



Restructuring energy markets for net-zero: the role of market-based solutions

Erkan Erdogdu¹

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Abstract

Climate change demands transformative economic restructuring, posing unique challenges for emerging economies in transition. This study examines the critical role of carbon pricing and emissions trading systems (ETS) in advancing sustainable development while achieving net-zero greenhouse gas (GHG) emissions. Focusing on the EU-Turkiye relationship, the paper explores how transitional economies can align carbon markets with growth strategies, navigating the interplay of economic equity, environmental sustainability, and global cooperation. The research redefines climate change as a challenge of market design, arguing that integrating negative externalities into economic systems via carbon pricing can drive the shift to low-carbon economies. A key finding highlights the energy sector's pivotal role, particularly through ETS, in balancing emissions reductions with economic resilience. The study advances existing literature by proposing equitable burden-sharing mechanisms between developed and developing nations, addressing the historical responsibility of developed countries and the developmental needs of emerging economies. This work offers a framework to harmonize climate policy with broader development goals, emphasizing scalable, market-based solutions. By presenting the EU-Turkiye partnership as a case study, the findings provide actionable insights for integrating economic restructuring with climate mitigation, contributing to a global model for sustainable transition.

Keywords Climate change mitigation (Q54) · Carbon pricing (Q52) · Emissions trading systems (Q58) · Renewable energy (Q42) · International cooperation (F53)

✉ Erkan Erdogdu
erkan@erdogdu.net; eerdogdu@epdk.gov.tr

¹ Energy Market Regulatory Authority, EPDK, Mustafa Kemal Mh. 2078. Sokak No 4, 06510 Cankaya, Ankara, Turkey

1 Introduction

Climate change stands as one of the most critical challenges of our time, threatening ecosystems, economies, and human well-being. The global commitment to achieving net-zero greenhouse gas (GHG) emissions represents a cornerstone of climate policy. This ambitious goal requires a drastic reduction in emissions of carbon dioxide and other GHGs, such as methane, nitrous oxide, and sulfur dioxide, alongside efforts to offset remaining emissions through natural or engineered carbon sinks. Net-zero, by definition, ensures that residual emissions are balanced by removals, stabilizing the climate system.

Economists have traditionally characterized climate change as a negative externality—a cost imposed on society rather than the polluter. However, labeling it as “the greatest market failure in history” oversimplifies the issue. Markets are social constructs, and their failures often arise from flaws in design rather than inherent deficiencies. This paper argues that integrating externalities, such as GHG emissions, into market mechanisms can transform these perceived failures into solutions, providing pathways toward sustainable economic restructuring.

Carbon pricing, implemented through mechanisms such as carbon taxes and emissions trading systems (ETS), emerges as a pivotal tool in combating climate change. These strategies assign a tangible cost to emissions, incentivizing cleaner technologies and driving behavioral change. However, achieving net-zero comes with significant economic costs. Effective carbon pricing must translate into higher production costs and final prices for carbon-intensive goods and services, sufficient to reduce consumption, drive low-carbon innovation, and stimulate cooperation between energy and climate policies. An OECD study covering 72 countries—responsible for approximately 80% of global emissions in 2021—revealed that 58% of the 40 billion tonnes of GHG emissions remain unpriced (OECD 2023). In practice, fully pricing carbon leads to increased costs for carbon-intensive goods and services, underscoring the economic complexities of its implementation.

The global nature of climate change necessitates collective action. Regional or national efforts, in isolation, cannot adequately address this pervasive issue. Yet, developing economies face distinct challenges. Their reliance on fossil fuels for industrialization and economic growth often clashes with stringent climate policies promoted by developed nations. Moreover, the historical responsibility of industrialized countries—whose unchecked emissions have significantly contributed to the current crisis—further complicates the debate on equitable burden-sharing.

Addressing these disparities requires policies that not only account for historical contributions to climate change but also foster inclusive solutions. Developed nations must provide financial and technological assistance to enable sustainable transitions in emerging economies. Furthermore, global frameworks must prioritize intergenerational equity, ensuring that current development does not compromise the future.

The energy sector, as the largest contributor to global GHG emissions, is central to transformative change. Decarbonizing energy systems requires not only

technological innovation but also robust policies like ETS, which establish caps on emissions and create markets for trading allowances. This paper examines these dynamics within the context of the EU-Turkiye partnership, showcasing how transitional economies can integrate carbon pricing mechanisms into broader development strategies.

In 2021, global GHG emissions, including those from land use change and forestry (LUCF), reached 49.55 billion tons of CO₂ equivalent (BtCO₂e), up from 32.74 BtCO₂e in 1990—a 51% increase over three decades. Five countries—China (25.8%), the USA (11.2%), India (6.9%), Russia (4.0%), and Brazil (3.1%)—accounted for over half of these emissions. The European Union (EU27) contributed 6.3% to the total, while the 150 lowest-emitting nations collectively represented less than 12%. Energy use drives 74.3% of global emissions, with electricity and heat production contributing 43.3%, transportation 20.8%, and manufacturing 17% (ClimateWatch 2024a). These statistics affirm the energy sector's pivotal role in climate change mitigation.

The Paris Agreement of 2015 marked a watershed moment, uniting nations in the fight against climate change. This binding international treaty aims to limit the rise in global average temperatures to well below 2 °C above pre-industrial levels, with aspirations of capping the increase at 1.5 °C. Achieving the latter target necessitates a peak in global emissions by 2025, followed by a 43% reduction by 2030 (UNClimateChange 2024). The agreement operates on a five-year cycle, requiring nations to submit progressively ambitious national climate action plans, known as nationally determined contributions (NDCs).

Energy markets, particularly electricity markets, are integral to mitigating climate change. Three key policies have emerged as central to this effort: investing in energy efficiency and low-carbon technologies, electrifying services such as heating and transportation, and encouraging or mandating the use of less carbon-intensive energy sources, particularly through ETS. This paper focuses on ETS as a primary tool, with the other policies reserved for future research.

In energy markets, emissions reductions are achieved by promoting cleaner energy sources and ensuring that carbon costs are internalized by producers and consumers. Policy tools for cleaner energy include feed-in tariffs (FIT), feed-in premiums (FIP), renewable portfolio standards (RPS), and renewable energy auctions. Carbon pricing mechanisms, such as carbon taxes and ETS, form the second category of tools.

Harmonized and efficient carbon and energy markets generate three critical incentives via ETS: they drive investments in low-carbon energy supplies, curtail electricity demand by passing carbon costs to consumers, and reduce reliance on carbon-heavy power plants by decreasing their competitiveness in the merit order. These outcomes collectively support the transition to net-zero.

The remainder of this paper is structured as follows. Section 2 reviews existing literature on carbon pricing and ETS and their roles in achieving net-zero transitions. Section 3 investigates burden-sharing mechanisms, using the EU-Turkiye relationship as a case study. Section 4 models the consequences of non-cooperation in climate policy. Section 5 discusses the findings and their implications for

emerging economies. Finally, Sect. 6 provides actionable recommendations for policymakers, emphasizing equitable and scalable climate solutions.

2 Literature review

The role of carbon pricing in achieving net-zero transitions has been a focal point in both academic and policy discussions. This literature review explores three main themes: policy mechanisms, economic impacts, and case studies, highlighting the research gaps this paper aims to address.

2.1 Policy mechanisms

Carbon pricing, encompassing carbon taxes and ETS, has been identified as one of the most effective strategies for mitigating GHG emissions (Stergiou et al. 2023). The primary aim of these tools is to internalize the negative externalities of GHG emissions, assigning them a monetary value that incentivizes reductions and fosters investments in low-carbon technologies. Unlike carbon taxes, which impose a fixed cost on emissions, ETS operates through a cap-and-trade framework, allowing market participants to trade emissions allowances within a predefined cap. This market-based approach provides flexibility, cost efficiency, and adaptability across diverse economic contexts (Dilanchiev et al. 2024).

Several studies highlight the transformative potential of ETS in reshaping energy markets. By increasing retail electricity prices to reflect carbon costs, ETS promotes energy efficiency and reduces the operating hours of carbon-intensive power plants, thereby altering the merit order in energy dispatch models (Zhu et al. 2024). The inclusion of benchmarks in ETS designs further incentivizes innovation and enhances resource allocation, particularly in regions with advanced financial systems (Song et al. 2024; Zhu et al. 2024).

Complementary policy tools such as FIT, FIP, RPS, and auctions have also proven critical in accelerating the adoption of renewable energy technologies. Despite their effectiveness, these mechanisms face challenges such as economic volatility, political uncertainty, and integration across policy frameworks (Chen & Yan 2024). Poorly timed or uncoordinated policies can exacerbate market disruptions, as evidenced by fluctuations in China's carbon markets driven by crude oil price changes and regulatory ambiguities (Zhu & Li 2024).

Newbery et al. (2019) argue that the EU carbon price is significantly lower than both the social cost of carbon and the “target-consistent” prices needed to meet ambitious goals like the 40% reduction target for 2030. Using a political-economy approach, they examine the design and impact of a power-sector carbon price floor (CPF) at both EU and national levels. They propose a CPF to raise the low allowance price (EUA) to €25–30/tCO₂, increasing annually by 3–5% above inflation until at least 2030. Ruhnau et al. (2022) address the uncertainty in future carbon prices and emissions in the European electricity sector, estimating that at a carbon price of €27/t in 2030, emissions could drop by 36–57% compared to

2016 levels. Stiglitz (2019) discusses the rationale for deviating from a uniform carbon price across all uses, places, and times, highlighting situations where distributional concerns justify a tax or regulation that significantly reduces carbon use in carbon-intensive sectors, particularly where consumers are disproportionately wealthy. He et al. (2023) use 36 OECD countries as their research samples to empirically investigate the impact of environmental taxes on mitigating climate change. Their findings indicate that environmental taxes effectively decrease the frequency of extreme weather events and significantly reduce carbon dioxide emissions in these countries.

Markandya et al. (2015) explore the balance between economic growth and low-carbon goals for both developing and developed nations up to 2035, discovering that abatement costs severely impede economic progress in developing regions. Zhang et al. (2024) examine different carbon quota allocation strategies and determine that the benchmark-based method (Method B) results in greater emission reductions compared to the grandfather-based method (Method G). In terms of social welfare, Method B is more advantageous when the environmental damage coefficient is low, while Method G is preferable when the coefficient is high.

Analyzing panel data from 84 developed and developing countries worldwide between 2006 and 2019, Shang et al. (2024) find that higher renewable energy usage lowers climate risk. Arndt (2023) demonstrates a perceived trade-off between energy security and climate protection, influencing energy supply preferences in Western Europe. Consequently, those prioritizing energy security favor coal, gas, and nuclear power over renewables.

Utilizing data from the 2021 Climate Change Performance Index, Puertas and Marti (2021) conduct an empirical analysis to evaluate the effectiveness of countries' climate change efforts, confirming the link between actions and outcomes. Their findings reveal that concern for climate change mitigation is not influenced by a country's wealth, and no consistent pattern emerges among geographically adjacent countries. Muellner et al. (2021) assess the maximum CO₂ reduction potential across different nuclear energy expansion scenarios, concluding that nuclear power's role in combating climate change is, and will remain, minimal.

Drews and van den Bergh (2015) investigate the reasons behind citizens' support or opposition to climate policies. Tvinnereim and Ivarsflaten (2016) reveal that the distribution of costs significantly influences public support for different climate policies. Analyzing individual-level data on employment sectors and climate policy preferences, they discover that those employed in the fossil fuel industry are less inclined to back climate policies that impose high costs on their sector, but show support for policies with lower industry costs.

Pichler and Sorger (2018) explore the idea of delegating climate policy to a supranational environmental authority and create a straightforward model of a world comprising numerous countries. These countries derive benefits from energy consumption but endure the negative effects of global warming and local air pollution, both stemming from fossil fuel combustion, and independently decide on investments in clean energy technologies. The authority, equipped with an optimally designed mandate, imposes severe penalties on the costs of local air pollution compared to those of global warming.

These findings underscore the importance of robust governance frameworks and adaptive policymaking to ensure the stability and credibility of carbon markets.

2.2 Economic impacts

The economic implications of carbon pricing and ETS are multifaceted, influencing market dynamics, innovation trajectories, income distribution, and sectoral competitiveness. Understanding these impacts is essential for evaluating the opportunities and challenges associated with these mechanisms.

Carbon pricing policies have been shown to stimulate technological innovation and drive the transition toward cleaner energy systems. By internalizing the cost of emissions, these policies create market conditions conducive to the development and deployment of low-carbon technologies. For instance, pilot ETS programs in China have demonstrated the critical role of digital finance in enhancing the effectiveness of carbon markets (Zhu et al. 2024). However, emerging economies often lack the institutional capacity to replicate such successes, highlighting the need for tailored approaches.

Regional and sectoral heterogeneity significantly affects the outcomes of carbon pricing. In China, ETS has been associated with widening economic disparities between developed and developing cities, raising equity concerns (Dong & Xiao 2024). Similarly, studies from OECD countries reveal that higher ETS prices can lead to substantial GDP reductions, with the energy sector being particularly sensitive (Lin & Jia 2019). These findings emphasize the importance of equity-sensitive designs that minimize adverse distributional effects.

Income inequality remains a persistent concern. Climate change policies often disproportionately affect low-income groups, particularly in nations where industrialization depends heavily on fossil fuels (Bettarelli et al. 2024). Markkanen and Anger-Kraavi (2019) highlight the co-benefits and adverse effects of climate policies, noting that their social impacts vary based on policy design and implementation. Effective revenue recycling mechanisms, such as using carbon tax revenues for social equity programs, are critical for addressing these disparities. Dorband et al. (2019) examine the effects of moderate carbon price increases on different income groups in 87 predominantly low- and middle-income countries, finding that in nations with per capita incomes below USD 15,000 (PPP-adjusted 2011 USD), carbon pricing generally has progressive distributional effects. They argue that mitigating climate change, raising domestic revenue, and reducing economic inequality can be compatible goals, even in low- and middle-income countries.

