SUPPORTING THE ENERGY TRANSITION: HOW REGULATIONS AND MARKET-BASED INSTRUMENTS SHAPE THE CHANGING ENERGY LANDSCAPE IN GREECE AND THE EU-27

DOI: 10.26341/issn.2241-4010-2026-4a-2-L02215

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Abstract
This paper provides a comprehensive review of energy transition dynamics within the EU27, with a particular focus on Greece's long-term sustainability strategy and the phase-out of its lignite-dependent energy system. The study analyzes shifts in the composition and structure of the energy mix in Greece and the EU27 and conducts a comparative analysis of electricity generation over the past two decades. It also evaluates national and regional emissions mitigation objectives anchored in decarbonization targets set by the Greek National Energy and Climate Plan (NECP) and the Just Transition Development Plan.

The paper argues that achieving these climate targets requires a coordinated approach combining direct regulatory measures, mandated phase-outs, and energy plans, alongside market-based instruments such as carbon pricing. Based on a critical review of the literature and current regulatory frameworks, the study provides an analytical discussion of the distinct and complementary roles of these mitigating mechanisms, focusing on carbon taxation and cap-and-trade schemes. Current global data on emissions trading systems and carbon tax revenues are incorporated to assess their effectiveness in reducing emissions and achieving decarbonization objectives.

Keywords*: energy transition, power generation, market-based tools, RES, decarbonization, cap-and-trade, carbon taxation.*

1. INTRODUCTION

Fossil fuel combustion has profound and far-reaching impacts on the environment. The release of carbon dioxide (CO_2) is the primary driver of global climate change, while other harmful emissions, including sulfur dioxide, nitrogen oxides, and particulate matter, significantly affect public health worldwide (World Health Organization, 2021).

Among fossil fuels, coal has particularly severe environmental consequences. Coal-fired power plants and coal mining activities cause extensive local environmental degradation, including habitat destruction, soil erosion, water and air pollution, acidification, and resource depletion (Papavasiliou, Roumpos, & Michalakopoulos, 2016; Finkelman, Wolfe, & Hendryx, 2021). Lignite combustion is therefore a major source of greenhouse gas emissions, releasing roughly twice as much CO_2 per unit of energy as natural gas, along with higher levels of harmful air pollutants (Soeder, 2021).

Despite its considerable environmental and health impacts, coal continues to play a major role in the global energy system. In 2024, coal accounted for 28% of global energy supply, following oil (34%) and ahead of natural gas (25%) (Energy Institute, 2025). In electricity generation, coal reached an all-time high of 35% in 2023 and declined slightly to

34% in 2024, followed by renewables (32%), natural gas (22%), nuclear (9%), and oil (2%). China remains the largest coal consumer, responsible for 56% of global demand, while India surpassed the combined consumption of Europe and North America for the first time in 2024. Global coal use rose to 8.77 billion tonnes in 2024—another record high—and is expected to remain at these levels until at least 2027, depending largely on developments in China (IEA, 2024).

Limiting global warming to 1.5–2°C and achieving net-zero CO_2 emissions requires a profound transformation of national and global energy systems. According to the IPCC (2023), this objective demands a 25% reduction in CO_2 emissions by 2030 and their near-complete elimination by 2070. Aligned with the objectives of the 2015 UN Paris Agreement, most European and OECD countries have committed to phasing out coal-fired power generation by 2030. In Europe, 23 countries have announced coal phase-out plans. Sweden (2020), the UK (2024), Portugal (2021), Belgium (2016), and Austria (2020) have already eliminated coal from their electricity mix (Beyond Fossil Fuels, n.d.). Cyprus, Switzerland, Albania, Norway, Estonia, Latvia, and Lithuania never incorporated coal into their power generation systems.

Other European nations have adopted later phase-out targets: Slovakia, Ireland, and Spain (2025); France and Hungary (2027); Denmark, Italy, and Greece (2028); Finland and the Netherlands (2029); North Macedonia (2030); Romania (2032); Slovenia, Czechia, and Croatia (2033); Montenegro (2035); Germany (2038); and Bulgaria (2040)[1].

Greece, once heavily dependent on lignite for electricity generation, is actively participating in this energy transition. As one of Europe's largest lignite producers, Greece historically relied on this domestic resource to support its energy needs (Heinrich Böll Stiftung, 2015). The country originally announced a coal phase-out target of 2026, later revised to 2028 in line with broader European climate objectives (Beyond Fossil Fuels, n.d.).

The growing share of renewable energy sources (RES) in the EU-27 electricity mix, combined with the sharp decline in solid fossil fuel use, has led to substantial reductions in greenhouse gas emissions across Europe (European Environment Agency, 2024). Electricity generation represents only one dimension of the required mitigation effort. Achieving climate neutrality requires rapid and sustained emissions reductions across all major sectors: energy, industry, land use, transport, and infrastructure.

Reducing greenhouse gas emissions relies on both direct and indirect policy interventions affecting fossil fuel use. Climate and energy policies have been central to the delignification process, with carbon pricing mechanisms playing a particularly critical role. In this context, the European Green Deal (European Commission, 2019) established a strategic roadmap to achieve a climate-neutral EU economy by 2050, with main objectives being energy decarbonization, transition to RES, energy efficiency, achievement of net-zero greenhouse gas emissions (carbon neutrality), and air, water, and soil pollution elimination.

