1% annual reduction in energy intensity.

Although the overall trend points toward decarbonisation, with an average annual $CO_2$ reduction rate of 2.25%, some years show temporary reversals. These spikes are primarily due to the rapid pace of electrification outpacing the deployment of renewable energy infrastructure. When renewable generation falls short of meeting electricity demand, especially during periods of high electrification, the system compensates by burning fossil fuels, resulting in transient increases in $CO_2$ emissions. This dynamic highlights the importance of aligning electrification strategies with the availability and reliability of clean energy sources and motivates further analysis using behavioural models to explore demand-side flexibility and policy interventions.

We used this trend as input for the *TaxvsETS* ABM. We calculated the average percentage yearly reduction in emissions for the whole period from the *pymedeas2* outputs, which resulted in 2.25%. This was introduced in the ABM as the annual emissions cap reduction in the ETS scenario. This percentage reduction obtained is incredibly similar to the real EU ETS trend (2021-onwards −2.2% per year) (European Energy Agency 2021). The other key variable set to compare the impact and effectiveness of the two policies was the CT. To ensure the comparability of the two scenarios, the CT had to be set at a level that would create the same incentive as the ETS for energy companies to reduce their emissions. To do this, we ran the ETS scenario 100 times and calculated a median 'ETS premium,' i.e. the sum of the average permit price and average sanction paid by the energy companies across the simulations. This resulted in a value of £33.76, and we adopted this value as input for the CT. The use of Pounds Sterling (£) for the economic variables in the ABM reflects the units adopted in the original version of the model, which was developed for the UK.

Finally, we ran 100 repetitions of the three scenarios: 1. the ETS scenario; 2. the CT based on the median ETS premium; and 3. a baseline 'No-Policy' scenario. We ran only 100 repetitions per scenario due to the relative stability of the results returned by the model, which are quite deterministic (see for instance figures 4, and 5, which show confidence intervals around the data points, which show little variability for most variables and data points). Using Python, we aggregated the runs for each scenario and extracted key indicators from the simulation results. The results for the indicators time to zero emissions, energy prices and cumulative emissions are presented in tables 1–3, comparing the results for each scenario. Note that given that the No-policy scenario does not meet the condition that brings the model to stop (i.e. emissions reaching 0, i.e. full decarbonisation of the electricity system), this scenario is artificially stopped at year 48. Results for this scenario are reported in the tables and plots below for comparison purposes.

The CT policy proved most effective in decarbonising the energy system, with emissions reaching zero in 6 years (median), compared to 15 years (median) under the ETS. The tax also led to the lowest level of cumulative emissions however leading to the highest energy prices (median £53.41), followed