Fant et al. (2020) analyze the effects of climate change on U.S. electricity transmission and distribution infrastructure, finding that total costs could rise significantly, with annual climate change expenditures increasing by up to 25%. Their findings indicate that the impacts of climate change will likely be substantial. Doda and Fankhauser (2020) assess the supply-side distributional effects of emissions reduction policies, concluding that carbon pricing outperforms all other instruments and results in more equitable supply-side outcomes.

Kuosmanen et al. (2020) estimate the average annual GHG abatement costs per capita for 28 OECD countries from 1990 to 2015, revealing that actual costs have been much lower than anticipated in the late 1990s. Borissov et al. (2019) examine the effects of carbon pricing on human capital, sectoral shifts, and economic growth, finding that a temporary policy can suffice for transitioning to a clean economy and also spur economic growth. Dutta et al. (2023) study the impact of climate risk on green energy assets' returns and volatility, arguing that increasing climate risk boosts investment in alternative energy, driving up demand and prices while reducing volatility. Lindvall and Karlsson (2023) review the relationship between democracy and climate policy, concluding that democracies generally produce better climate policy outcomes than autocracies, particularly in policy, law, and regulation adoption.

The interaction between carbon pricing and market dynamics also merits attention. Disruptions in global and local carbon markets can lead to economic instability, particularly in carbon-intensive sectors such as energy and finance (Zhu & Li 2024). Stabilizing these markets requires coordinated global and local policy measures that align economic incentives with environmental goals.

2.3 Case studies

Empirical case studies offer valuable insights into the design, implementation, and outcomes of carbon pricing mechanisms across diverse contexts. The European Union Emissions Trading System (EU ETS) is a prominent example, serving as a model for other regions. The EU ETS has successfully reduced emissions in covered sectors, including energy-intensive industries and power generation, while incentivizing investments in low-carbon technologies (Wang et al. 2024). Its phased approach to cap-setting and allowance allocation has allowed for continuous refinement, ensuring adaptability to emerging challenges.

China's pilot carbon markets provide another rich case study. These pilots have tested various ETS designs, revealing the importance of flexibility and regional linkages. For example, interconnected dynamics between provincial carbon markets have influenced pricing and trading behaviors, underscoring the need for comprehensive regulatory frameworks (Yan et al. 2023). However, volatility driven by policy uncertainties remains a challenge, highlighting the importance of robust governance (Chen & Yan 2024).

Beyond the EU and China, studies from other regions offer additional insights. Hu et al. (2022) examine OECD countries, while Ruamsuke et al. (2015) focus on Southeast Asia. Specific country-level studies include Chung and Kim (2018) on South Korea; Sugiyama et al. (2019) on Japan; Goodman (2016) on Germany and India. Research also spans Kazakhstan (Kerimray et al. 2015), the UK (Grubb & Newbery 2018; Guo & David 2023; Lee & Reiner 2023), the USA (Grainger & Ruangmas 2017; Trachtman 2020), Canada (Hennessey et al. 2017), and Mexico (von Lüpke & Well 2019). African studies include contributions from Blimpo et al. (2024), Michaelowa et al. (2020), Msimango et al. (2023) and Newell and Bulkeley (2016).

Emerging economies face unique challenges in implementing ETS. Türkiye, for instance, must align its carbon pricing mechanisms with EU standards to mitigate economic risks associated with the Carbon Border Adjustment Mechanism (CBAM). Establishing a Turkish ETS presents opportunities for cost-effective decarbonization but requires significant capacity-building and support to address local constraints.

Complementary policies such as renewable energy auctions and feed-in tariffs have also shown promise. In Germany, Japan, and India, these mechanisms have reduced investment risks and accelerated the deployment of clean energy technologies. However, gaps remain in understanding their scalability and integration with broader climate policy frameworks (Goodman 2016; Sugiyama et al. 2019).

2.4 Research gaps

Despite extensive research, critical gaps persist in understanding the effectiveness of carbon pricing and ETS, particularly in emerging markets. Existing studies often focus on developed regions with mature policy frameworks, neglecting the unique socio-economic and institutional challenges faced by transitional economies.

One major gap lies in the interplay between global and local carbon markets. International agreements like the Paris Agreement advocate for harmonized carbon pricing mechanisms, yet the interaction between global frameworks and regional policies remains underexplored. For instance, the spillover effects of carbon pricing in interconnected markets such as the EU and its trading partners require deeper investigation (Yan et al. 2023).

The socio-economic implications of ETS in developing countries are another underexplored area. Policies like CBAM pose significant challenges for economies reliant on carbon-intensive exports, exacerbating inequalities and economic disruptions (Bettarelli et al. 2024; Dong & Xiao 2024). Tailored studies are needed to address these issues, focusing on equity-sensitive designs and innovative revenue recycling mechanisms.

Technological innovation presents additional research opportunities. While studies from China demonstrate the role of digital finance in enhancing ETS effectiveness, empirical evidence from other emerging markets is scarce. Understanding how technology can be leveraged to optimize ETS in diverse contexts remains a critical area for further inquiry (Zhu et al. 2024).

Policy implementation and governance also require more attention. Volatility in carbon markets, driven by economic and regulatory uncertainties, undermines their stability and effectiveness. Robust frameworks that align local conditions with global standards are essential for overcoming these challenges (Chen & Yan 2024).

Finally, longitudinal studies examining the long-term impacts of carbon pricing mechanisms are limited. While short-term effects such as emissions reductions are well-documented, their sustained impact on economic resilience, energy transitions, and poverty alleviation is less understood. Addressing these gaps is crucial for developing scalable, inclusive solutions for global climate mitigation.

This paper aims to address some of these gaps by using the EU-Turkiye relationship as a case study to explore how carbon pricing and ETS can be effectively integrated into emerging economies' development strategies. It also emphasizes the need for equitable burden-sharing mechanisms that account for historical emissions and varying levels of economic development. By focusing on the specific challenges and opportunities in transitional economies, this study contributes to the development of scalable, inclusive climate policy solutions.

3 Burden sharing in climate policy: the case of the EU and Turkiye

3.1 Turkish net-zero policy

Table 1 presents the latest energy balance for Turkiye (IEA 2024). In 2022, Turkish total primary energy supply reached 156.5 million tons of oil equivalent (mtoe). Fossil fuels—coal, oil, and natural gas—comprised 81.8% of this supply, while renewables contributed 17%. The total final energy consumption was 112.8 mtoe, with industry consuming 29.6%, road transportation 25%, residential usage 22.1%, and commercial and public services 12.7%. Electricity production in 2022 was 328.4 TWh, with 42% generated from renewable sources. In summary, Turkiye relies heavily on non-renewable energy sources for its primary energy supply (about 83%), though this dependence drops to 58% for electricity generation.

In 2022, Turkish GHG emissions soared to 558.3 million tons of CO₂ equivalent (CO₂e), marking a 144.9% rise from 1990 levels. The energy sector is responsible for 71.8% of these emissions, followed by agriculture at 12.8%, industrial processes at 12.5%, and waste at 2.9% (TUIK 2024a). Land-use change and forestry typically act as carbon sinks, capturing more CO₂ than they emit, resulting in negative emissions. Figure 4 illustrates the progression of historical emissions up to 2022 (ClimateWatch 2024b).

To date, Turkish climate change policy has dominantly concentrated on promoting the adoption of low-carbon energy sources in electricity generation using five primary tools shown in Fig. 1: the development of large hydroelectric power plants, the implementation of a feed-in tariff system (YEKDEM), renewable energy resource area tenders (YEKA), regulations for unlicensed power generation, and the provision to establish storage facilities paired with wind or solar installations. (Fig. 2).

Thanks to large hydropower plants, one-fifth of all power generation come from hydro sources. Apart from hydroelectric power, the growth of Turkish renewable energy capacity surged with the launch of the “Renewable Energy Resources Support Mechanism” (YEKDEM) in 2011. In this mechanism, Turkish transmission system operator, TEIAS, conducts capacity allocation auctions for pre-license applications received by the Energy Market Regulatory Authority (EMRA). This initiative allocated renewable energy capacities from 2011 to 2020 and offered foreign currency-based incentives. As a result, there was a notable increase in wind and solar energy capacities. Under YEKDEM regulations, renewable energy license holders receive feed-in tariffs (FIT) for ten years post-commissioning, applicable

Table 1 Energy balance table for Türkiye (2022, ktce)

	Coal and coal products	Oil and oil products	Natural gas	Biofuels and waste	Hydro	Geothermal	Solar/wind/other	Electricity	Total	Renewables
Production	18.835,3	3.662,9	312,7	5.090,3	5.744,0	11.514,2	5.943,4	0,0	51.102,8	26.539,7
Imports	24.284,4	54.735,3	45.007,8	0,0	0,0	0,0	0,0	553,6	124.581,1	0,0
Exports	-557,3	-9.447,2	-478,8	0,0	0,0	0,0	0,0	-319,3	-10.802,6	0,0
International marine/aviation bunkers and stock changes	-797,1	-4.772,7	-2.816,2	0,0	0,0	0,0	0,0	0,0	-8.386,1	0,0
Total energy supply	41.765,2	44.178,2	42.025,5	5.090,3	5.744,0	11.514,2	5.943,4	234,4	156.495,3	26.539,7
Power plants	-26.112,0	-218,5	-9.826,8	-1.859,9	-5.744,0	-9.560,0	-4.574,2	27.185,6	-30.709,9	-21.615,3
Energy industry own use	-1.073,5	-1.816,1	-1.170,4	0,0	0,0	0,0	0,0	-1.698,9	-5.758,8	0,0
Losses	0,0	0,0	-2,5	0,0	0,0	0,0	0,0	-2.499,3	-2.501,8	0,0
Other transformation	-3.805,9	-708,2	-1.359,5	-314,1	0,0	0,0	-500,7	1.989,3	-4.699,2	-314,1
Total final consumption	10.773,8	41.435,4	29.666,2	2.916,3	0,0	1.954,2	868,6	25.211,0	112.825,6	4.610,3
Industry	7.492,0	3.588,3	9.051,7	1.128,8	0,0	0,0	84,7	12.034,9	33.380,4	84,7
Transport	0,0	29.605,9	257,6	144,8	0,0	0,0	0,0	153,9	30.162,2	144,8
Road	0,0	27.994,1	70,7	144,8	0,0	0,0	0,0	0,0	28.209,6	144,8
Other transport	0,0	1.611,9	186,9	0,0	0,0	0,0	0,0	153,9	1.952,7	0,0
Residential	728,4	371,3	14.827,0	1.642,7	0,0	1.327,4	783,9	5.306,1	24.986,8	3.754,0
Commercial and public services	2.553,4	368,6	4.832,9	0,0	0,0	0,0	0,0	6.561,5	14.316,4	0,0

Table 1 (continued)

	Coal and coal products	Oil and oil products	Natural gas	Biofuels and waste	Hydro	Geothermal	Solar/wind/other	Electricity	Total	Renewables
Other final consumption	0,0	7.501,3	697,1	0,0	0,0	626,8	0,0	1.154,6	9.979,8	626,8
Electricity output (GWh)	112.879,8	1.234,0	75.058,7	8.088,2	66.802,5	11.118,8	53.197,4	0,0	328.379,3	137.827,4

Fig. 1 Key Turkish policies for low-carbon electricity generation

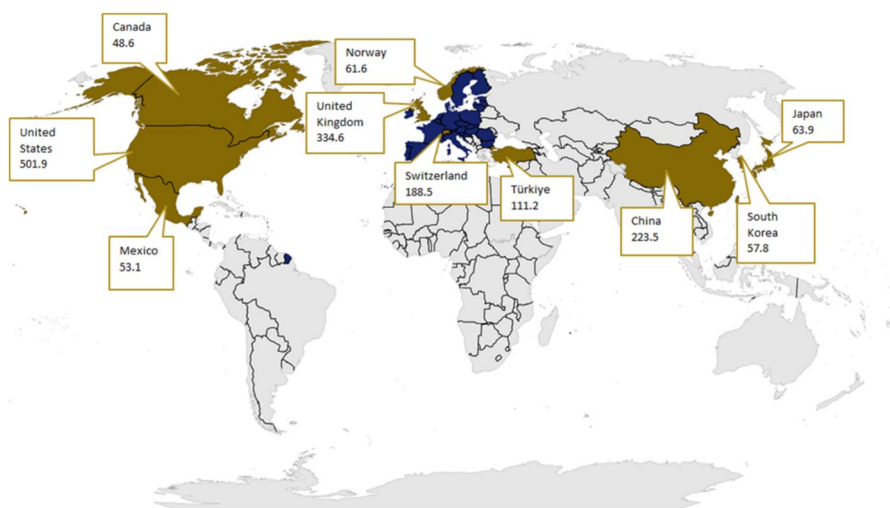
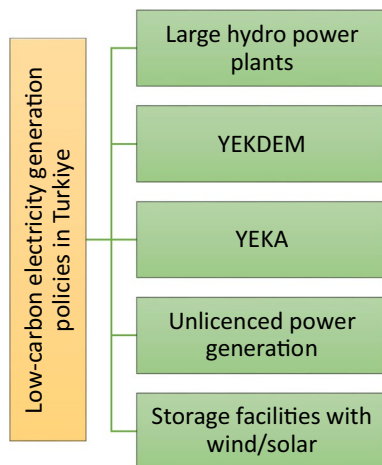


Fig. 2 Principal partners for EU exports of goods, 2023 (billion Euro)

only to plants operational by December 31, 2020. Participation in YEKDEM is voluntary; license holders can choose between YEKDEM benefits or selling electricity on the open market through bilateral agreements.