2. EVOLUTION OF THE ENERGY LANDSCAPE IN GREECE AND THE EU27

The impact of delignification and broader decarbonization efforts in Europe is clearly reflected in the evolution of domestic greenhouse gas emissions, which have declined substantially over the past twenty years. In the EU27, total net domestic greenhouse gas emissions reached 2,827,024 Gg CO_2-equivalent in 2024, representing a 33% reduction compared to 2004. Greece achieved an even sharper decrease: its net greenhouse gas emissions fell to 65,070 Gg CO_2-equivalent in 2024, corresponding to a 50% reduction since

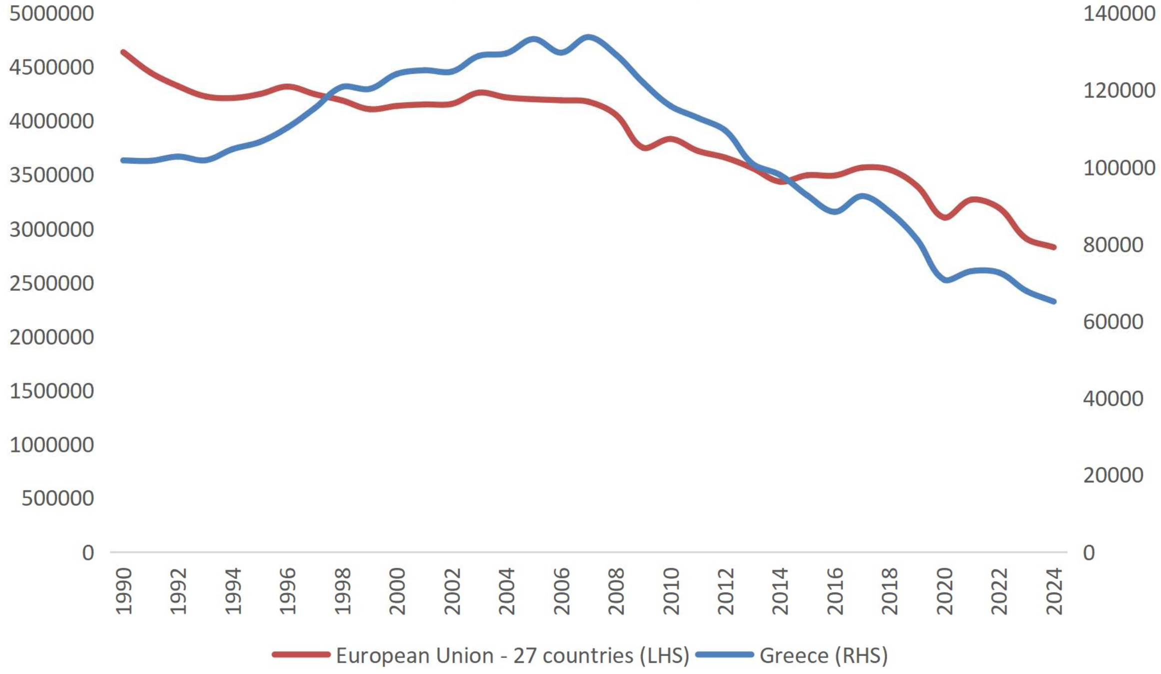
[1] In Serbia, coal phase-out is under discussion, while no official timelines exist for Bosnia-Herzegovina, Kosovo, Turkey, or Poland.

2004, which is the second-largest decline among EU27 member states after Denmark (eea.europa.eu).

Fossil fuels use reduction is the primary cause of this emissions mitigation. Fossil fuels dominated primary energy production in both Greece and the EU27 for decades. In recent years, renewable energy sources (RES) and natural gas have significantly increased their shares in the energy mix, leading to substantial changes in the structure of energy systems. Distinct shifts in the fuel mix are observable across different stages of the energy flows, reflecting broader trends in decarbonization and diversification.

Over the past twenty years, the energy profiles of both the EU27 and Greece have changed markedly in terms of overall quantities and the composition of fuels. A clear transition away from lignite has taken place in both cases, accompanied by a steady rise in RES and natural gas.

Figure 1: Domestic net greenhouse gas emissions in Gg CO_2-equivalent.



Source: processed data of European Environment Agency (eea.europa.eu)

To capture these developments more systematically, we employ the Standard International Energy Product Classification (SIEC), which provides a detailed categorization of energy products by type of energy flow. This classification includes solid and liquid fossil fuels, non-fossil fuels such as renewables and biofuels, electricity, non-renewable waste, heat, and nuclear heat. In the following sections, we combine the SIEC framework with Eurostat's Complete Energy Balance Sheets to enable consistent comparisons across time and regions, as well as a more granular analysis of energy transitions.

Primary Production

In Greece, primary energy production, defined as the extraction or capture of energy from natural resources within a country's territory, declined substantially over the period examined, mirroring a broader EU27 trend. Greece's domestic production fell from 115,988 GWh in 2003 to 61,610 GWh in 2023, a 47% reduction. In 2023, primary energy production in Greece was driven mainly by RES and biofuels, which together accounted for nearly 75% of total production. The remaining 25% consisted entirely of solid fossil fuels, specifically lignite. In

2003, lignite comprised 82% of domestic production. Between 2003 and 2023, lignite production fell by 84%, while RES output increased by 144%.

In the EU27, total primary energy production decreased by 20% between 2003 and 2023. Solid fossil fuels made up 14% of primary production in 2023, down by 59% compared to 2003. RES accounted for 46% of primary production, representing a cumulative increase of 140% since 2003. Nuclear heat, which is not part of Greece's energy mix, contributed 29% of EU27 production in 2023, though this represents a decline of 33% compared with 2003. Other EU27 sources included natural gas (5%) and crude oil (3%), both of which declined sharply (by 73% and 60%, respectively).

Energy Trade

Energy trade refers to the import and export of energy products across national borders and it can include both indigenous production and energy products that have been transformed, such as electricity or refined petroleum.

Unlike domestic production, Greece's energy imports increased by 26% from 2003 to 2023, reaching 419,674 GWh in 2023—nearly seven times higher than domestic production. Energy exports also rose sharply, tripling to 217,822 GWh in 2023, resulting in a net import balance of 201,853 GWh. Greece's imports consisted mainly of oil and petroleum products (86% of the total, primarily crude oil) and natural gas (11%). Natural gas imports rose by 105% between 2003 and 2023, while oil imports increased by 21%. Electricity imports were relatively small at 8,151 GWh in 2023, though this represented a 96% increase since 2003. Export growth was driven by a 200% increase in oil product exports (primarily refined petroleum), a 117% rise in lignite exports, and a 56% increase in electricity exports.

