EXPLORING COST-EFFECTIVE POLICY PATHWAYS FOR DECARBONISING GERMANY'S ELECTRICITY SYSTEM

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Overview

Decarbonising electricity systems is critical to achieving global climate goals, particularly in countries like Germany, where the electricity sector faces significant challenges due to its high reliance on fossil fuels and the scale of the transformation required. The electricity sector accounts for a large share of greenhouse gas emissions, and its decarbonisation is pivotal not only for reducing direct emissions, but also for enabling progress in other sectors such as transport and heating, which increasingly depend on electrification. Germany’s energy transition, or Energiewende, has made considerable strides in deploying renewable energy; however, the pace of change is insufficient to meet its ambitious climate targets. Accelerating this transformation requires robust and adaptive policy mixes that address the complex interactions between technologies, market dynamics, and regulatory frameworks.

While energy system modelling (ESM) is widely used to analyse policy designs, traditional approaches usually rely on predefined scenarios, which limit their capacity to explore dynamic and interdependent policy effects from a plethora of policy mix configurations.This study addresses these challenges by using MANGOpol, a novel framework designed to simultaneously co-design policy mixes and energy system transformations. The study focuses on the decarbonization of Germany's electricity system and covers the horizon between 2025 and 2050, exploring a wide range of renewable energy technologies, storage options, and policy instruments, providing actionable insights to guide the energy transition.

Methods

The study uses MANGOpol, a bi-level optimisation model that integrates policy decisions as endogenous variables within energy system modelling framework. Unlike traditional scenario studies, MANGOpol dynamically explores the interactions between policies and energy system design through its co-design methodology. The framework operates on two levels: the Policy Mix Designer (PMD) which represents the policymaker’s perspective and acts as leader, while the lower level is the Energy System Planner (ESP), englobing the energy system's perspective.

At the PMD level, the policymakers' goals include: (i) minimising cumulative CO_2 emissions, (ii) minimising the total societal expenditure (comprising the system costs and policy costs), and (iii) achieving interim or long-term targets, such as reaching net-zero emissions as early as possible. The ESP optimises the energy system's design and operation, determining cost-optimal investment, deployment, and operation of supply and storage technologies to meet hourly electricity demands.

The timeline of the study spans from 2025 to 2050, divided into six 4-year decision periods to align with Germany’s policy cycles. This temporal granularity allows for the exploration of both short-term adjustments and long-term strategies. The model evaluates a vast range of various policy instruments, including carbon taxes, technology-specific subsidies, bans on emitting technologies, and R&D policies.

To solve the bi-level optimisation, the framework employs a genetic algorithm (NSGA-II), which is well-suited for exploring complex, multi-objective solution spaces. This approach enables the simultaneous optimisation of competing objectives, such as cost and emissions, while navigating the non-linearities inherent in the co-design of policy mixes and the energy systems.

The model is also able to incorporate two-step technology learning curves to capture cost reductions for key technologies, based on cumulative installations and policy interventions. By dynamically linking technology advancements with policy outcomes, MANGOpol provides actionable insights into the design, sequencing, and effectiveness of policy mixes, supporting a robust and adaptive pathway for achieving decarbonisation targets

Results

The preliminary results demonstrate that policy mixes, rather than single interventions, are essential for addressing the complexities of transforming the German electricity system,. Combinations of instruments in a policy mix, such as carbon taxes and renewable energy subsidies, create synergies that amplify their effectiveness and ensure a more robust and adaptive transition. Implementing these policies early in the transition is crucial, as early action consistently outperforms delayed interventions in achieving better cost-emissions trade-offs. The analysis also reveals that achieving net-zero emissions before 2050 is feasible, provided an ambitious and early policy mix is introduced.

The inclusion of dynamic learning curves further further highlight the importance of timely interventions. Policies that promote the early adoption of renewable energy technologies drive substantial cost reductions in subsequent periods by accelerating technology deployment and innovation. These findings underscore the cumulative value of early action and its role in aligning near-term efforts with long-term climate goals.

The exploration of a broad policy design space allows the identification of essential (must-have) and counterproductive (must-avoid) policies, as well as synergies and trade-offs between various policy instruments. Additionally, a sensitivity analysis highlights the robustness of the findings, identifying critical factors such as the pace of technology installations and the projection of technology costs that influence the effectiveness of the policy mix.

Conclusions

In summary, this study applies a bi-level optimisation framework to analyse policy mixes for the decarbonisation of Germany's electricity system, focusing on the interactions between policy instruments and energy system design to achieve net-zero emissions. By integrating policy decisions as endogenous variables, the framework captures the dynamic interactions between policy instruments and energy system design, enabling a comprehensive assessment of their combined effects. Preliminary results underscore the importance of early and coordinated policy interventions, with moderate carbon taxes and renewable energy subsidies proving more effective than delayed or isolated measures.

The framework's ability to incorporate dynamic learning curves and multi-stage temporal analysis highlights its potential for assessing both near-term impacts and long-term outcomes. This application also identifies key synergies and trade-offs between policies, offering actionable insights for designing cost-effective pathways to net-zero emissions. These findings underline the necessity of designing cohesive and adaptive policy mixes to align near-term actions with long-term decarbonisation objectives, ensuring a robust and cost-effective pathway to net-zero emissions.