After the initial YEKDEM program ended in June 2021, new tariffs for renewable energy plants to be operational between July 1, 2021, and December 31, 2025, were announced on May 1, 2023. In the revised YEKDEM, incentives were provided in Turkish Lira (TL) instead of foreign currency, with quarterly tariff adjustments. The May 2023 revision significantly raised feed-in tariffs (FiT) for the new YEKDEM period. The updated tariffs apply for 15 years for geothermal plants and pumped-storage hydroelectric facilities and 10 years for other facilities. The revised

mechanism also included new renewable energy technologies for the first time, such as offshore wind plants, wind or solar integrated electricity storage facilities, pumped-storage hydroelectric plants, and tidal energy plants. However, the absence of a capacity auction and the TL-based incentives limited the new capacities commissioned under this program.

Beyond YEKDEM, licensed renewable energy investments can be made through Renewable Energy Resource Area (YEKA) tenders. Unlike YEKDEM, YEKA tenders establish purchase guarantees based on tender results and cover larger areas. The Ministry of Energy and Natural Resources (MENR) designates renewable energy zones, ensuring grid connection and land permits for a specified power capacity. The winning firm, selected through a tender process, is granted right to use the YEKA region and capacity, committing to sell the electricity generated at the bid price during the contract period. As of February 2025, there have been multiple YEKA tenders, including four for solar energy (totalling 3,800 MW) and four for wind energy (totalling 4,050 MW). Besides, initiatives for renewable energy procurement and certification in Türkiye began in 2020, with the YEK-G regulation establishing a renewable energy tariff and qualification certificates. The YEK-G system, introduced in June 2021, enables tracking, proving, and disclosing that electricity supplied to consumers is generated from renewable energy sources (RES) by licensed entities. Energy Exchange Istanbul (EXIST) operates the YEK-G system and organized YEK-G market.

Additionally, renewable energy development in Türkiye includes projects under the updated unlicensed power generation regulation and opportunities to establish storage facilities integrated with wind or solar plants. As of November 19, 2022, entities that set up electricity storage facilities can establish wind or solar plants with the same capacity as the storage facility and sell electricity at market prices without requiring pre-license auctions.

Turkish energy policy focuses on increasing renewable energy use and reducing import dependency to enhance supply security. Mechanisms like YEKDEM and YEKA have spurred significant investments in renewable energy, particularly wind and solar. Nuclear energy is also considered for improving supply security and lowering GHG emissions.

Türkiye signed the United Nations Framework Convention on Climate Change (UNFCCC) on May 24, 2004, ratified the Kyoto Protocol on August 26, 2009, and officially endorsed the Paris Agreement on October 7, 2021. Initially, Türkiye's NDC aimed for a 21% reduction in GHG emissions by 2030, but this target was updated in April 2023 to a more ambitious 41% reduction, targeting 695 Mt CO₂ equivalent for 2030, using 2012 as the base year. Türkiye also plans to peak its emissions by 2038. So, for Türkiye, achieving its net-zero target entails reducing GHG emissions to a level that its "carbon sinks"—including forests, wetlands, agricultural soils, coastal ecosystems, and reforestation projects—can offset by the year 2053. According to Climate Action Tracker (2025), this offset capacity is estimated to range between 80 and 140 million tonnes of CO₂ equivalent by 2053. However, our forecast suggests a more pessimistic figure of just 60.7 million tonnes (Fig. 3). Consequently, Türkiye must ensure its sectoral GHG emissions remain below this threshold by 2053 to meet its net-zero target. (Fig. 4).

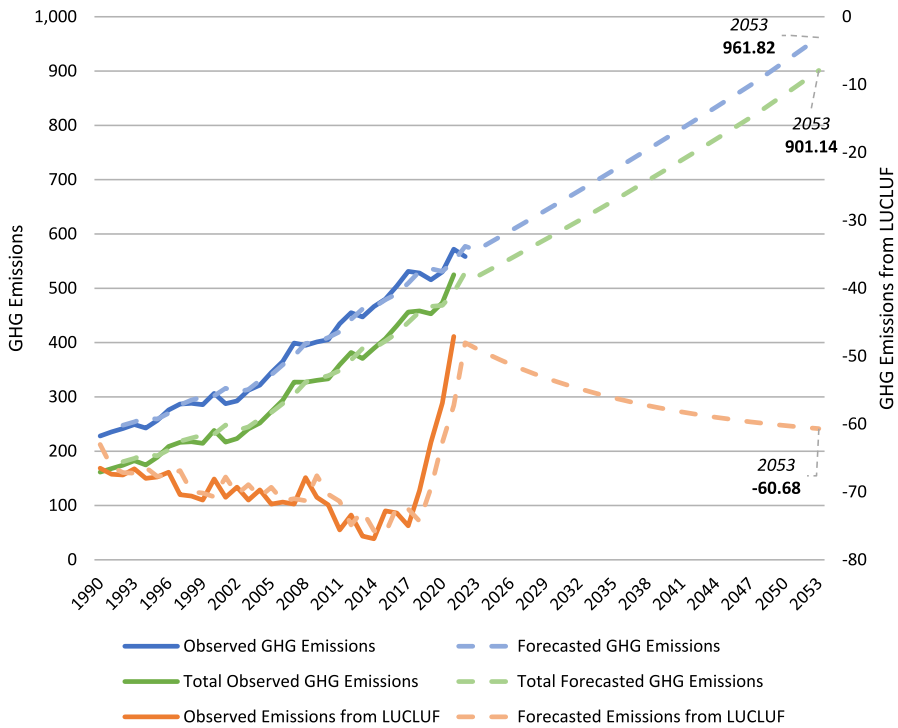


Fig. 3 Actual and forecasted Turkish GHG emissions (million tonnes CO₂ equivalent), 1990–2053

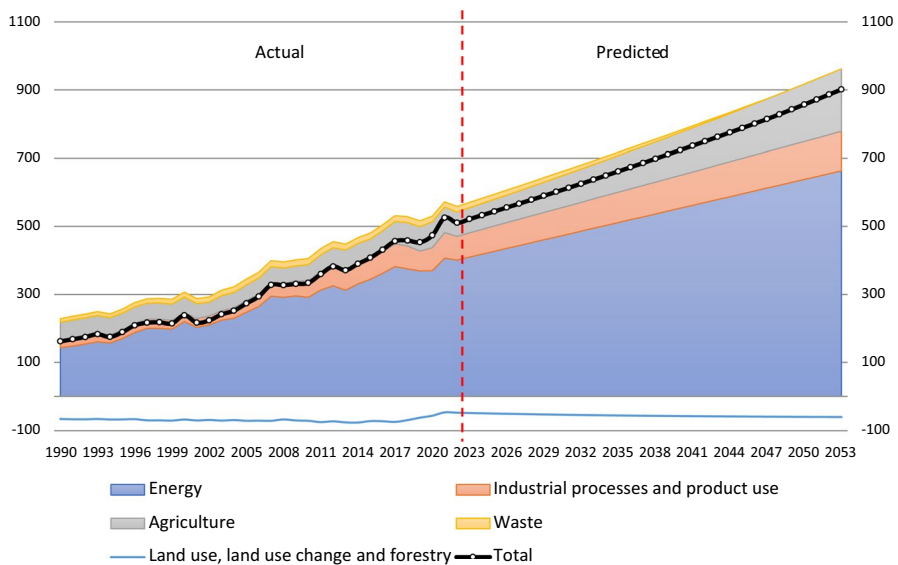


Fig. 4 Actual and forecasted Turkish GHG emissions by (million tonnes CO₂ equivalent), 1990–2053

Ratifying the Paris Agreement in late 2021 positioned Türkiye as a latecomer in the global push toward net-zero emissions. The 2030 NDC target shows minimal action, lacking both an adaptation component and a detailed plan for financial needs or climate-related loss and damage. Although Türkiye is on track to meet its updated NDC commitments by 2030, it has yet to outline concrete steps for the period between 2030 and 2053.

In 2023, Türkiye's imports totaled \$361.8 billion, while exports reached \$255.4 billion; and the EU-27 accounted for 29.3% of imports and 40.8% of exports (TUIK 2024b). The EU's CBAM, set to start in 2026, will levy a carbon tax on imports from non-EU countries if their carbon pricing falls below the EU ETS levels. The CBAM serves as the primary catalyst for Türkiye's recent climate policy initiatives, especially as an EU candidate lacking access to the EU ETS. This mechanism will heavily influence Türkiye's economy and climate strategies, making the establishment of a Turkish ETS the primary avenue for aligning with global net-zero goals under the Paris Agreement.

3.2 EU ETS and CBAM instruments

The EU ETS is a pivotal element in the EU's strategy to address climate change, serving as the primary mechanism for cost-effective GHG reduction. As the world's first major carbon market, it remains one of the largest.

The allocation of emission allowances within an ETS determines how the responsibility of meeting emissions targets is distributed among sectors. These allowances can be either given for free or sold through auctions. Free allocation can be done using two main methods: grandfathering and benchmarking. Grandfathering allocates allowances based on historical emissions, which may inadvertently benefit past high emitters. As a result, most ETSs now prefer benchmarking, which allocates allowances based on emissions performance relative to a specific standard, encouraging early action and higher environmental standards.

The EU ETS has undergone several phases of allocation. In Phase 1 (2005–07), allowances were primarily allocated through grandfathering, with some variations in auctioning and benchmarking across member states. During Phase 2 (2008–12), 90% of allowances were grandfathered, with the majority of the remainder allocated based on benchmarks and some auctioned. By Phase 3 (2013–20), the allocation shifted to 43% based on benchmarks and 57% auctioned. In Phase 4 (2021–2030), guided by the revised EU ETS Directive, free allocation continues for another decade, focusing on sectors at high risk of relocating outside the EU, which receive 100% of their allowances for free. For less exposed sectors, free allocations will be gradually phased out, decreasing from a maximum of 30% to zero by the end of Phase 4.

As the EU intensifies its climate goals, the risk of 'carbon leakage'—where companies move carbon-intensive production to countries with looser climate policies or where EU products are replaced by higher-carbon imports—becomes more pronounced. The EU's CBAM aims to equalize the carbon cost of goods entering the EU, encouraging cleaner production practices globally. By ensuring that imported

goods bear a carbon cost equivalent to domestic production, CBAM supports the EU's climate objectives and mitigates the risk of carbon leakage (EU 2024).

CBAM will fully apply from 2026, following a transitional phase from 2023 to 2025. This gradual implementation aligns with the phasing out of free allowances under the EU ETS to aid EU industry decarbonization. From 2026, EU importers of CBAM-covered goods must register with national authorities to purchase CBAM certificates, priced based on the weekly average auction price of EU ETS allowances in €/tonne of CO₂. Importers will declare their goods' embedded emissions and surrender the corresponding certificates annually. If a carbon price has already been paid in the country of production, it will be deducted from the required certificates.

3.3 Key elements and foundations of the cooperation

The EU is Türkiye's largest market for exports, and as indicated in Fig. 2, Türkiye ranks as the EU's fifth largest trade partner (EuroStat 2024). This underscores the robust trade relationship between the two and any effective cooperation should aim for a transition to net-zero emissions without harming trade, based on the three key principles. First, both the EU and Türkiye must recognize that achieving net-zero will incur costs. Second, they must agree that global warming requires global solutions; the EU alone cannot reach net-zero without the cooperation of other countries like Türkiye. Therefore, the EU should consider Türkiye's concerns and include measures to mitigate potential economic losses for Türkiye. Third, it is important to acknowledge that the EU's development heavily relied on unrestricted carbon resource use, which has significantly contributed to the current climate crisis. Expecting a developing country like Türkiye to completely avoid carbon resource use for environmental reasons is unrealistic. A fair and effective approach would involve a market-based system that promotes intergenerational justice while addressing climate change. This necessitates good-faith collaboration between the EU and Türkiye. To be effective, the EU's CBAM, EU ETS, and local Turkish ETS must align with these principles.

Currently, the EU has set clear targets and strategies for GHG reduction, but Türkiye has gaps in its approach. Türkiye continues to invest in domestic lignite coal and fossil gas to reduce dependency on imported fuels. However, for an effective transition to net-zero, Türkiye must maximize its renewable energy potential to avoid fossil fuel dependency and enhance energy security. Türkiye should be encouraged to develop a coal phase-out plan for the power sector and implement corresponding policies. Additionally, Türkiye needs to establish a more ambitious 2030 NDC target that exceeds current policies and drives significant emissions reductions. Effective cooperation between the EU and Türkiye should motivate Türkiye to act on these issues.

The EU's proposed CBAM has significant implications for Türkiye. If implemented as currently envisioned, it could increase costs for Türkiye, potentially harming its competitiveness and negatively impacting economic growth and employment. CBAM presents substantial risks to the Turkish economy, necessitating collaborative measures between the EU and the Turkish government to mitigate these risks.

The most feasible market-based solution for a cooperative net-zero transition between the EU and Türkiye is to establish a local ETS in Türkiye that aligns with EU standards and is overseen by the EU. This system would eliminate the need for CBAM certificates for Turkish imports if a carbon price has already been paid in Türkiye. Implementing such a local ETS would help Türkiye mitigate the economic impacts of CBAM and reduce national GHG emissions cost-effectively. Beyond mitigating CBAM impacts, adopting a local ETS could provide broader social and economic benefits to Türkiye and accelerate its overall decarbonization.

Such a policy would likely lead to the relocation of some industrial facilities from the EU to Türkiye due to lower carbon prices. However, over time, this would increase demand for carbon certificates in Türkiye, thereby raising their prices. Once carbon prices in the EU ETS and Turkish ETS equalize, the industrial shift toward Türkiye would cease. This solution meets the three criteria mentioned earlier: it is a market-based approach that assigns a carbon price in both regions, reducing demand for carbon-intensive goods. It is a global solution that can be replicated in other countries, and most importantly, it is fair and acceptable. The temporary relocation of some industries from the EU to Türkiye can be seen as the price the EU pays for its past unrestricted use of carbon resources during its development.