In the EU27, energy imports declined slightly (by 3%) over the same period, totaling 14,140,780 GWh in 2023. Imports were roughly twice the level of primary production. Energy exports rose by 32% to 5,051,956 GWh. The EU27 import structure was dominated by oil and petroleum products (65%), followed by natural gas (25%), solid fossil fuels (5.4%), electricity (3%), and RES/biofuels (2%). EU27 energy exports consisted mainly of oil and petroleum products (73%), natural gas (12%), electricity (8%), solid fossil fuels (3%), and RES/biofuels (3%).

Final Energy Consumption

Final energy consumption corresponds to the energy that is actually used by end-users, after transformation and losses, and it includes the gross inland consumption (net imports and primary production) as well as the net transformation output minus any distribution losses and the energy's sector own use (SIEC). In Greece, available energy for final consumption reached 176,850 GWh in 2023, falling by 25% since 2003. The sectoral structure of energy demand shifted over time, with industry's share declining and transport's share increasing.

In 2023, final energy consumption consisted of 54% oil and petroleum products (down from 68% in 2003), 12% natural gas (up from 5%), 26% electricity, and 12% RES (up from 5%). Sectorally, industry relied on oil (30%), natural gas (23%), RES (6%), and especially electricity (40%). Transport remained overwhelmingly fossil-fuel-dependent, using 99% oil and only 0.3% electricity. The commercial and public services sector, along with agriculture and forestry, primarily used electricity (68% and 65%, respectively). Household consumption consisted of 10% natural gas, 24% oil, and 31% RES, including 9% solar thermal, 3% ambient heat (heat pumps), and 19% solid biofuels.

Table 1: Energy mix per fuel in 2023 in the EU-27 (GWh)]

Type of fuel	Primary production	Imports	Exports	Total energy supply	Final consumption - energy use
Greece (GWh) - 2023					
Solid fossil fuels	15,251	381	1,684	13,713	704
	24.8%	***0.1%***	***0.8%***	***6.0%***	***0.4%***
Natural gas	30	47,720	2,619	46,208	12,493
	0.0%	***11.4%***	***1.2%***	***20.1%***	***7.1%***
Oil and petroleum products (excluding biofuel portion)	586	362,717	210,238	118,669	94,780
	1.0%	***86.4%***	***96.5%***	***51.6%***	***54.2%***
Renewables and biofuels	45,641	706	43	46,438	20,778
	74.1%	***0.2%***	***0.0%***	***20.2%***	***11.9%***
Non-renewable waste	102	-	-	102	-
	0.2%			***0.0%***	
Electricity	-	8,151	3,238	4,913	45,817
		1.9%	***1.5%***	***2.1%***	***26.2%***
Heat	-	-	-	-	297
					0.2%
Total	61,610	419,674	217,822	230,043	174,869
	100%	***100%***	***100%***	***100%***	***100%***
EU27 (GWh) - 2023					
Solid fossil fuels	878,492	761,247	165,409	1,460,510	169,641
	13.7%	***5.4%***	***3.3%***	***10.0%***	***1.7%***
Manufactured gases	-	-	-	-	49,367
					0.5%
Peat and peat products	5,836	334	104	10,866	2,941
	0.1%	***0.0%***	***0.0%***	***0.1%***	***0.0%***
Oil shale and oil sands	30,762	-	-	27,417	-
	0.5%			***0.2%***	
Natural gas	341,442	3,480,762	623,841	3,170,374	2,000,442
	5.3%	***24.6%***	***12.3%***	***21.6%***	***19.7%***
Oil and petroleum products (excluding biofuel portion)	219,148	9,248,224	3,690,966	4,965,583	3,797,897
	3.4%	***65.4%***	***73.1%***	***33.8%***	***37.4%***
Renewables and biofuels	2,957,489	235,967	164,094	3,030,573	1,284,930
	46.0%	***1.7%***	***3.2%***	***20.7%***	***12.6%***
Non-renewable waste	154,990	7,344	251	162,143	56,046
	2.4%	***0.1%***	***0.0%***	***1.1%***	***0.6%***
Nuclear heat	1,836,966	-	-	1,836,966	-
	28.6%			***12.5%***	
Electricity	-	406,836	407,281	-445	2,329,109
		2.9%	***8.1%***	***0.0%***	***22.9%***
Heat	8,398	65	11	8,452	467,345
	0.1%	***0.0%***	***0.0%***	***0.1%***	***4.6%***
Total	6,433,522	14,140,780	5,051,956	14,672,438	10,157,719
	100%	***100%***	***100%***	***100%***	***100%***

Source: processed data of Eurostat's Complete Energy Balance Database (ec.europa.eu/eurostat/)

In the EU27, available energy for final consumption reached 10,958,177 GWh in 2023, a 10% decline since 2003. Final energy use in industry fell by 22% over this period, maintaining a 25% share in 2023. Households accounted for 26% of final consumption in 2023 (down from 28% in 2003), with household energy demand falling by 14% over the period. Other sectors held a combined 17% share, with commercial and public services being the most energy-intensive components.

By fuel type, EU27 final consumption consisted of 37% oil, 20% natural gas, 13% RES, 23% electricity, 5% heat, and 1% non-renewable waste. The transport sector remained oil-dependent but less so than in Greece, with oil accounting for 90% of transport final use and RES for 6%. RES use was notably higher in the EU27's "other sectors" (40%), whereas in Greece these sectors used 99% oil and almost no RES.

In Greece, available energy for final consumption has consistently remained lower than net imports. In contrast, in the EU27 it has remained higher. These patterns reflect differing levels of energy dependency: the EU27 maintains a significantly higher share of domestic primary production. In Greece, the ratio of primary production to available energy fell from 64% in 1990 to just 35% in 2023. In the EU27, the corresponding ratio decreased more moderately, from 74% to 59%, highlighting the region's comparatively lower dependency on imports.