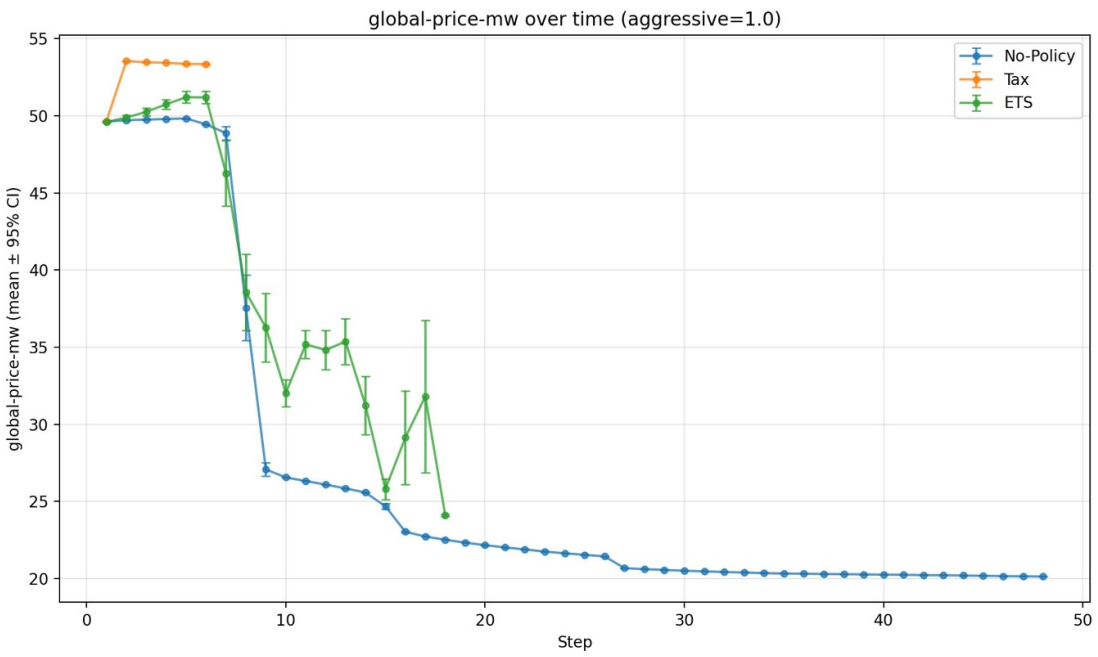


**Figure 5.** Energy prices under the different scenarios (£/MW) (including confidence interval around data points).

**Table 1.** Time to zero emissions (years) (including standard deviation (STD_DEV) and standard error (SE)).

| SCENARIO | MIN | MEDIAN | MEAN | MAX | STD_DEV | SE |
|---|---|---|---|---|---|---|
| ETS | 11 | 14 | 13.88 | 18 | 1.372751 | 0.1372 751 |
| TAX | 4 | 5 | 5.23 | 6 | 0.446196 | 0.0446 196 |
| NO-POLICY | 48 | 48 | 48.00 | 48 | 0 | 0 |

**Table 2.** Energy Prices (£)(including standard deviation (STD_DEV) and standard error (SE)).

| SCENARIO | MIN | MEDIAN | MEAN | MAX | STD_DEV | SE |
|---|---|---|---|---|---|---|
| ETS | 24.014419 | 49.373539 | 42.227355 | 61.197463 | 10.315693 | 0.2768877076 |
| TAX | 49.327288 | 53.406568 | 52.722881 | 53.885041 | 1.503622 | 0.06574879942 |
| NO-POLICY | 20.10721 | 21.58071 | 26.182623 | 50.296686 | 10.24319 | 0.1478477126 |

by ETS (median £49.39), and lowest, of course, with no policy (median £21.8). Investment behaviour shifted accordingly: under the tax scenario, mean investment in wind in Year 5 significantly outpaced the ETS scenario, while solar investment remained consistently flat across all scenarios (table B1). Furthermore, cumulative coal investments were lowest in the tax scenario, a trend driven by higher unit costs (table B2), confirming the tax's strong deterrent effect on fossil fuels.

In figures 5 and 6 below we also show the results for energy prices and cumulative missions from the different scenarios.

## 4. Discussion

The one-way integration of *pymedeas2* SD and the *TaxvsETS* ABM models shows the potential of hybrid modelling to inform European decarbonisation policy by assessing different carbon pricing mechanisms.

The integrated framework provides an environment that links macro-level system constraints with behavioural dynamics. In the present implementation, the one-way coupling transfers a realistic emissions reduction trajectory derived from pymedeas2 to the ABM, enabling the assessment of alternative carbon pricing policies under the net zero pathway, thus ensuring that policy scenarios tested are aligned with feasible physical and economic transitions, strengthening the policy relevance of the results. This narrows the gap between macro-level decarbonisation scenarios and micro-level behavioural responses while providing a foundation for future, more tightly coupled modelling frameworks.