3.4 Key considerations for successful cooperation

Effective cooperation involves establishing functional local ETSs that ensure local carbon pricing covers all emissions costs, thereby facilitating trade between cooperating countries without requiring additional payments. The integration of industries from cooperating countries into local ETSs that also cover the power sector may present several challenges. Firstly, there may be short-term competitiveness issues as well as socio-economic consequences, such as reduced investment in industries and job losses. Additionally, environmental concerns arise from carbon leakage, where industrial production—and its associated emissions—shifts to non-cooperating regions. Beyond these direct risks, indirect costs must also be considered. These include potential increases in the prices of other goods covered by ETSs due to higher energy costs. Furthermore, the implementation of ETSs may involve investment risks linked to uncertainties in policy design, as well as compliance costs related to measurement, reporting, and verification.

The practice of freely allocating carbon allowances has been prevalent in many ETSs to mitigate competitiveness issues and prevent carbon leakage within the industrial sector. However, this approach does not align with cooperative frameworks that necessitate precise local carbon pricing. In collaborative setups, such as those between EU countries and Türkiye, it is crucial to transition from free allocation to auctioning carbon allowances. This change helps to rectify market distortions, generates revenue to fund net-zero transition initiatives, and improves the overall efficacy of ETSs.

4 The outcomes of non-cooperation: a modeling approach

If the EU ETS and CBAM are implemented without cooperation with Türkiye, the establishment of a local Turkish ETS will either be completely hindered or result in a system where substantial quantities of free carbon permits are distributed to protect local industries. This would lead to such low prices for carbon permits that the Turkish ETS would fail to achieve a significant reduction in carbon emissions. Furthermore, Türkiye would perceive the EU's CBAM as an additional tax on its exports to the EU, likely prompting retaliatory measures through new tariffs on EU imports. The primary outcomes of this lack of cooperation would be a marked decrease in free trade between the EU and Türkiye and the continuation of current trends in Turkish GHG emissions. In this section, we develop an econometric model to forecast Turkish emissions if no effective measures are taken to reduce them.

4.1 Data and methodology

Annual data on Turkish GHG emissions across various sectors, measured in million tonnes of CO₂ equivalent for the 1990–2022 period, were sourced from TUIK (2024a) and the data on GHG emissions from land-use change and forestry the are taken from Climate Action Tracker (2025). Summary statistics of each variable is presented in Table 2. Projections for future GHG emissions from each sector up to 2053 are derived using historical values under a business-as-usual scenario. The sectors analyzed include “energy,” “industrial processes and product use,” “agriculture,” “waste,” and “land use, land use change, and forestry.” In this analysis, the Autoregressive Integrated Moving Average (ARIMA) model is utilized, widely regarded as one of the most effective econometric tools for time series forecasting.

Table 2 Summary statistics

VARIABLE NAME	VARIABLE LABEL	NUMBER OF OBSERVATIONS	MEAN	STD. DEV	MINIMUM	MAXIMUM
YEARS	year	33	2006	9.67	1990	2022
ENERGY	energy	33	265.90	83.06	143.15	406.47
INDUSTRIAL PROCESSES AND PRODUCT USE	industry	33	41.92	17.43	22.69	74.72
AGRICULTURE	agriculture	33	53.83	9.97	40.71	76.44
WASTE	waste	33	15.43	2.53	10.32	18.43
LAND USE, LAND USE CHANGE, AND FORESTRY	landuse	32	-69.30	5.65	-76.90	-47.10

The Autoregressive (AR) component of the ARIMA model uses historical data to predict future values. The Integrated (I) component transforms the data into a stationary series by differencing it. This transformation is essential for accurate modeling of non-stationary data. The Moving Average (MA) component employs past forecast errors in a regression-like model. The ARIMA model's flexibility allows it to handle various types of time series data through parameter adjustments, often yielding reliable and precise forecasts when properly tuned.

Therefore, ARIMA is a suitable model for this study. Mathematically, the model is denoted as ARIMA(p, d, q), where p represents the order of the autoregressive part, d signifies the degree of differencing required to achieve stationarity, and q indicates the order of the moving average part.

In our analysis, we adhere to the standard ARIMA methodology, which includes (1) identifying the order (utilizing tools such as the ACF and PACF to determine appropriate values for p and q), (2) differencing the series (to ascertain the value of d needed to achieve stationarity), (3) fitting the model, (4) diagnosing the model (examining the residuals to ensure they approximate white noise), and (5) forecasting (using the fitted model for future predictions). The intricate details of ARIMA are not elaborated here due to space constraints, but comprehensive explanations can be found in Box et al. (2008), Hamilton (1994) and Hyndman and Athanasopoulos (2018), who offer an in-depth understanding of ARIMA models and their applications in econometrics.

4.2 Estimation process

The estimation process begins with a visual inspection of each variable to understand its structural patterns. Time series plots are used to identify trends, revealing that most variables exhibit strong non-stationary trends, with the exception of the *land-use* variable. Differencing is applied to the variables, which removes trends and suggests potential stationarity. This is further verified using the Dickey-Fuller test, with results indicating that original variables are generally non-stationary, while differenced variables achieve stationarity (Appendix A).

Autocorrelation and partial autocorrelation functions are analyzed via correlograms (Appendix D). Original variables exhibit a slow decay in autocorrelation, consistent with non-stationarity, while differenced variables show rapid decay, supporting stationarity. Based on these findings, various ARIMA model configurations

Table 3 Selected ARIMA models for each variable

Variable Label	Model Spec	Coef. (Cons.)	P> t	Coef. (AR L1)	P> t	Coef. (MA L1)	P> t
energy	ARIMA(1,1,1)	8.4400	0.000	0.4656	0.016	-0.9999	0.000
industry	ARIMA(0,1,0)	1.4755	0.011	–	–	–	–
agriculture	ARIMA(0,2,1)	0.0950	0.013	–	–	-1	0.000
waste	ARIMA(1,2,1)	-0.0282	0.000	-0.3797	0.030	-1	0.000
landuse	ARIMA(1,0,0)	-63.0187	0.000	0.9418	0.000	–	–

are tested. A total of 320 models are explored across variables, combining different autoregressive (AR), differencing (I), and moving average (MA) parameters (Appendix B). The Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) are used to balance model fit and complexity, with the preferred models selected based on their minimal AIC/BIC values and statistical significance (Table 3).

Residual diagnostics follow to ensure the adequacy of the selected models. Residuals are examined visually and tested for white noise using the Dickey-Fuller test (Appendix C), with all p-values below 0.05, confirming stationarity. The stability and invertibility of models are verified by ensuring that the roots of AR and MA components lie within the unit circle (Appendix D).

Forecasting is conducted after validating model adequacy. Time series are extended to 2053, with forecasted values appended. Figures 3 and 4 display the results, showing that the ARIMA models closely replicate historical values, demonstrating strong predictive performance. Projections indicate that, without intervention, Türkiye's GHG emissions (*excluding land use, land use change and forestry*) will increase by 17.3% by 2030, 40.0% by 2040, and 72.3% by 2053 compared to 2022 levels of 558.3 million tonnes of CO₂ equivalent.

4.3 Assessing robustness and stability of the models

ARIMA models inherently mitigate endogeneity concerns, as they are designed to account for dependencies within time-series data, where dependencies on past values and error terms are explicitly accounted for. In ARIMA models, the current value of the series is modeled as a function of its past values and past shocks, which naturally incorporates any feedback or autocorrelation effects that might otherwise be sources of endogeneity in other types of models. The moving average component explicitly includes past errors, mitigating concerns about correlation between predictors and the error term. Additionally, ARIMA models are predictive in nature and do not aim to infer causal relationships, which is where endogeneity typically becomes problematic. The use of differencing to achieve stationarity further stabilizes relationships over time, reducing the impact of endogenous feedback loops. Endogeneity is more of a concern in cross-sectional or panel data models, where omitted variables, measurement errors, or reverse causality could bias estimates. In ARIMA, the self-contained nature of the time-series dynamics and the focus on forecasting rather than causal inference make endogeneity less relevant.

To test robustness, the selected ARIMA models undergo formal evaluation using AIC and BIC criteria. Additionally, models are validated by back-casting historical values and comparing predictions with observed data, demonstrating high accuracy and confirming good model fit. Residual analyses show no significant autocorrelation or discernible patterns, further supporting the reliability of the results (Appendix C). The findings confirm that the selected models are robust and suitable for projecting future trends, providing a reliable foundation for assessing Türkiye's GHG emissions trajectory.

ARIMA models are a popular choice for time series forecasting and have proven to be effective in many applications. Like any econometric model, ARIMA has its limitations. It assumes linearity, which may not capture all complexities of certain datasets, and works best with stationary data, requiring transformations for non-stationary series. While primarily suited for univariate time series, its focus on historical patterns may limit its performance in long-term forecasting if significant structural changes occur. However, these limitations are not unique to ARIMA and do not undermine its reliability. When used with care and an understanding of its scope, ARIMA models provide accurate and valuable insights.

5 Discussion of the results

The interplay between global and local challenges in achieving net-zero is evident in this study, particularly through the lens of the EU-Turkiye relationship. The global nature of climate change demands collective action, yet localized economic realities often hinder uniform responses. For Turkiye, its reliance on fossil fuels for energy security and economic growth underscores the tension between immediate economic priorities and long-term environmental goals. Meanwhile, the EU's aggressive decarbonization agenda and the introduction of the CBAM amplify the pressure on Turkiye to align its policies. This duality highlights the necessity for equitable burden-sharing mechanisms to address disparities between developed and emerging economies.

The policy implications of this study are profound, especially for emerging economies navigating the dual pressures of economic development and environmental sustainability. The findings suggest that the establishment of a localized ETS in Turkiye, aligned with EU standards, could mitigate the adverse effects of CBAM while fostering economic and environmental alignment. This alignment would not only reduce trade tensions but also enhance Turkiye's net-zero policies. For policymakers, this underscores the importance of designing mechanisms that balance economic equity with environmental objectives, such as incorporating technology transfer and financial support as part of climate cooperation frameworks.

The broader geopolitical implications of non-cooperation are equally significant. Without alignment, Turkiye risks trade disruptions and economic marginalization within the EU market, while the EU risks undermining its global leadership on climate issues by alienating key trade partners. This study suggests that inclusive and adaptive policy frameworks are critical to ensuring cooperative solutions. A shared focus on market-based mechanisms, like ETS, offers a scalable model that other regions could adopt to balance global climate commitments with local economic contexts.

Generalizing these findings to other regions reveals a broader applicability. Countries in Southeast Asia, Africa, and Latin America face similar challenges as they transition to low-carbon economies. The principles of equitable policy design, international cooperation, and localized market mechanisms can inform climate strategies across these regions. For example, aligning ETS frameworks with regional

economic capacities and integrating socio-economic protections can enhance policy acceptability and effectiveness.

Turkish experience highlights that heavily subsidized natural gas and electricity for residential consumers disrupt market functionality and order. Such subsidies encourage fossil fuel use, undermining carbon pricing goals. To address this, subsidies should target only the most vulnerable groups, while eliminating support for others. Incentives for fossil fuels also delay the transition to clean energy. Therefore, purchase guarantees for fossil-fuel-based electricity and capacity mechanisms favoring fossil power plants should be abolished.

To enhance market predictability, data access should be improved, and a “carbon market board” could oversee local ETS development in emerging economies. In electricity and industry, free allocation of emission allowances weakens ETS price signals. Auction-based allocation is essential, paired with effective penalties for exceeding carbon limits. A carbon price stability mechanism, through price floors, ceilings, or market reserves, can further stabilize the system.

The study also delves into practical strategies for aligning Turkish and EU policies despite their differing economic capacities. It advocates for a phased approach to harmonization, beginning with capacity-building initiatives and financial incentives to support Türkiye’s transition. Addressing potential trade-offs, such as equity concerns and socio-economic impacts on vulnerable populations, requires targeted revenue recycling mechanisms. These could include investments in renewable energy, subsidies for low-income groups, and retraining programs for workers in carbon-intensive industries.

Ultimately, this study underscores that achieving net-zero demands a multi-dimensional approach that integrates technical, economic, and social considerations. The findings provide a roadmap for harmonized policy action, highlighting the potential of ETS to drive emissions reductions while fostering economic equity and geopolitical stability.

6 Conclusion

This paper emphasizes the transformative potential of ETSs as a market-based mechanism for achieving net-zero. The EU-Turkiye relationship serves as a case study to explore the challenges and opportunities in aligning local policies with global climate objectives. While ETS offers a flexible and cost-effective pathway to emissions reductions, its success depends on equitable designs, robust governance frameworks, and international cooperation.

Key findings highlight the importance of harmonized climate action, particularly in the context of the EU’s CBAM, which serves as both a challenge and an opportunity for Türkiye. This mechanism incentivizes policy alignment but also risks economic disparities without sufficient support for emerging economies. Addressing these disparities through financial aid, technology transfer, and capacity-building initiatives is essential for ensuring a fair transition to low-carbon economies.

The study provides actionable recommendations for policymakers, including the development of localized ETS frameworks that align with global standards,

restructuring energy subsidies to support renewable energy adoption, and implementing equity-sensitive designs to address socio-economic impacts. These measures can serve as a blueprint for other transitional economies, offering scalable solutions for global climate governance.

Future research should focus on the long-term socio-economic impacts of ETS and other market-based mechanisms, particularly in vulnerable regions. Investigating innovative approaches to revenue recycling and equity-sensitive policy designs will be critical to enhancing the inclusivity and effectiveness of climate strategies.

In conclusion, achieving net-zero requires a blend of market-based mechanisms, equitable burden-sharing, and strong international cooperation. The EU-Turkiye case has offered and will offer valuable lessons for global climate governance, demonstrating the importance of adaptive and inclusive policy frameworks in addressing the complex challenges of climate change.