Electricity Generation Mix During the Energy Transition Era

The carbon intensity of electricity generation in Europe, measured in grams of CO2 per kilowatt-hour (gCO2/kWh), decreased from 500.6 gCO2/kWh in 1990 to 334.7 gCO2/kWh in 2010, and further to 207.1 gCO2/kWh in 2023. This downward trend was temporarily interrupted in 2021 and 2022, when GHG emissions rose due to the post-COVID economic rebound and the energy market disruptions triggered by the war in Ukraine.

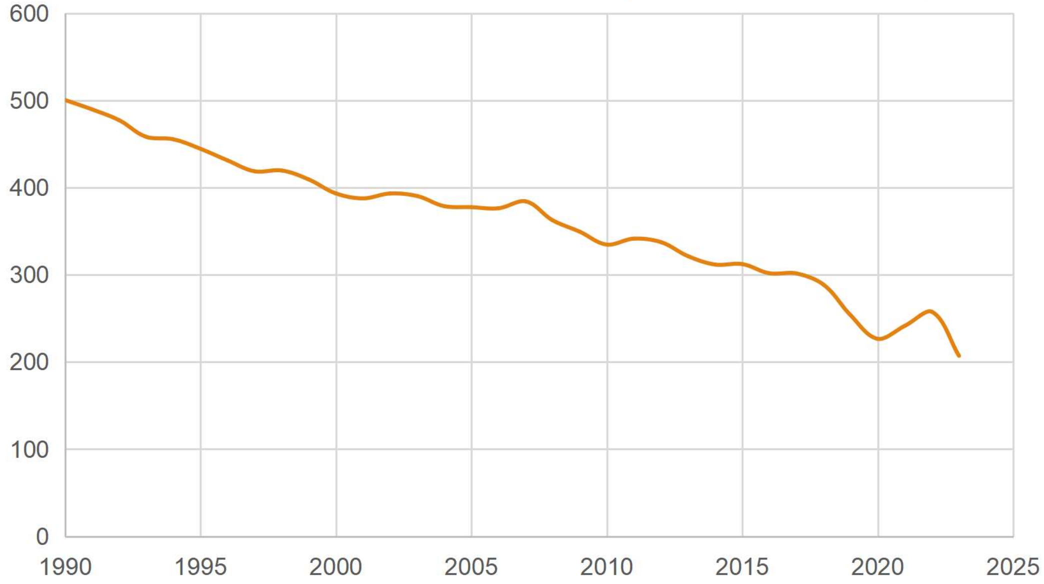
Electricity generation (excluding heat production) from all producers and autoproducers in Greece amounted to 49,917 GWh in 2023. Historical data reveal a peak in 2008, just before the onset of the Greek economic crisis, reaching 63,750 GWh. Over the last two decades (2003–2023), electricity generation has declined by 15%, accompanied by a significant transformation in the country's energy mix.

In the 1990s, electricity production in Greece was dominated by fossil fuels. In 1993, 72% of electricity generated originated from lignite and 20% from oil, resulting in fossil fuels comprising 90% of the mix. Natural gas accounted for only 0.2%, while RES, primarily hydropower, contributed about 6% of total electricity generation.

This composition began to shift in the early 2000s, with natural gas gaining ground. By 2003, the share of natural gas in Greece's electricity production had risen to 14%, while lignite had fallen to 60% and oil to 9%. Renewable sources and biofuels increased their share to 10%. Among RES used for electricity generation in 2003, hydropower was the main source, accounting for 81%. Wind power began to emerge, representing 17% of RES, while biofuels made up the remaining 2%.

By 2013, the electricity mix had shifted further, although lignite still accounted for a substantial 46% of electricity generation. RES and biofuels expanded their share to 25%, while natural gas reached 19%. Oil use declined further to 9%. The 2010s marked a turning point in the penetration of other RES, particularly wind and solar power. By 2013, wind comprised 29% of total RES-based generation, solar 25%, while hydropower's share had fallen to 44%.

Figure 2: GHG emission intensity of electricity generation, EU level (gCO2/kWh).



Source: processed data of European Environment Agency (eea.europa.eu)