**Table 3.** Cumulative emissions (TonCO2) (including standard deviation (STD_DEV) and standard error (SE)).

| SCENARIO | MIN | MEDIAN | MEAN | MAX | STD_DEV | SE |
|---|---|---|---|---|---|---|
| ETS | 41.54 M | 63.37 M | 63.04 M | 94.84 M | 9.81 M | 0.98 M |
| TAX | 8.81 M | 10.30 M | 10.31 M | 11.83 M | 0.57 M | 0.06 M |
| NO-POLICY | 1,866.95 M | 1,906.07 M | 1,909. 64 M | 1,981.08 M | 19.94 M | 1.99 M |

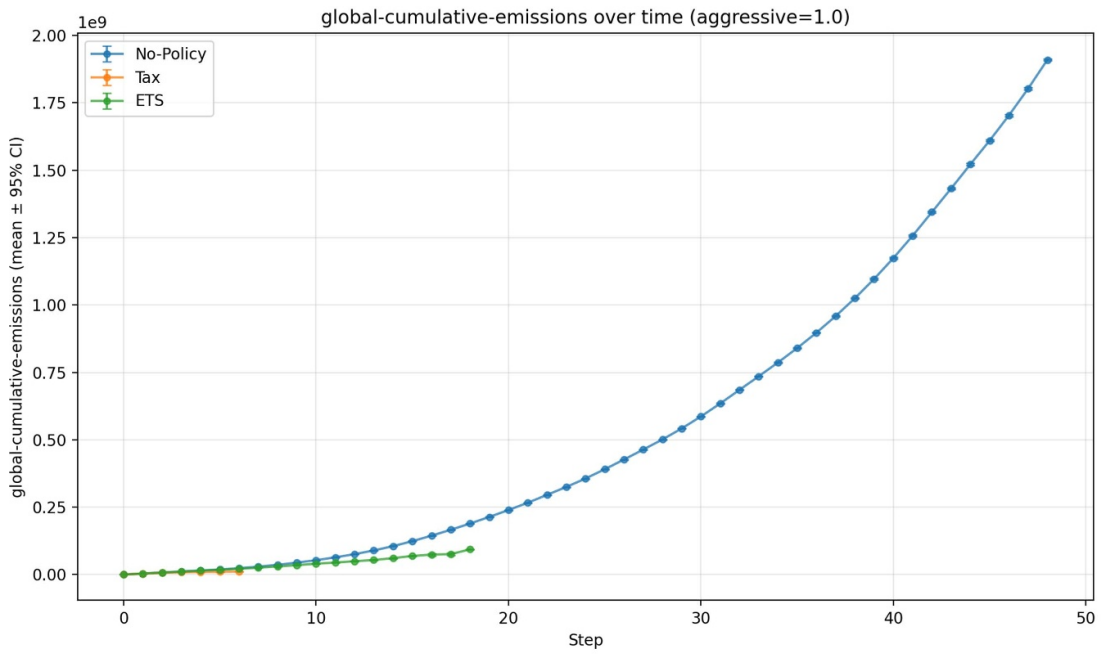


**Figure 6.** Cumulative Emissions (TonCO2) (including confidence interval around data points).

Simulations suggest that, when applied to a competitive electricity market with consistent reduction targets, a CT results in faster and more effective decarbonisation (Parry *et al* 2022, Grodecka-Messi and Kuralbayeva 2014) than an ETS. These findings are consistent with previous work (Natalini *et al* 2026) and reinforce the argument that policy effectiveness is contingent not just on market mechanisms, but also on the parameters of the system in which they are applied, for instance, the biophysical limitations of a possible energy transition. The effectiveness of CT in this context suggests it may be a more suitable tool for sectors where rapid decarbonisation is required and where market responses can be directly shaped by price.

While the results favour the CT from a performance perspective, it is important to acknowledge the broader political economy and fairness dimensions associated with each policy instrument. The ETS can be regressive in practice, as large polluters often purchase sufficient allowances to maintain emissions levels, i.e. 'paying to pollute.' This dynamic creates a perception of inequality, particularly when smaller firms or households are subject to stricter compliance costs. By contrast, CTs apply a uniform price signal across the market but offer more flexibility for tailoring through exemptions, rebates, or differentiated rates, allowing for protection of vulnerable groups. From a political standpoint, the ETS is often more acceptable to market-liberal stakeholders, as it preserves flexibility and introduces a tradable asset into the economy. CTs, however, tend to face greater opposition, particularly from business lobbies and right-leaning policymakers who view them as direct forms of government intervention. Despite their potential economic efficiency, CTs may thus be more difficult to implement due to political resistance (Perman *et al* 2013).