Appendix A: Dickey-Fuller test (for unit root) results

Dickey-Fuller test results for the variables (H_0 : Random walk with drift).

VARIABLE LABEL	COEFFICIENT (L1)	P> T	COEFFICIENT (CONSTANT)	P> T	Z(T)	P-VALUE FOR Z(T)
ENERGY	−0.0042	0.883	9.1409	0.247	−0.148	0.4417
INDUSTRY	0.0063	0.856	1.2181	0.429	0.183	0.5719
AGRICULTURE	0.0230	0.624	−0.6119	0.810	0.495	0.6879
WASTE	−0.0838	0.015	1.4772	0.007	−2.588	0.0074
LANDUSE	0.1950	0.191	14.2789	0.173	1.338	0.9044

Dickey-Fuller test (with trend) results for the variables (H_0 : Random walk with or without drift).

VARIABLE LABEL	COEF. (L1)	P> T	COEF. (TREND)	P> T	COEF. (CONS.)	P> T	Z(T)	P-VALUE FOR Z(T)
ENERGY	−0.5867	0.001	5.0672	0.001	77.9631	0.001	−3.571	0.0324
INDUSTRY	−0.2211	0.039	0.4326	0.027	3.4130	0.054	−2.158	0.5133
AGRICULTURE	−0.0723	0.225	0.1448	0.022	2.0776	0.428	−1.239	0.9022
WASTE	−0.0138	0.816	−0.0227	0.168	0.7738	0.280	−0.235	0.9909
LANDUSE	0.2840	0.035	0.1874	0.003	17.5100	0.058	2.210	1.0000

Dickey-Fuller test results for the differenced variables (H_0 : Random walk with drift).

VARIABLE LABEL	COEFFICIENT (L1)	P> T	COEFFICIENT (CONSTANT)	P> T	Z(T)	P-VALUE FOR Z(T)
ENERGY	−1.2122	0.000	9.9682	0.001	−6.545	0.0000

VARIABLE LABEL	COEFFICIENT (L1)	P> T	COEFFICIENT (CONSTANT)	P> T	Z(T)	P-VALUE FOR Z(T)
INDUSTRY	-1.1011	0.000	1.6367	0.022	-5.558	0.0000
AGRICULTURE	-0.5609	0.004	0.2683	0.544	-3.131	0.0020
WASTE	-0.9640	0.000	0.1751	0.085	-5.053	0.0000
LANDUSE	-0.6888	0.003	0.5771	0.337	-3.226	0.0016

Appendix B: Akaike's information criterion (AIC) and Bayesian information criterion (BIC) for alternative ARIMA model specifications

Variables: <i>Model Spec</i>	Energy		Industry		Agriculture		Waste		Landuse	
	AIC	BIC	AIC	BIC	AIC	BIC	AIC	BIC	AIC	BIC
ARIMA(0,0,0)	388.33	391.32	285.26	288.25	248.38	251.38	157.80	160.80	204.59	207.53
ARIMA(0,0,1)	351.78	356.27	249.73	254.22	211.51	216.00	121.98	124.97	190.95	195.35
ARIMA(0,0,2)	335.46	341.44	225.38	231.36	190.69	195.18	102.25	108.24	179.93	185.79
ARIMA(0,0,3)	313.68	321.16	207.59	213.57	178.53	183.02	86.83	92.81	179.99	187.32
ARIMA(0,1,0)	255.54	258.47	167.99	170.92	151.28	154.21	49.78	52.71	163.72	166.58
ARIMA(0,1,1)	254.88	259.27	169.33	173.72	146.62	151.01	51.75	56.15	164.54	168.84
ARIMA(0,1,2)	252.38	258.25	168.65	174.51	148.61	154.47	52.40	58.26	164.01	169.75
ARIMA(0,1,3)	251.53	257.39	167.63	173.49	149.82	157.15	54.43	61.76	164.41	171.58
ARIMA(0,2,0)	275.32	278.19	186.05	188.91	150.83	153.70	68.78	71.64	166.60	169.41
ARIMA(0,2,1)	252.04	254.91	168.55	172.85	146.75	149.62*	44.54	47.40	154.89	159.09
ARIMA(0,2,2)	254.22	259.95	167.40	171.71	146.16	151.90	43.56	49.29	154.85	160.45
ARIMA(0,2,3)	253.51	260.68	163.88*	169.62*	147.61	154.78	45.58	52.75	156.69	163.69
ARIMA(0,3,0)	298.25	301.05	206.70	209.51	172.20	175.00	96.72	99.52	195.34	198.07
ARIMA(0,3,1)	270.90	273.70	184.42	187.22	150.26	153.06	70.97	73.77	165.11	167.84
ARIMA(0,3,2)	253.73	257.93	170.66	174.86	153.02	158.62	52.62	56.83	154.59	160.06
ARIMA(0,3,3)	254.83	260.44	171.85	177.45	148.75	154.36	48.54	54.14	149.53*	155.00*
ARIMA(1,0,0)	281.28	285.77	185.28	189.77	162.37	166.86	60.79	65.28	173.56	177.96
ARIMA(1,0,1)	282.49	288.48	186.20	192.19	156.29	162.28	62.42	68.40	174.13	179.99
ARIMA(1,0,2)	284.12	291.61	187.19	194.67	158.13	165.62	62.17	69.65	173.37	180.70
ARIMA(1,0,3)	285.77	294.75	185.14	194.12	157.98	166.96	64.20	73.18	CNC	CNC
ARIMA(1,1,0)	256.17	260.57	169.71	174.11	147.48	151.88	51.74	56.13	163.58	167.88
ARIMA(1,1,1)	249.88*	254.28*	171.02	176.89	148.53	154.40	51.09	56.96	162.48	168.21
ARIMA(1,1,2)	251.69	257.55	172.78	180.11	CNC	CNC	55.70	63.03	162.62	169.79
ARIMA(1,1,3)	255.49	264.29	172.20	180.99	152.17	160.97	CNC	CNC	164.56	173.16
ARIMA(1,2,0)	268.03	272.33	184.56	188.86	151.86	156.16	53.82	58.12	155.81	160.01
ARIMA(1,2,1)	254.97	260.71	168.12	172.42	147.56	153.29	42.80*	47.11*	155.24	160.85
ARIMA(1,2,2)	255.95	261.68	168.65	174.39	147.25	154.42	45.46	52.63	156.02	163.03
ARIMA(1,2,3)	256.36	264.96	165.61	172.78	147.93	155.10	48.09	56.69	CNC	CNC

Variables:	Energy		Industry		Agriculture		Waste		Landuse	
<i>Model Spec</i>	AIC	BIC	AIC	BIC	AIC	BIC	AIC	BIC	AIC	BIC
ARIMA(1,3,0)	284.93	289.14	202.34	206.54	164.62	168.82	78.04	82.24	174.24	178.35
ARIMA(1,3,1)	264.84	269.04	183.68	187.89	151.55	155.75	59.80	65.40	156.69	162.16
ARIMA(1,3,2)	255.16	260.76	172.45	178.05	154.92	161.93	49.94	55.54	152.79	158.26
ARIMA(1,3,3)	257.56	264.57	172.80	179.81	151.06	158.06	51.25	58.25	152.34	160.55
ARIMA(2,0,0)	282.30	288.29	186.62	192.61	155.77	161.76	62.16	68.14	172.77	178.63
ARIMA(2,0,1)	274.35	280.34	186.65	194.13	155.80	161.79	64.48	71.96	170.50	177.82
ARIMA(2,0,2)	276.37	285.35	188.58	197.56	154.24	161.72	43.02	50.50	169.56	176.89
ARIMA(2,0,3)	287.41	297.88	CNC	CNC	157.76	168.23	44.70	53.68	173.21	183.47
ARIMA(2,1,0)	256.72	262.59	167.08	172.94	148.88	154.74	50.60	56.47	161.45	167.19
ARIMA(2,1,1)	251.65	257.51	168.34	175.67	150.50	157.83	49.05	56.38	162.93	170.10
ARIMA(2,1,2)	253.26	260.59	169.78	178.57	146.50	153.83	CNC	CNC	163.71	172.31
ARIMA(2,1,3)	255.23	264.02	165.47	174.27	153.09	163.35	49.73	58.53	165.58	175.62
ARIMA(2,2,0)	266.05	271.78	170.14	175.87	151.74	157.48	52.93	58.66	156.22	161.83
ARIMA(2,2,1)	255.92	263.09	165.33	172.50	145.89*	151.63	46.88	54.05	157.22	164.22
ARIMA(2,2,2)	258.01	266.61	166.36	174.96	148.89	157.49	CNC	CNC	157.98	166.39
ARIMA(2,2,3)	256.34	266.38	168.83	178.87	148.41	157.01	48.79	58.83	153.70	162.11
ARIMA(2,3,0)	279.94	285.55	189.59	195.19	160.20	165.81	76.02	81.62	171.00	176.47
ARIMA(2,3,1)	265.55	272.55	173.05	180.05	152.06	157.67	57.39	62.99	156.58	163.41
ARIMA(2,3,2)	266.92	273.93	169.58	177.98	154.98	163.39	51.86	58.87	154.84	161.68
ARIMA(2,3,3)	268.25	276.66	169.50	177.91	151.55	159.96	53.40	61.81	157.52	167.09
ARIMA(3,0,0)	283.67	291.15	188.05	195.53	157.74	165.22	58.26	65.74	169.92	177.25
ARIMA(3,0,1)	277.37	286.35	188.54	197.52	157.81	166.79	47.03	56.01	CNC	CNC
ARIMA(3,0,2)	CNC	CNC	190.46	200.94	157.23	167.71	44.71	53.69	CNC	CNC
ARIMA(3,0,3)	CNC	CNC	CNC	CNC	156.45	166.93	46.67	57.14	CNC	CNC
ARIMA(3,1,0)	257.20	264.52	167.54	174.87	150.84	158.17	52.03	59.36	163.17	170.34
ARIMA(3,1,1)	253.59	260.92	168.07	176.87	152.78	161.58	50.74	59.54	164.93	173.54
ARIMA(3,1,2)	257.23	267.49	168.39	178.65	148.66	158.92	52.75	63.01	165.68	175.72
ARIMA(3,1,3)	255.16	265.42	172.68	184.41	151.68	161.94	55.13	66.85	163.49	174.96
ARIMA(3,2,0)	263.97	271.14	165.99	173.16	153.54	160.71	43.42	50.59	155.12	162.13
ARIMA(3,2,1)	254.77	261.94	166.44	175.04	149.73	158.33	43.91	52.51	159.40	167.81
ARIMA(3,2,2)	259.61	269.65	166.62	175.22	148.40	157.01	45.70	55.73	155.80	165.61
ARIMA(3,2,3)	256.34	266.38	168.68	180.15	146.26	154.87	45.53	57.00	156.39	166.20
ARIMA(3,3,0)	276.63	283.63	182.46	189.46	153.99	161.00	65.69	72.69	152.80	159.64
ARIMA(3,3,1)	264.12	272.53	167.69	174.69	CNC	CNC	50.30	58.70	152.51	160.72
ARIMA(3,3,2)	267.31	275.72	170.45	180.26	CNC	CNC	48.63	57.04	153.57	163.15
ARIMA(3,3,3)	CNC	CNC	170.28	180.09	154.16	163.96	52.44	63.65	154.08	163.65

CNC: Can not be calculated

*Lowest value

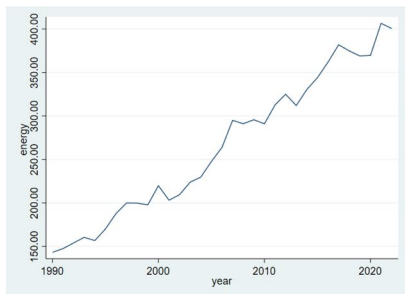
Appendix C: Dickey-Fuller test (for unit root) results on the residuals (H_0 : Random walk with drift)

VARIABLE LABEL	MODEL SPEC	COEF. (L1)	P> T	COEF. (CONS.)	P> T	Z(T)	P-VALUE FOR Z(T)
ENERGY	ARIMA(1,1,1)	-0.9702	0.000	-1.1398	0.580	-5.207	0.0000
INDUSTRY	ARIMA(0,1,0)	-1.1011	0.000	0.0120	0.984	-5.558	0.0000
AGRICUL- TURE	ARIMA(0,2,1)	-0.6791	0.002	-0.1318	0.764	-3.339	0.0012
WASTE	ARIMA(1,2,1)	-1.0258	0.000	0.0749	0.358	-5.272	0.0000
LANDUSE	ARIMA(1,0,0)	-0.6215	0.005	0.3021	0.602	-3.001	0.0027

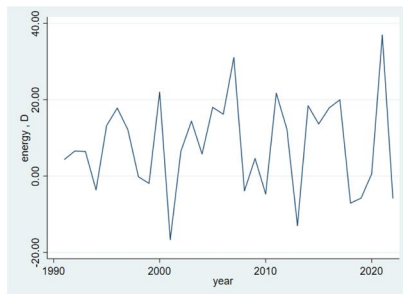
Appendix D: Plots of data, differenced data, residuals, autocorrelations and partial autocorrelations for each model

Variable: Energy.