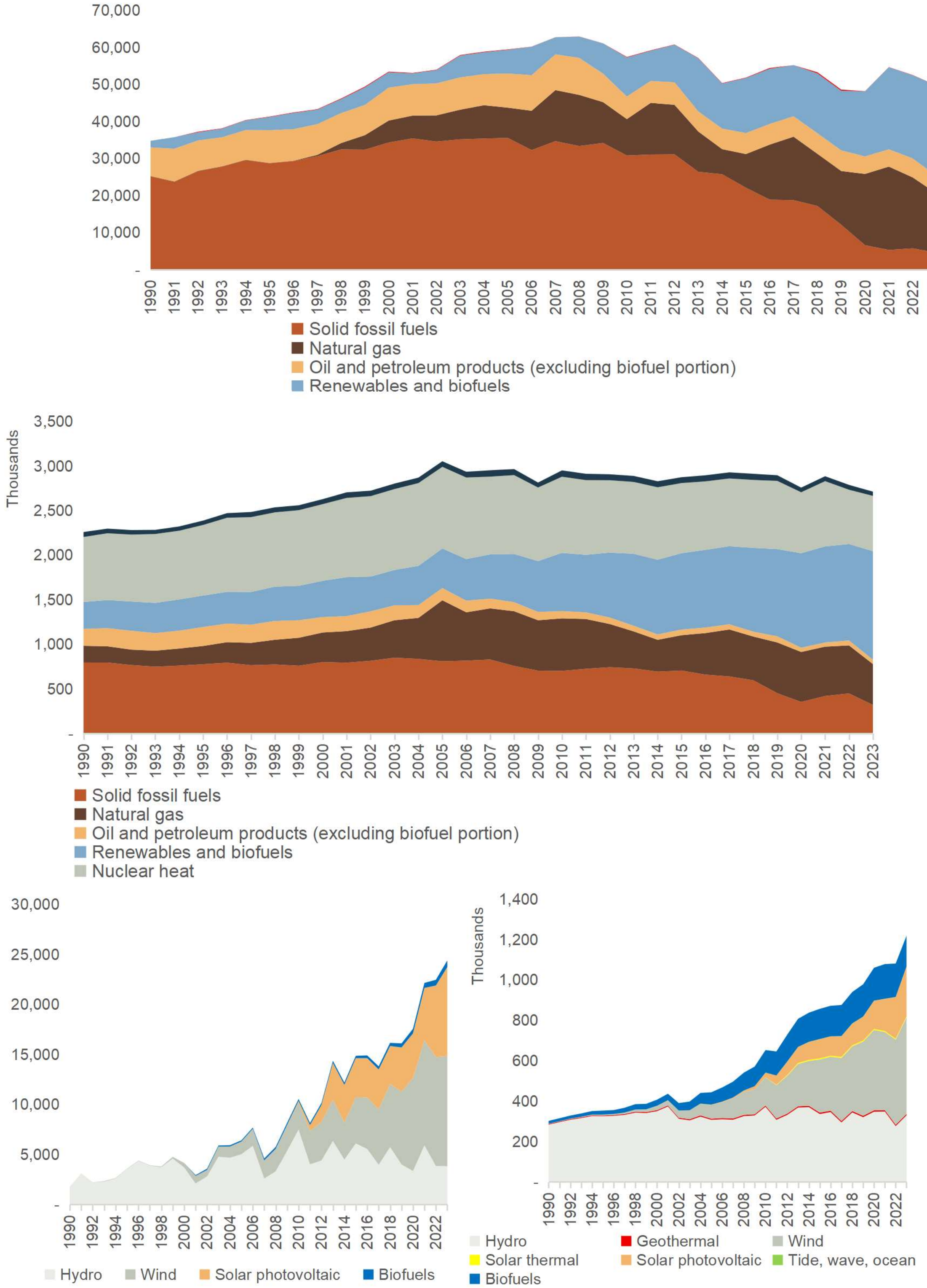
By 2023, the share of electricity produced from RES and biofuels had quadrupled since 2003, reaching 24,386 GWh and accounting for 44% of total power generation. Wind and solar photovoltaic emerged as the dominant RES technologies, contributing 45% and 36% of RES-based generation, respectively. Hydropower declined to 16%, while biofuels increased to 3%, marking a sixfold rise since 2003. The 2023 electricity mix also shows a doubling of natural gas use since 2003, reaching 32% of total generation. Over the same period, oil use declined by 46%, representing a 9% share in 2023, equal to that of lignite.

In the EU27, electricity generation (excluding heat production) increased steadily until 2003 and remained relatively stable thereafter, reaching 2,748,558 GWh in 2023. RES dominate the European mix, contributing 44% of total power generation, having more than tripled their share since 2003, when they accounted for 14%. As of 2023, several countries display notably high RES penetration: Denmark (87%), Austria (80%), Latvia (78%), Lithuania (74%), as well as Portugal, Croatia, and Sweden (all close to 70%).

Lignite accounted for 12% of EU27 power generation in 2023, a decline of 62% since 2003. Among EU countries still generating electricity from lignite, Poland leads with 59% of its total power generation, followed by Czechia (39%), Bulgaria (29%), Germany (24%), Slovenia (20%), and Romania (14%). Member states producing less than 10% of their electricity from lignite include Croatia, Denmark, the Netherlands, Hungary, Italy, Slovakia, Ireland, Finland, and Spain. Outside the EU, several European countries - such as Kosovo (87%), Serbia (59%), Bosnia and Herzegovina (56%), North Macedonia (40%), Montenegro (39%), and Turkey (35%) - continue to heavily rely on lignite for power generation.

Among other fossil fuels, natural gas accounted for 17% of the EU27 electricity mix in 2023, a modest increase of 9% since 2003, in contrast to Greece, where the share of natural gas doubled over the same period. Oil accounted for 2% in 2023, having dropped by 71% since 2003, while other sources (such as peat, heat, oil shale, manufactured gases, and non-renewable waste) contributed 2% of EU electricity generation.

Figure 3: Gross electricity production fuel mix in Greece (top) and the EU27 (middle), and variation in RES mix in Greece (bottom left) and the EU27 (bottom right) (in GWh)



Source: processed data of Eurostat's Complete energy balance database (ec.europa.eu/eurostat/)

The EU's electricity mix is more diversified than that of Greece, notably due to the significant contribution of nuclear heat, which accounts for 23% of EU electricity production, with 13 member states operating nuclear facilities. France leads, deriving 64% of its electricity from nuclear power, followed by Slovakia (61%), Hungary (45%), Finland (42%), Bulgaria (40%), Czechia and Belgium (both 39%), Slovenia (35%), and Sweden (29%). Other contributors include Spain (20%), Romania (19%), the Netherlands (3%), and Germany (1%). Although nuclear heat remains a key source, its use has declined by 32% between 2003 and 2023.

Table 2: RES in electricity generation per country in the EU27

Country	RES as a share of total electricity		Share of renewable energy sources by type in total RES, per country, 2023			
	2003	2023	Hydro	Wind	Solar photovoltaic	Other types (mainly geothermal and solar thermal)
Denmark	17%	87%	0%	66%	12%	22%
Austria	59%	80%	68%	13%	11%	8%
Latvia	59%	78%	76%	5%	5%	13%
Lithuania	2%	74%	10%	57%	16%	17%
Portugal	38%	70%	35%	38%	15%	12%
Croatia	41%	70%	67%	21%	3%	9%
Sweden	43%	69%	57%	30%	3%	10%
Germany	8%	53%	7%	52%	24%	17%
Finland	23%	52%	36%	36%	2%	27%
Spain	21%	50%	17%	45%	30%	8%
Luxembourg	4%	49%	7%	40%	24%	29%
Romania	24%	49%	64%	27%	8%	2%
Greece	10%	49%	16%	45%	36%	3%
Estonia	0%	49%	1%	24%	26%	49%
Netherlands	4%	47%	0%	52%	34%	13%
Ireland	5%	45%	7%	83%	5%	6%
EU27	14%	44%	27%	39%	20%	13%
Italy	16%	44%	35%	20%	26%	19%
Slovenia	22%	40%	80%	0%	16%	5%
Belgium	1%	33%	1%	56%	28%	14%
Poland	1%	27%	5%	53%	24%	18%
France	11%	27%	41%	36%	16%	8%
Hungary	1%	26%	2%	7%	74%	17%
Bulgaria	7%	25%	31%	16%	35%	19%
Slovakia	11%	22%	70%	0%	9%	21%
Cyprus	0%	21%	0%	19%	76%	5%
Czechia	2%	14%	21%	6%	26%	47%
Malta	0%	14%	0%	0%	97%	3%