Governance and transparency also pose different challenges. CTS are more exposed to manipulation and lobbying, particularly regarding the setting of tax rates or the design of exemptions. Their effectiveness depends heavily on the integrity and strength of governmental institutions. While ETS mechanisms

are not immune to strategic manipulation, such as through permit over-allocation, they benefit from market-based price discovery. However, they remain vulnerable to volatility and design flaws that can undermine their effectiveness.

The main limitation of this study lies in the stylised nature of the ABM, which represents a simplified competitive electricity market composed of heterogeneous energy companies. To keep the model simple (although not overly simple), the model design required a number of simplifications, such as the exogenous trend in electricity demand, but also the implementation of the tax and ETS policies in their basic versions. For instance, the ETS policy represented in the ABM does not include a price floor or stability reserve, which, of course, does not capture potential alternative setups for this policy that could address oscillations in permit prices and therefore increase its efficacy. For this reason, the results for the ETS policy presented and discussed here should not be generalised to emissions trading as a policy class. As for the exogenous demand, this could be a potential next step of this research. The ABM could be enriched with additional types of agents, e.g. consumers, to endogenise energy demand and potentially capture the impact of energy prices on energy choices and policy acceptability.

The modelling framework developed in this study lays the groundwork for more complex and granular analyses. Future developments could involve two-way coupling between *pymedeas2* and agent-based models, allowing feedback from micro-level behaviours to reshape system-level dynamics. Sector-specific refinements of the CT, accounting for different economic or social sensitivities across transport, industry, and residential use, could further enhance policy precision. Incorporating consumer behaviour, such as household energy decisions, prosumer activity, or cooperative investment patterns, would broaden the behavioural scope of the ABM. Lastly, exploring hybrid policy mixes that combine CT and ETS elements, possibly alongside complementary instruments like subsidies, standards, or green bonds, could lead to more balanced and politically viable decarbonisation strategies.

## 5. Conclusion

The increasing urgency to tackle the climate crisis requires renewed, strong efforts in decarbonising the EU energy system. However, different policies are available, which are likely to have different effectiveness and outcomes. Integrated modelling approaches can support policy design and evaluation by capturing interactions across multiple scales of the energy system.

In this study, we presented the one-way integration between two models, namely the *pymedeas2* SD model, which captures macro-level energy-economy-environment interactions under biophysical constraints, and *TaxvsETS* ABM. The linked framework combines a realistic EU decarbonisation pathway derived from pymedeas2 with firm-level responses to alternative carbon pricing mechanisms in a stylised electricity market.

This enabled us to assess whether the comparative performance of Carbon Taxes and ETS observed in the original ABM remains robust under an empirically informed EU decarbonisation pathway. From a policy perspective, our findings suggest that, under equivalent stringency and market conditions, a carbon tax may be more effective and reliable in driving rapid decarbonisation in the energy sector than an ETS. However, policy decisions must also account for political acceptability, equity, and governance considerations, which differ substantially between the two instruments.

The main limitation of this study lies in the stylised nature of the ABM and the simplified representation of carbon pricing policies. Therefore, the results should be interpreted as comparative insights into policy performance within the model rather than as quantitative predictions of real-world outcomes.

As a next step, a formal two-way coupling between pymedeas2 and the ABM would allow for dynamic feedback between agent behaviour and system-level constraints, offering an even richer simulation environment. More broadly, future work in the field should aim to integrate behavioural heterogeneity and institutional dynamics into large-scale energy transition models, enhancing the accuracy and policy relevance of integrated assessment modelling.

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## Data availability statement

The data produced by the simulations of the models support the findings of this study are included within the article. Both models are open access and available on the following repositories: *pymedeas2* model is available at: https://github.com/Earth-and-Energy-Systems-Lab/pymedeas2. The *Tax vs ETS ABM* is available at: www.comses.net/codebases/003518b1-a9e5-4fe8-b76d-97d81d0be6b6/releases/1.0.0/.