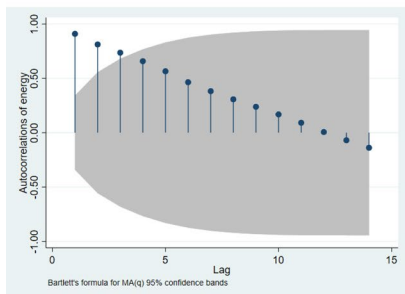
E1. Plotting the data



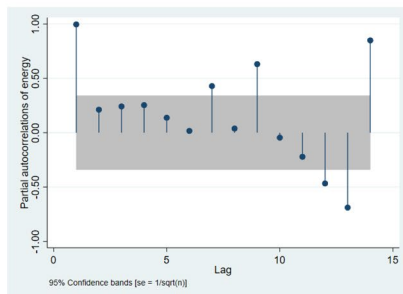
E2. Plotting the differenced data



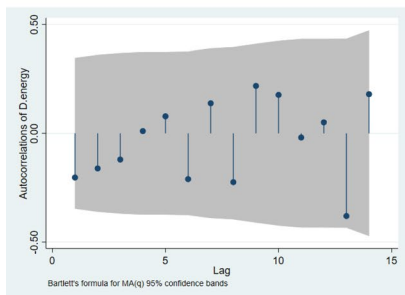
E3. Autocorrelations of data



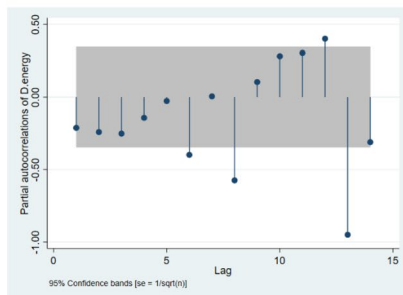
E4. Partial autocorrelations of data



E5. Autocorrelations of differenced data

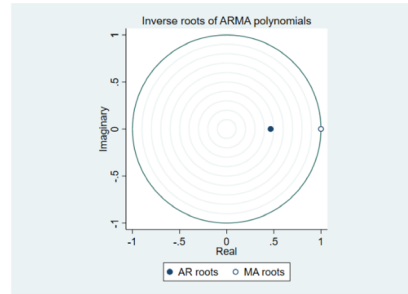
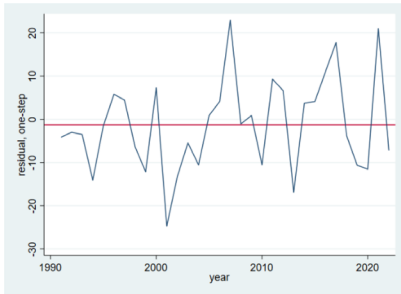


E6. Partial autocorrelations of differenced data

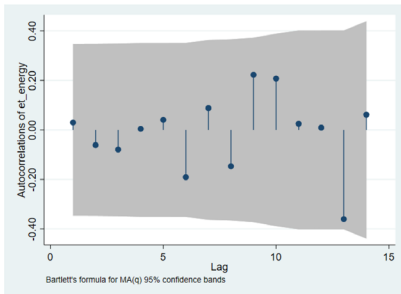


E7. The residuals from preferred model around the mean

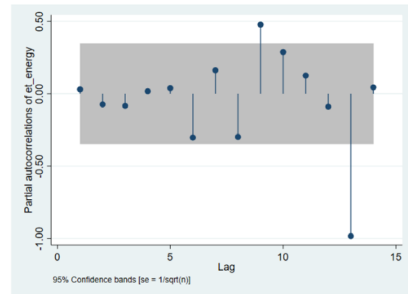
E8. Inverse roots of ARMA polynomials



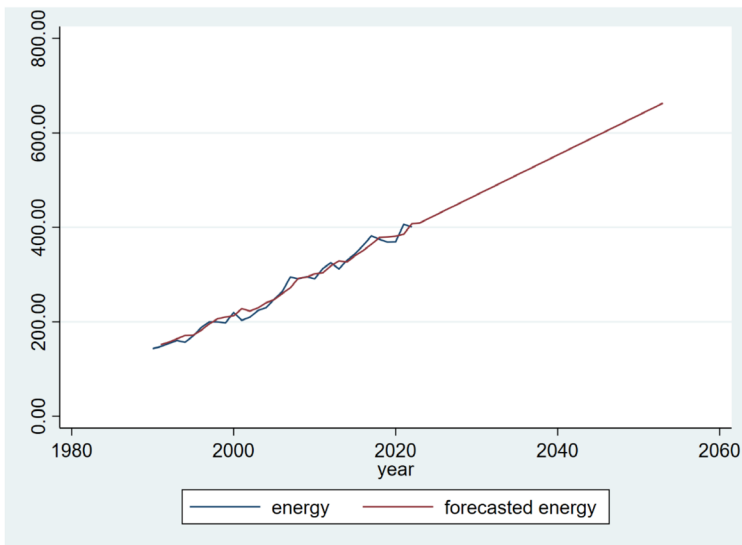
E9. The autocorrelations of error terms from preferred model with 95% confidence bands



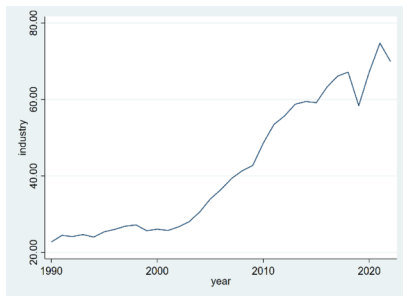
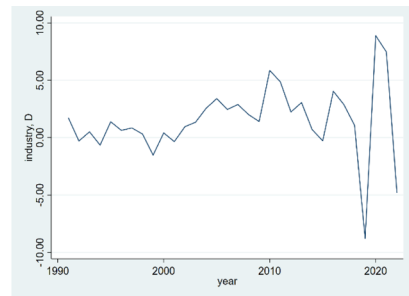
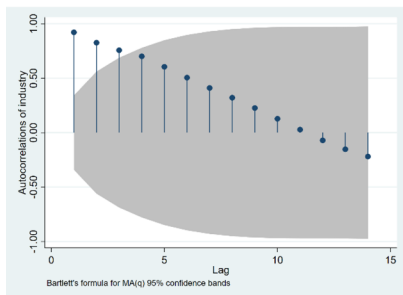
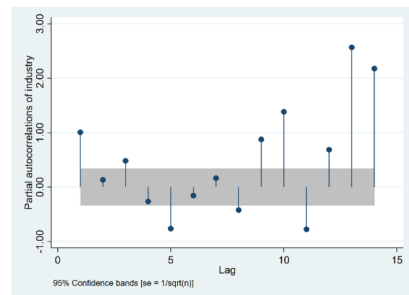
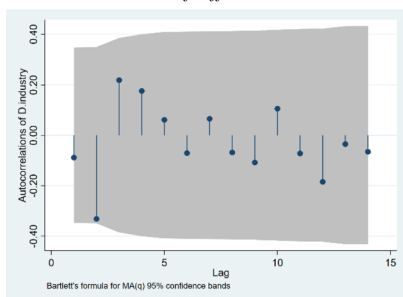
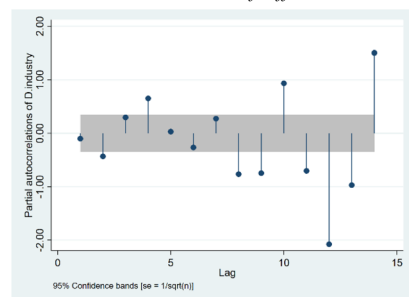
E10. The partial autocorrelations of error terms from preferred model with 95% confidence bands

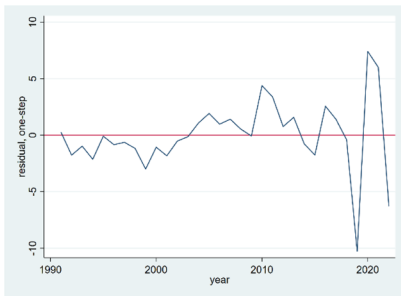


E11. Actual and forecasted data



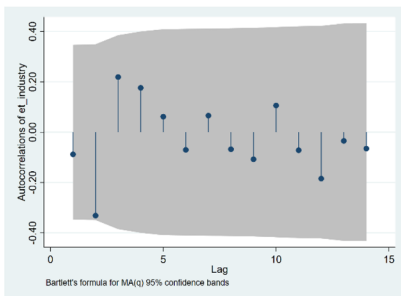
Variable: Industrial processes and product use.

11. Plotting the data*12. Plotting the differenced data**13. Autocorrelations of data**14. Partial autocorrelations of data**15. Autocorrelations of differenced data**16. Partial autocorrelations of differenced data**17. The residuals from preferred model around the mean**18. Inverse roots of ARMA polynomials*

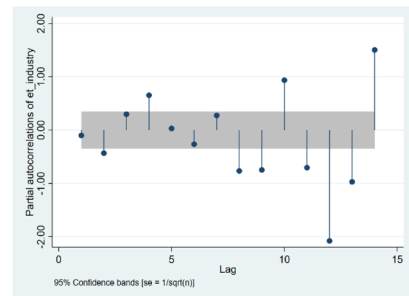


The model does not contain AR or MA terms.

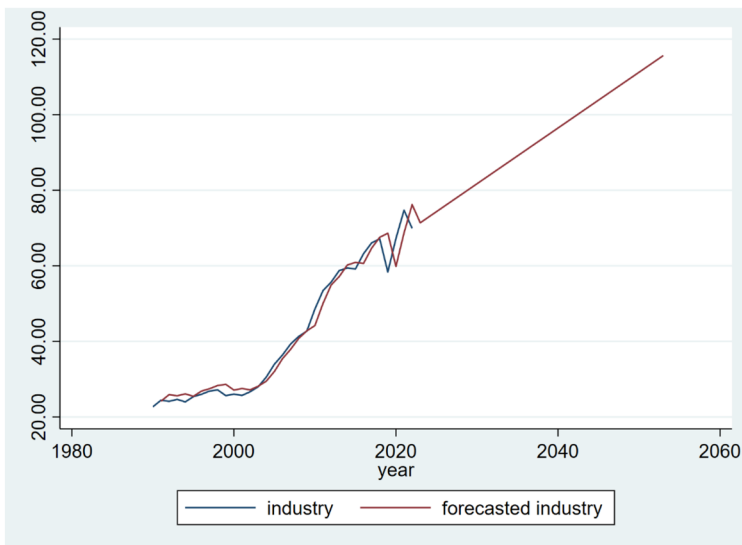
19. The autocorrelations of error terms from preferred model with 95% confidence bands



110. The partial autocorrelations of error terms from preferred model with 95% confidence bands

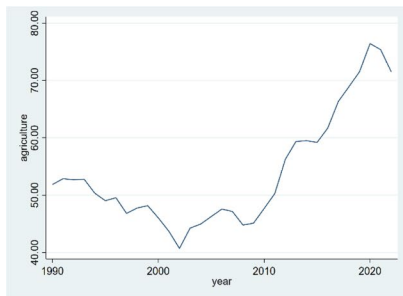


111. Actual and forecasted data

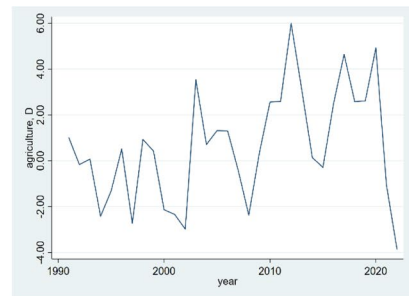


Variable: Agriculture.

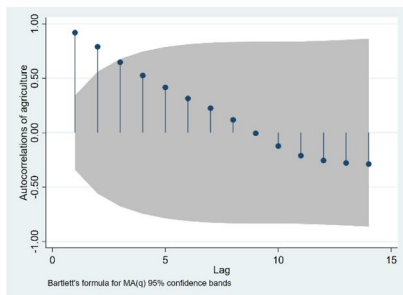
A1. Plotting the data



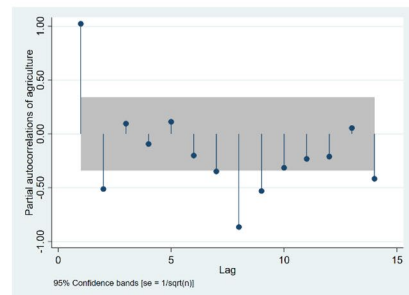
A2. Plotting the differenced data



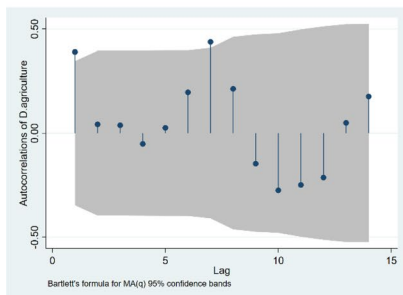
A3. Autocorrelations of data



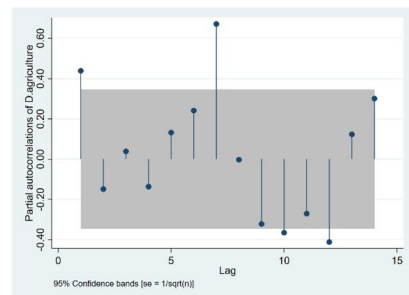
A4. Partial autocorrelations of data



A5. Autocorrelations of differenced data

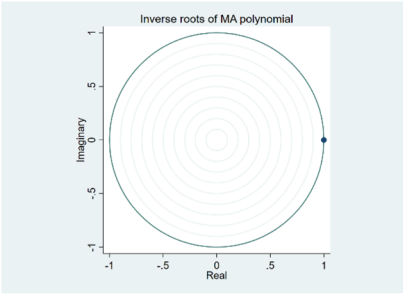
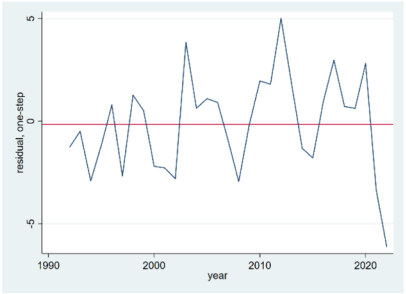