Source: processed data of Eurostat's Complete energy balance database https://ec.europa.eu/eurostat/

Regarding the use of renewable energy sources (RES) and biofuels by fuel type in the EU-27, a clear shift in composition is observed. In 2003, hydroelectric power was the dominant renewable, as in Greece, accounting for 77% of total RES-based electricity generation. Since then, it has been gradually overtaken by other renewables, primarily wind and solar photovoltaics. By 2023, wind and solar accounted for 39% and 20%, respectively, of total RES-based electricity generation in the EU, marking a substantial increase since 2003.

Among all RES technologies, wind power has recorded the most significant growth, now contributing the largest share to RES electricity generation. Wind power constitutes the largest share of the RES mix in most countries, followed by solar photovoltaics. In countries such as Ireland (where wind accounts for 83% of total RES), Denmark (66%), and Lithuania (57%), wind is the dominant RES for electricity generation. This is achieved through both onshore and offshore wind turbine installations, with offshore wind gaining increasing ground, particularly in Denmark, the Netherlands, Germany, and France (Wind Europe, 2024).

Beyond the EU-27, countries such as Iceland, Norway, and Albania have achieved near-total reliance on RES and biofuels for electricity generation, with shares approaching 100% in both 2003 and 2023. Specifically, in Iceland in 2023, 70% of electricity was generated from hydropower and 30% from geothermal energy. In Norway, approximately 90% of electricity production continues to be generated from hydroelectric power plants.

3. REGULATORY FRAMEWORKS DRIVING GREECE'S TRANSITION AWAY FROM LIGNITE

Challenges of the Transition in Lignite-dependent Areas

For countries such as Greece, the economic and social costs of transitioning away from lignite mining present significant challenges, particularly in lignite-dependent regions. Several studies have examined the multifaceted difficulties associated with this transition. Initial estimates indicated that, without mitigating interventions, the closure of lignite plants in Western Macedonia alone would directly result in more than 6,000 job losses and over €1 billion in local value-added losses. When broader multiplicative effects are included, these losses could reach approximately 13,000 jobs and nearly €2.5 billion in local value added (WWF 2016). These losses could be offset through strategic development plans focused on sustainable practices, the expansion of RES infrastructure, industrial tourism, ecotourism, and the establishment of research centers (WWF 2016).

A demographic survey assessing the socioeconomic implications of delignification in Kozani, Florina, Amyntaio, Megalopolis, and Tripolis found that while most respondents (92%) were aware of the impending phase-out, roughly half reported that their income depended, to varying degrees, on local lignite-fired plants (Dianeosis, 2020). Social concerns were pronounced: 71% expressed negative or somewhat negative views regarding plant closures. At the same time, respondents acknowledged both environmental benefits and economic challenges, with majorities anticipating improvements in air quality (72%), public health (68%), and quality of life (67%), but also expecting adverse effects on regional economic growth (87%), household income (42%), and employment levels (86%).

Further quantification of economic and social impacts in the regions of Kozani, Florina, and Arcadia concluded that, without intervention measures, phasing out lignite-fired power plants by 2028 would generate substantial regional economic damage. Impacts differed across regions, with Florina potentially being the most severely affected, facing projected losses of up to 28% of local GDP, 15% of employment, and 28% of income from work (IOBE 2020).

Ziouzios et al. (2021) highlighted that transitioning high-carbon-intensive economies requires comprehensive strategies tailored to regional conditions rather than one-size-fits-all approaches. Their recommendations included productive diversification, rehabilitation of depleted lignite mines, strategic spatial planning, creation of local energy communities, development of major infrastructure projects, and reskilling of the workforce.

Other research examined the role of circular economy principles following surface coal mine closures. Pavloudakis et al. (2024) argued that post-mining transition should exceed minimum legal and environmental permit requirements by maximizing material recovery and preparing land for new productive uses. This approach, they suggested, would better support sustainable development while mitigating socio-economic impacts on affected communities - a critical factor in Greece's broader energy transition.

The National Energy and Climate Plan

Greece is adapting to the energy transition by also considering the regions most affected by lignite phase-out. It has developed a regulatory framework, including the National Energy and Climate Plan (2024) and the National and Territorial Just Transition Plan (2020), to support a fair and effective transition. These regulations aim both to promote direct measures for reducing carbon emissions through the gradual elimination of lignite use and to mitigate the associated socioeconomic impacts.

The Greek National Energy and Climate Plan (NECP 2024) outlines the country's strategy for transitioning to a sustainable energy system while addressing climate change. In alignment with the European Green Deal, the plan sets ambitious carbon neutrality objectives, targeting a 58% reduction in greenhouse gas emissions (GHG) by 2030 compared to 1990, and an 80% reduction by 2040, with almost full carbon neutrality by 2050.

The NECP aligns with European targets such as those in the Fit for 55 package, introducing comprehensive measures for energy efficiency. The plan prioritizes cost-effective investments in solar, wind, and hydroelectric power, emphasizing the development of energy storage and smart grid infrastructure. It promotes the complete shutdown of all lignite-fired power plants by 2028 and aims to increase the RES share to 75% by 2030 and 95.6% by 2035. Key pillars include investments in biogas, hydrogen, and energy-saving initiatives. The primary repurposing strategy for lignite mines is their transformation into RES hubs, particularly large-scale solar and wind installations (NECP 2024).