All data that support the findings of this study are included within the article (and any supplementary information files).

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## Conflict of interest

The author declares no competing interests.

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# Appendix A

In this section we report the values for key variables and parameters used to initialise the ABM.

**Table A1.** Values used to initialise key variables and parameters in the ABM. If variability was included in the model simulations, this is listed next to the value in the last in the 'Value initialised' column. In this column we also identified the parameters that were the subject of a sensitivity analysis.

| Variable | Definition | Value range | Value initialised |
|---|---|---|---|
| mean-start-capacity-coal | Coal start capacity for companies | [0,100] MW | 50 ±[0,20] |
| mean-start-capacity-gas | Gas start capacity for companies | [0,100] MW | 40 ±[0,20] |
| mean-start-capacity-wind | Wind start capacity for companies | [0,100] MW | 30 ±[0,20] |
| mean-start-capacity-solar | Solar start capacity for companies | [0,100] MW | 20 ±[0,20] |
| energy-demand-increase | Annual increase of electricity demand | [0,1] | 0.05 |
| coal-economies-scale | Learning factor for coal used (I unit cost) | [0,1] | 0.044 (SA) |
| gas-economies-scale | Learning factor for gas used (I unit cost) | [0,1] | 0.059 (SA) |
| wind-economies-scale | Learning factor for wind used (I unit cost) | [0,1] | 0.105 (SA) |
| solar-economies-scale | Learning factor for solar used (I unit cost) | [0,1] | 0.269 (SA) |
| start-capital | Companies' start capital | [0,300,000,000,000]£ | 1e10 |
| aggressivevsneutral | Parameter that defines companies' behaviours related to market leadership | [0,1] | [0.8,1.0] (SA) |
| ambitiousvnot-ambitious | Parameter that defines likelihood of companies to believe the ETS' effectiveness | [0,1] | [0.8] |
| fossilvsrenewables-preference | Parameter that defines likelihood of companies to have a preference for fossil fuels or renewables | [0,1] | [0.8] |
| avg-unit-cost-techvstot | Parameter that defines which portion of the final unit cost is calculated with either weighted average by company and technology or average of all technologies | [0,1] | [0.8] |
| investment-technology-threshold | Parameter that defines minimum percentage needed for a company to invest in a technology | [0,1] | 0.1 |
| start-tax | Variable that defines the start level of carbon tax | [0,100]£/tonCO2 | 34 |
| tax-increase | Variable that defines the 4 year increase of carbon tax | [0,100]£ | 0 |
| start-ets-cap | Variable that defines the start cap for the ETS | [0,10 000 000] | 4000 000 |
| ets-cap-reduction | Variable that defines the annual cap reduction for the ETS | [0,100]% | 2.2 (SA) |
| ets-sanction | Variable that defines sanction when companies emit more than permits owned | [0,100]£/tonCO2 | 100 |

## Appendix B

This appendix contains the data tables detailing the projected mean investments and mean unit costs at year 5 for each energy technology across the three policy scenarios.

**Table B1.** Mean values of cumulative investment at year 5 by technology and policy scenario.

| TECHNOLOGY | ETS | NO-POLICY | TAX | UNIT |
|---|---|---|---|---|
| Coal | 8.44E8 | 9.45E8 | 3.46E8 | £ |
| Gas | 0.00 | 0.00 | 0.00 | £ |
| Solar | 0.00 | 0.00 | 0.00 | £ |
| Wind | 1.79E9 | 1.40E9 | 3.92E9 | £ |

**Table B2.** Mean unit cost at year 5 by technology and policy scenario.

| TECHNOLOGY | ETS | NO-POLICY | TAX | UNIT |
|---|---|---|---|---|
| Coal | 1.65E6 | 1.65E6 | 1.67E6 | £ |
| Gas | 8.30E5 | 8.30E5 | 8.30E5 | £ |
| Solar | 1.23E7 | 1.23E7 | 1.23E7 | £ |
| Wind | 6.02E6 | 6.04E6 | 5.80E6 | £ |

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