A6. Partial autocorrelations of differenced data

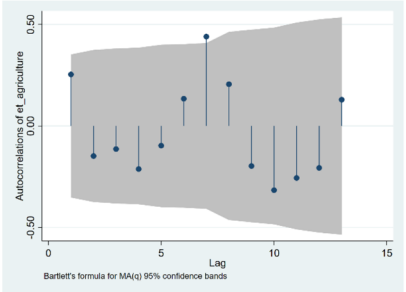


A7. The residuals from preferred model around the mean

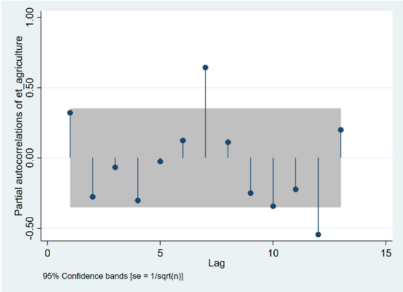
A8. Inverse roots of ARMA polynomials



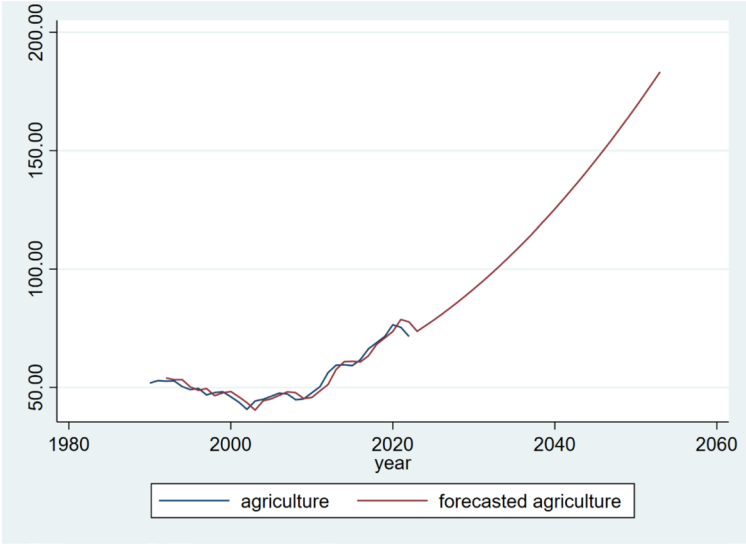
A9. The autocorrelations of error terms from preferred model with 95% confidence bands



A10. The partial autocorrelations of error terms from preferred model with 95% confidence bands

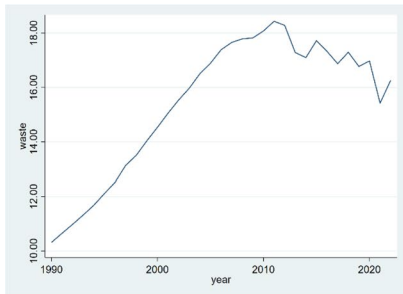


A11. Actual and forecasted data

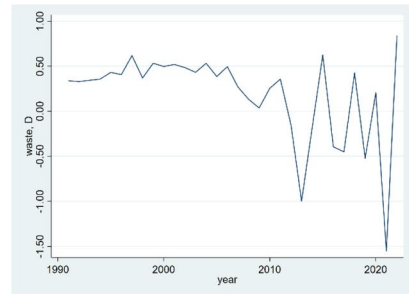


Variable: Waste.

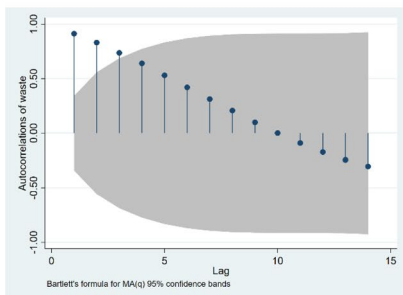
W1. Plotting the data



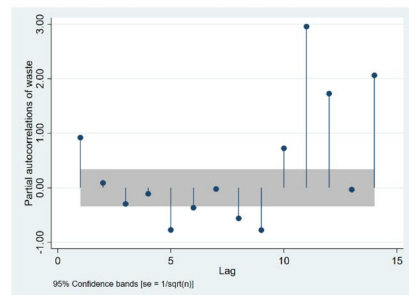
W2. Plotting the differenced data



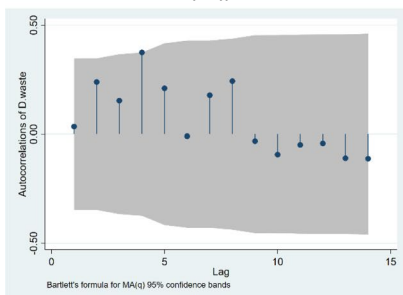
W3. Autocorrelations of data



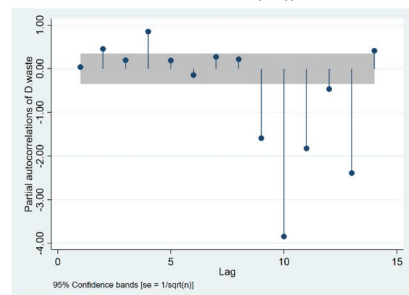
W4. Partial autocorrelations of data



W5. Autocorrelations of differenced data

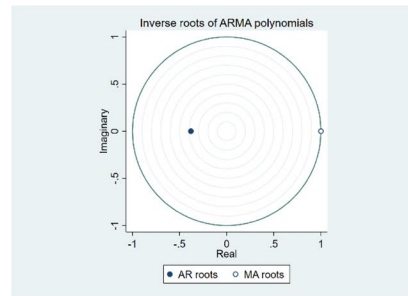
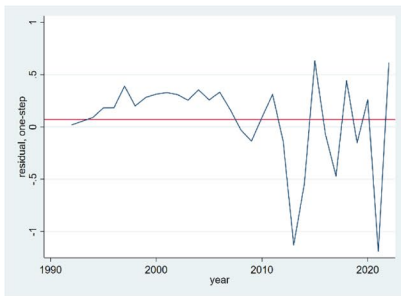


W6. Partial autocorrelations of differenced data

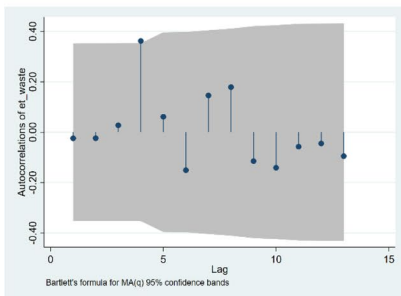


W7. The residuals from preferred model around the mean

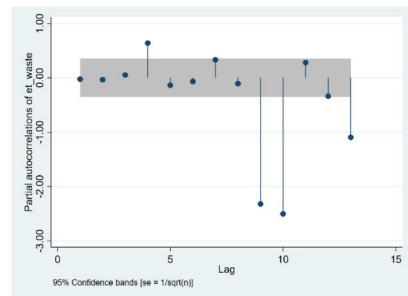
W8. Inverse roots of ARMA polynomials



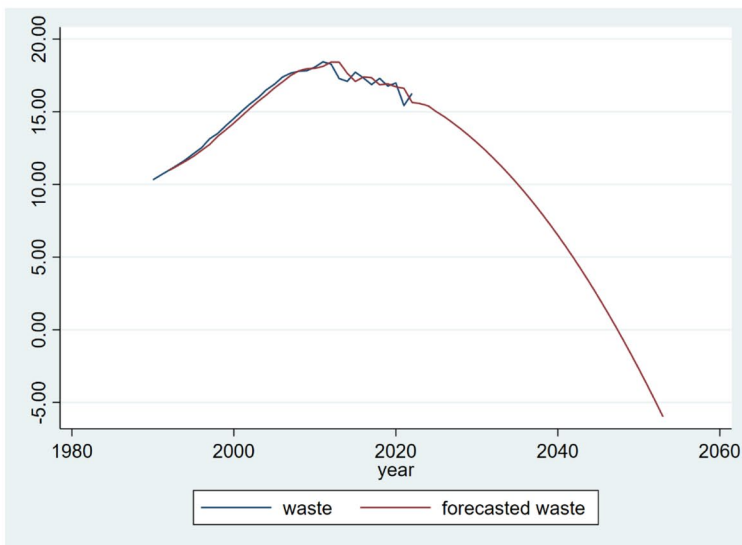
W9. The autocorrelations of error terms from preferred model with 95% confidence bands



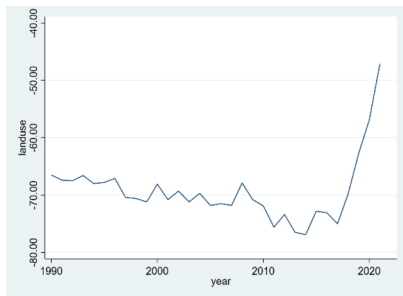
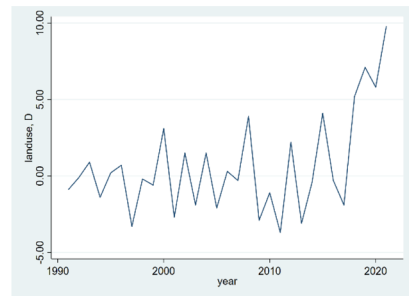
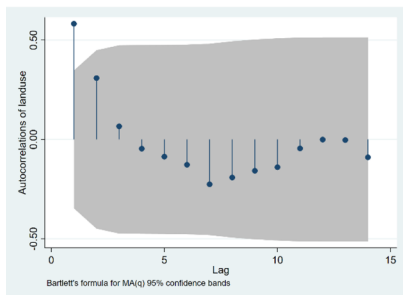
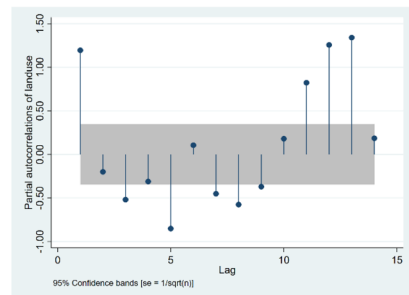
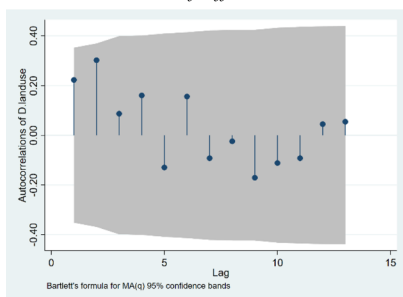
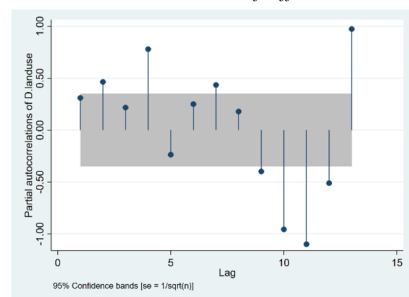
W10. The partial autocorrelations of error terms from preferred model with 95% confidence bands

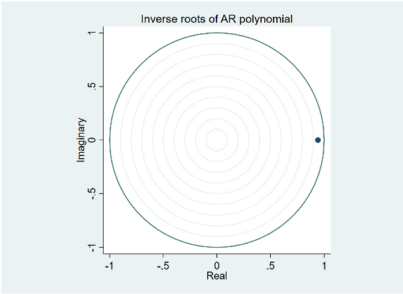
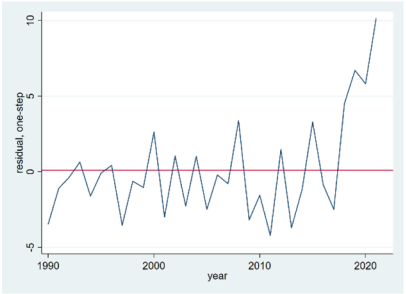


W11. Actual and forecasted data

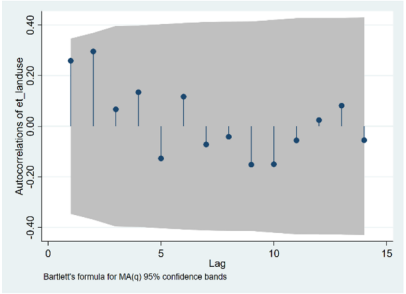


Variable: Land use, land use change, and forestry.

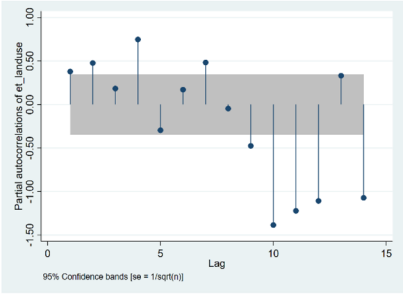
L1. Plotting the data*L2. Plotting the differenced data**L3. Autocorrelations of data**L4. Partial autocorrelations of data**L5. Autocorrelations of differenced data**L6. Partial autocorrelations of differenced data**L7. The residuals from preferred model around the mean**L8. Inverse roots of ARMA polynomials*



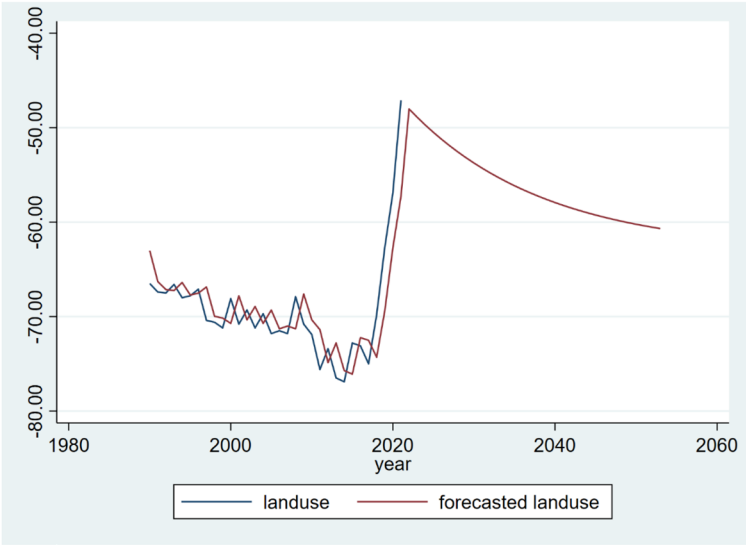
L9. The autocorrelations of error terms from preferred model with 95% confidence bands



L10. The partial autocorrelations of error terms from preferred model with 95% confidence bands



L11. Actual and forecasted data



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Data availability This study includes the analysis of datasets, with all relevant data and replication materials provided as supplementary material.