Although the NECP has become the cornerstone of Greece's energy and climate policy, it has also faced some criticism. Earlier versions were assessed as lacking transparency in fossil fuel subsidy phase-out strategies and insufficiently addressing climate vulnerabilities that could jeopardize target achievement (European Commission, 2023). Zervas et al. (2021) argued that the initial Plan followed a linear, single-scenario approach and failed to consider key uncertainties in the energy sector, including geopolitical instability, rapid technological progress, volatile fossil fuel prices, and extreme natural events. They also emphasized challenges associated with replacing lignite with natural gas, noting that increased reliance on imported gas could threaten energy security and that methane leakages along the supply chain could offset the emissions benefits of switching from lignite.

The 2024 NECP proposes a more advanced framework, incorporating detailed risk assessments for energy production, consumption, and sustainability, and ensuring greater preparedness across multiple potential scenarios.

The Just Transition Development Plan

The Just Transition Development Plan was designed to mitigate the negative socioeconomic effects of lignite phase-out in alignment with NECP targets. Its primary objective is to support lignite-dependent regions by preserving employment, promoting workforce reskilling, and ensuring an equitable transition that integrates environmental, economic, and social priorities. The Plan emphasizes investments in RES, innovation-driven industrial clusters, and key development pillars such as clean energy, industry, smart agriculture, sustainable tourism, technology, and education (Just Transition Plan 2020).

Financially, Greece's Just Transition Development Plan foresees approximately €5 billion in investments, supported through public subsidies, state-backed loans, commercial lending, and private equity. Supporting measures include tax incentives, expedited permitting, wage subsidies, relocation grants, and targeted credit lines to stimulate private investment.

By 2028, the Plan projects the creation of roughly 8,000 jobs and extensive reskilling programs for affected workers. Key initiatives include a 2 GW photovoltaic rollout, voluntary early retirement schemes, mine-site restoration, natural gas district heating networks, spatial planning fast-tracks, circular economy pilot projects, and support for energy communities.

For the former lignite regions, proposals include photovoltaic parks, agri-tech and eco-tourism development, and major public infrastructure upgrades. Innovative initiatives include high-efficiency Combined Heat and Power (CHP) and gas-fired units, biomass co-firing, and green hydrogen hubs. The latter are also supported by the Greek White Dragon initiative, aimed at converting lignite-fired plant infrastructure for green hydrogen production by adapting natural gas pipelines for hydrogen storage and transport (Polychroniou, 2022). Studies indicate that these targeted actions and funding mechanisms can effectively counteract the negative economic impacts of lignite phase-out, potentially transforming affected regions into dynamic growth centers (IOBE 2020).

Recent announcements by the Public Power Corporation (PPC) also demonstrate progress toward NECP and Just Transition Plan objectives. PPC has presented a strategic transformation plan for Western Macedonia, positioning the region as an emerging energy and technology hub. Key initiatives include converting Ptolemaida V to a natural gas unit by 2027, with plans for future hydrogen integration. The Corporation's RES strategy involves large-scale projects such as 1.2 GW of solar farms, 300 MW of battery storage, and expanded hydroelectric capacity. Former lignite mines in Ptolemaida are being repurposed for RES installations, leveraging the existing high-voltage distribution network. Capitalizing on its energy infrastructure, available land, skilled workforce, and streamlined permitting, Western Macedonia is also positioned to become a significant data center hub, with initial plans for a 300 MW data center and potential expansion to 1,000 MW.

4. THE ROLE OF MARKET-BASED TOOLS IN DECARBONIZATION

While climate change mitigation objectives are global, their implementation varies across countries. The gradual delignification of energy production through regulatory initiatives represents a direct approach to reducing GHG emissions by lowering reliance on fossil fuels. Complementing these regulatory measures, market tools such as carbon pricing have been shown to effectively curb emissions. These pricing mechanisms are gaining momentum worldwide and are increasingly recognized as fundamental instruments for controlling carbon use and limiting emissions (World Bank 2023, 2024).

Carbon pricing is adaptable to various economic, political, and environmental frameworks, acting as a Pigouvian tool that discourages excessive carbon use and reduces GHG emissions (EPRS 2020). These instruments are not fixed or uniform across regions, jurisdictions, or sectors, and they often incorporate exemptions and different design features. They also differ substantially in their operational structure, operating either "upstream" - targeting producers and fuel distributors or "downstream"- directly affecting end users (EPRS 2020). Their scope varies as well, ranging from taxes on fossil fuels to levies on electricity generation, and they may cover only CO2 or a broader set of GHGs, either at national or sub-national level.

Carbon pricing provides a clear signal to emitters by internalizing the negative externality of greenhouse gas emissions — namely their social and environmental costs. Faced with a carbon price, firms can either pay for their emissions, adopt cleaner alternatives, or pass the additional cost on to consumers (EPRS 2020). Although politically challenging to implement, well-designed carbon pricing policies can facilitate the shift to cleaner energy sources, generate public revenue, and deliver significant environmental benefits (EPRS 2020).

Among market-based mechanisms, carbon taxation and emissions trading systems (ETSs), commonly known as cap-and-trade schemes, are the two most prominent. A carbon tax sets a direct price on carbon by taxing the carbon content of fossil fuels per ton of emitted CO2, thus controlling the price but not the quantity of emissions. In contrast, an ETS directly controls the quantity of emissions by introducing a cap on total allowable emissions or emission intensity (i.e., emissions per unit of GDP), while letting the market determine the carbon price.

Cap-and-trade systems reduce aggregate emissions by establishing a cap and issuing a limited number of tradable allowances that correspond to this cap (Aldy and Stavins 2012, Goulder and Schein 2013). Allowances may be allocated for free or auctioned in the primary market, and firms can subsequently trade them in secondary markets. Firms with low abatement costs can sell unused allowances, whereas firms with higher abatement costs can buy them (Narassimhan et al. 2018). At the end of each compliance period, companies must surrender allowances equal to their verified emissions, facing penalties if they exceed their permitted limits.