Declarations

Conflict of interests The author has no relevant financial or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper to disclose. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process The author declares that no generative AI tools or AI-assisted technologies were employed in the research, drafting, writing, or editing of this manuscript. All content was generated through the independent work of the author, and responsibility for the originality, accuracy, and integrity of the manuscript remains solely with the Author.

References

- Arndt, C. (2023). Climate change vs energy security? The conditional support for energy sources among Western Europeans. *Energy Policy*, 174, Article 113471. <https://doi.org/10.1016/j.enpol.2023.113471>
- Bettarelli, L., Furceri, D., Pizzuto, P., & Shakoob, N. (2024). Climate change policies and income inequality. *Energy Policy*, 191, Article 114176. <https://doi.org/10.1016/j.enpol.2024.114176>
- Blimpo MP, Dato P, Mukhaya B, Odarno L (2024) Climate change and economic development in Africa: A systematic review of energy transition modeling research. *Energy Policy* 187:114044
- Borissov K, Brausmann A, Bretschger L (2019) Carbon pricing, technology transition, and skill-based development. *Eur Econ Rev* 118:252–269. <https://doi.org/10.1016/j.euroecorev.2019.05.011>
- Box, G. E. P., Jenkins, G. M., & Reinsel, G. C. (2008). *Time Series Analysis* [Book]. <https://doi.org/10.1002/9781118619193>
- Chen X, Yan B (2024) Research on jumps and volatility in China's carbon market. *Econ Chang Restruct* 57(1):9. <https://doi.org/10.1007/s10644-024-09592-2>
- Chung J-B, Kim E-S (2018) Public perception of energy transition in Korea: Nuclear power, climate change, and party preference. *Energy Policy* 116:137–144. <https://doi.org/10.1016/j.enpol.2018.02.007>
- Climate Action Tracker (2025) Türkiye. The Climate Action Tracker. <https://climateactiontracker.org/countries/turkey/>
- ClimateWatch. (2024b). *Turkey Climate Change Data*. World Resources Institute. www.climatewatchdata.org/countries/TUR
- ClimateWatch. (2024a). *Global Historical Emissions*. World Resources Institute. www.climatewatchdata.org
- Dilanchiev A, Urinov B, Humbatova S, Panahova G (2024) Catalyzing climate change mitigation: investigating the influence of renewable energy investments across BRICS. *Econ Chang Restruct*. <https://doi.org/10.1007/s10644-024-09702-0>
- Doda B, Fankhauser S (2020) Climate policy and power producers: The distribution of pain and gain. *Energy Policy* 138:111205. <https://doi.org/10.1016/j.enpol.2019.111205>
- Dong Z, Xiao Y (2024) Carbon emissions trading policy and climate injustice: A study on economic distributional impacts. *Energy* 296:131074. <https://doi.org/10.1016/j.energy.2024.131074>

- Dorband II, Jakob M, Kalkuhl M, Steckel JC (2019) Poverty and distributional effects of carbon pricing in low- and middle-income countries – A global comparative analysis. *World Dev* 115:246–257. <https://doi.org/10.1016/j.worlddev.2018.11.015>
- Dreus S, van den Bergh JCJM (2015) What explains public support for climate policies? A review of empirical and experimental studies. *Climate Policy* 16(7):855–876. <https://doi.org/10.1080/14693062.2015.1058240>
- Dutta A, Bouri E, Rothovius T, Uddin GS (2023) Climate risk and green investments: New evidence. *Energy* 265:126376. <https://doi.org/10.1016/j.energy.2022.126376>
- EU. (2024). Carbon Border Adjustment Mechanism. taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en
- EuroStat. (2024). International trade in goods by partner. ec.europa.eu/eurostat/statistics-explained/index.php?title=International_trade_in_goods_by_partner
- Fant C, Boehlert B, Strzepek K, Larsen P, White A, Gulati S, Li Y, Martinich J (2020) Climate change impacts and costs to U.S. electricity transmission and distribution infrastructure. *Energy* 195:116899. <https://doi.org/10.1016/j.energy.2020.116899>
- Goodman J (2016) The ‘climate dialectic’ in energy policy: Germany and India compared. *Energy Policy* 99:184–193. <https://doi.org/10.1016/j.enpol.2016.03.014>
- Grainger C, Ruangmas T (2017) Who Wins from Emissions Trading? Evidence from California. *Environ Resource Econ* 71(3):703–727. <https://doi.org/10.1007/s10640-017-0180-1>
- Grubb M, Newbery D (2018) UK Electricity Market Reform and the Energy Transition: Emerging Lessons. *The Energy Journal* 39(6):1–26. <https://doi.org/10.5547/01956574.39.6.mgru>
- Guo B, David N (2023) The Cost of Carbon Leakage: Britain’s Carbon Price Support and Cross-border Electricity Trade. *The Energy Journal* 44(1):9–32. <https://doi.org/10.5547/01956574.44.1.bguo>
- Hamilton, J. D. (1994). *Time Series Analysis*. Princeton University Press. press.princeton.edu/books/hardcover/9780691042893/time-series-analysis
- He P, Zhang S, Wang L, Ning J (2023) Will environmental taxes help to mitigate climate change? A comparative study based on OECD countries. *Economic Analysis and Policy* 78:1440–1464. <https://doi.org/10.1016/j.eap.2023.04.032>
- Hennessey R, Pittman J, Morand A, Douglas A (2017) Co-benefits of integrating climate change adaptation and mitigation in the Canadian energy sector. *Energy Policy* 111:214–221. <https://doi.org/10.1016/j.enpol.2017.09.025>
- Hyndman, R. J., & Athanasopoulos, G. (2018). *Forecasting: principles and practice*. OTexts.
- IEA. (2024). World Energy Balances. www.iea.org/data-and-statistics/data-product/world-energy-balances
- Kerimray A, Baigarin K, De Miglio R, Tosato G (2015) Climate change mitigation scenarios and policies and measures: the case of Kazakhstan. *Climate Policy* 16(3):332–352. <https://doi.org/10.1080/14693062.2014.1003525>
- Kexiang Hu, Sinha A, Tan Z, Shah MI, Abbas S (2022) Achieving energy transition in OECD economies: Discovering the moderating roles of environmental governance. *Renew Sustain Energy Rev* 168:112808. <https://doi.org/10.1016/j.rser.2022.112808>
- Kuosmanen T, Zhou X, Dai S (2020) How much climate policy has cost for OECD countries? *World Dev* 125:104681. <https://doi.org/10.1016/j.worlddev.2019.104681>
- Lee J, Reiner DM (2023) Determinants of public preferences on low-carbon energy sources: Evidence from the United Kingdom. *Energy* 284:128704. <https://doi.org/10.1016/j.energy.2023.128704>
- Lin B, Jia Z (2019) Impacts of carbon price level in carbon emission trading market. *Appl Energy* 239:157–170. <https://doi.org/10.1016/j.apenergy.2019.01.194>
- Lindvall D, Karlsson M (2023) Exploring the democracy-climate nexus: a review of correlations between democracy and climate policy performance. *Climate Policy* 24(1):87–103. <https://doi.org/10.1080/14693062.2023.2256697>
- Markandya A, Antimiani A, Costantini V, Martini C, Palma A, Tommasino MC (2015) Analyzing Trade-offs in International Climate Policy Options: The Case of the Green Climate Fund. *World Dev* 74:93–107. <https://doi.org/10.1016/j.worlddev.2015.04.013>
- Markkanen S, Anger-Kraavi A (2019) Social impacts of climate change mitigation policies and their implications for inequality. *Climate Policy* 19(7):827–844. <https://doi.org/10.1080/14693062.2019.1596873>
- Michaelowa A, Hoch S, Weber A-K, Kassaye R, Hailu T (2020) Mobilising private climate finance for sustainable energy access and climate change mitigation in Sub-Saharan Africa. *Climate Policy* 21(1):47–62. <https://doi.org/10.1080/14693062.2020.1796568>

- Msimango N, Orffer C, Inglesi-Lotz R (2023) South Africa's energy policy: Prioritizing competition and climate change for decarbonisation. *Energy Policy* 183:113815. <https://doi.org/10.1016/j.enpol.2023.113815>
- Muellner N, Arnold N, Gufler K, Kromp W, Renneberg W, Liebert W (2021) Nuclear energy - The solution to climate change? *Energy Policy*, 155. Article. <https://doi.org/10.1016/j.enpol.2021.112363>
- Newbery DM, Reiner DM, Ritz RA (2019) The Political Economy of a Carbon Price Floor for Power Generation. *The Energy Journal* 40(1):1–24. <https://doi.org/10.5547/01956574.40.1.dnew>
- Newell P, Bulkeley H (2016) Landscape for change? International climate policy and energy transitions: evidence from sub-Saharan Africa. *Climate Policy* 17(5):650–663. <https://doi.org/10.1080/14693062.2016.1173003>
- OECD. (2023). *Effective Carbon Rates 2023*. <https://doi.org/10.1787/b84d5b36-en>
- Pichler P, Sorger G (2018) Delegating climate policy to a supranational authority: a theoretical assessment. *Eur Econ Rev* 101:418–440. <https://doi.org/10.1016/j.eurocorev.2017.10.014>
- Puertas R, Marti L (2021) International ranking of climate change action: An analysis using the indicators from the Climate Change Performance Index. *Renew Sustain Energy Rev* 148:111316. <https://doi.org/10.1016/j.rser.2021.111316>
- Ruamsuke K, Dhakal S, Marpaung COP (2015) Energy and economic impacts of the global climate change policy on Southeast Asian countries: A general equilibrium analysis. *Energy* 81:446–461. <https://doi.org/10.1016/j.energy.2014.12.057>
- Ruhnau O, Bucksteeg M, Ritter D, Schmitz R, Böttger D, Koch M, Pöstges A, Wiedmann M, Hirth L (2022) Why electricity market models yield different results: Carbon pricing in a model-comparison experiment. *Renew Sustain Energy Rev* 153:111701. <https://doi.org/10.1016/j.rser.2021.111701>
- Shang Y, Sang S, Tiwari AK, Khan S, Zhao X (2024) Impacts of renewable energy on climate risk: A global perspective for energy transition in a climate adaptation framework. *Appl Energy* 362:122994. <https://doi.org/10.1016/j.apenergy.2024.122994>
- Song T, Li H, Feng Z (2024) Policy and market mechanisms for promoting sustainable energy transition: role of government and private sector. *Econ Chang Restruct* 57(4):153. <https://doi.org/10.1007/s10644-024-09734-6>
- Stergiou E, Rigas N, Zaroutieri E, Kounetas K (2023) Energy, renewable and technical efficiency convergence: a global evidence. *Econ Chang Restruct* 56(3):1601–1628. <https://doi.org/10.1007/s10644-022-09479-0>
- Stiglitz JE (2019) Addressing climate change through price and non-price interventions. *Eur Econ Rev* 119:594–612. <https://doi.org/10.1016/j.eurocorev.2019.05.007>
- Sugiyama M, Fujimori S, Wada K, Endo S, Fujii Y, Komiyama R, Kato E, Kurosawa A, Matsuo Y, Oshiro K, Sano F, Shiraki H (2019) Japan's long-term climate mitigation policy: Multi-model assessment and sectoral challenges. *Energy* 167:1120–1131. <https://doi.org/10.1016/j.energy.2018.10.091>
- TUIK. (2024a). *Greenhouse gas emissions by sectors (CO2 equivalent), 1990 - 2022* <https://data.tuik.gov.tr/Kategori/GetKategori?p=cevre-ve-enerji-103>
- TUIK. (2024b). *Imports by country groups and year (general trade system)* <https://data.tuik.gov.tr/Kategori/GetKategori?p=dis-ticaret-104>
- Trachtman S (2020) What drives climate policy adoption in the U.S. states? *Energy Policy*. <https://doi.org/10.1016/j.enpol.2019.111214>
- Tvinnereim E, Ivarsslaten E (2016) Fossil fuels, employment, and support for climate policies. *Energy Policy* 96:364–371. <https://doi.org/10.1016/j.enpol.2016.05.052>
- UNClimateChange. (2024). *The Paris Agreement*. United Nations. <https://unfccc.int/process-and-meetings/the-paris-agreement>
- von Lüpke H, Well M (2019) Analyzing climate and energy policy integration: the case of the Mexican energy transition. *Climate Policy* 20(7):832–845. <https://doi.org/10.1080/14693062.2019.1648236>
- Wang W, Wang J, Haitao Wu (2024) Assessing the potential of energy transition policy in driving renewable energy technology innovation: evidence from new energy demonstration city pilots in China. *Econ Chang Restruct*. <https://doi.org/10.1007/s10644-024-09748-0>
- Yan Y, Liang W, Wang B, Zhang X (2023) Spillover effect among independent carbon markets: evidence from China's carbon markets. *Econ Chang Restruct* 56(5):3065–3093. <https://doi.org/10.1007/s10644-022-09431-2>

- Zhang X, Li Z, Li G (2024) Grandfather-based or benchmark-based: Strategy choice for carbon quota allocation methods in the carbon neutrality era. *Renew Sustain Energy Rev* 192:114195. <https://doi.org/10.1016/j.rser.2023.114195>
- Zhu X, Deng Q, Zhang S (2024) Toward low-carbon transition: Does carbon regulation matter for spatial development inequality? *Econ Chang Restruct* 57(6):248. <https://doi.org/10.1007/s10644-024-09829-0>
- Zhu W, Li S (2024) Nonlinear effects of climate risks on climate-sensitive sectors. *Econ Chang Restruct* 57(5):167. <https://doi.org/10.1007/s10644-024-09751-5>

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