Although ETSs have expanded more rapidly than carbon taxation, hybrid systems have emerged by combining elements of both approaches. These systems typically integrate carbon taxes with tradable permits under a cap-and-trade structure (Goulder and Schein 2013). By incorporating price floors or "safety valves," hybrid systems aim to reduce price volatility and improve predictability. Such mechanisms provide both stability and flexibility in carbon pricing, balancing the certainty of a price signal with the efficiency of market-based trading (Baranzini et al. 2017, Haites 2018, Emeka-Okoli 2024).

Other, less widely used market-based instruments for reducing GHG emissions include clean energy standards with specific technology targets in the electricity sector, fossil fuel subsidy phase-outs, and emission reduction credits (Aldy and Stavins 2012). Carbon crediting, typically voluntary and project-based, allows developers to earn credits for mitigating emissions through activities such as forest protection or renewable energy deployment. While carbon pricing imposes direct costs on emissions, carbon crediting provides offsets that allow entities to compensate for emissions rather than reduce them directly. However, critics argue that many credits do not correspond to genuine emission reductions, highlighting the need for stricter standards and reforms (Probst et al. 2024). In a similar way, Internal Carbon Pricing (ICP) has gained reputation as a corporate tool for driving emissions reductions. Despite its increasing adoption, ICP remains in an early stage of development and requires further refinement in both practice and empirical research (Sinclair-Desgagné et al. 2024).

Comparative Overview of Carbon Taxes and ETSs Worldwide

Based on World Bank data for compliance instruments, emissions coverage, prices, and revenues, a total of 142 carbon pricing mechanisms in the form of ETSs or carbon taxes have been recorded globally since 1990. As of 2024, 111 instruments were active across various jurisdictions. Of these, 36 (32%) were ETSs and 76 (68%) were carbon taxes, implemented in 68 national or subnational jurisdictions. Several countries apply multiple carbon tax rates for different fuel types or products. For example, Argentina and Mexico have 10 and 11 distinct tax rate labels respectively, covering gasoline, kerosene, diesel, gas oil, coal, solvents, and more. Notably, in 2004 no ETS existed, but only 12 carbon taxes were operational in seven European countries, namely Norway, Denmark, Slovenia, Finland, Latvia, and Poland.

As of 2024, Europe and Central Asia recorded the highest number of carbon pricing schemes (46), consisting of 39 carbon taxes and 7 ETSs. Latin America and the Caribbean followed with 30 instruments, East Asia and the Pacific with 18, and North America with 16. Sub-Saharan Africa had only one carbon pricing mechanism, namely a carbon tax in South Africa. In Latin America and the Caribbean and in Sub-Saharan Africa, no ETSs operate, whereas in North America and in East Asia and the Pacific, ETSs outnumber carbon taxes. In terms of income classification, 60% of all instruments are implemented in high-income countries, 39% in upper-middle-income countries, and just 1% in lower-middle-income countries.

Despite the rapid expansion of carbon pricing, fewer than 5% of global GHG emissions are currently priced at levels compatible with 2030 climate targets, and only around 1% are priced above the recommended range (World Bank 2024). In 2024, the average price across all carbon taxes and ETS allowance prices was 34.9 US$/tCO2e, recording an increase of 78% compared to 2004. The average carbon tax rate reached 37 US$/tCO2e, while the average ETS allowance price stood at 30.3 US$/tCO2e. Uruguay recorded the world’s highest carbon tax rate at 167 US$/tCO2e, while the highest ETS price was observed in the EU ETS at 61.3 US$/tCO2e. On average, allowance and tax prices in upper-middle-income countries reached only 6.6 US$/tCO2e in 2024, compared with an average of 53.6 US$/tCO2e in high-income countries.

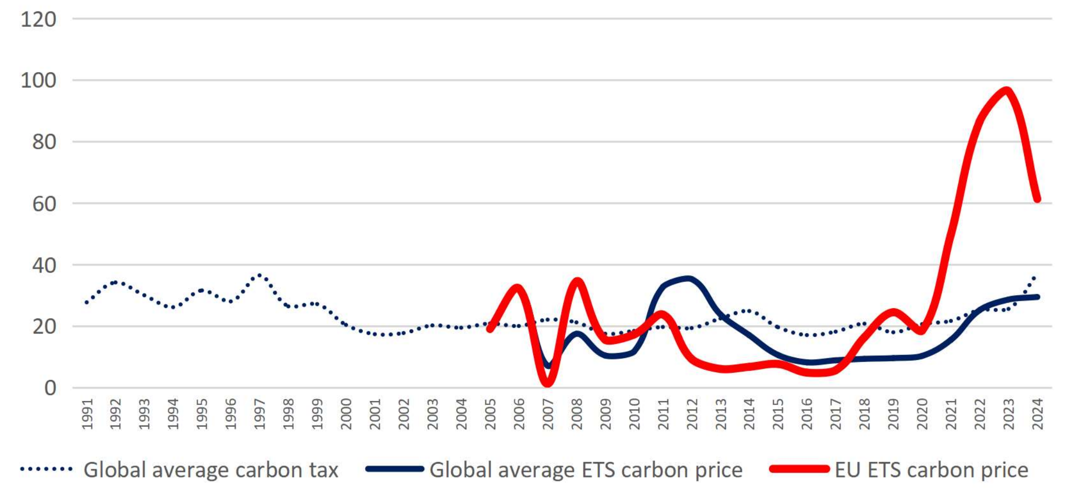
Global revenue from carbon pricing has risen substantially in parallel with the expansion of these mechanisms. Revenues reached 104.3 billion US$ in 2023, of which 75 billion US$ (72%) originated from ETS and 29.3 billion US$ (28%) from carbon taxes. By comparison, global revenues amounted to only 24.4 billion US$ in 2013 and 5.4 billion US$ in 2003. Until 2020, with the exception of 2013, ETS revenues remained consistently below those from carbon taxes. However, after 2021 - when ETS allowance prices increased sharply - ETS revenues surpassed carbon tax revenues. Between 2005 and 2020, carbon taxes generated on average 64% of global carbon pricing revenue, compared with 36% from ETSs. By 2023, this pattern had reversed, with ETSs accounting for 72% of worldwide revenues and carbon taxes for only 28%.

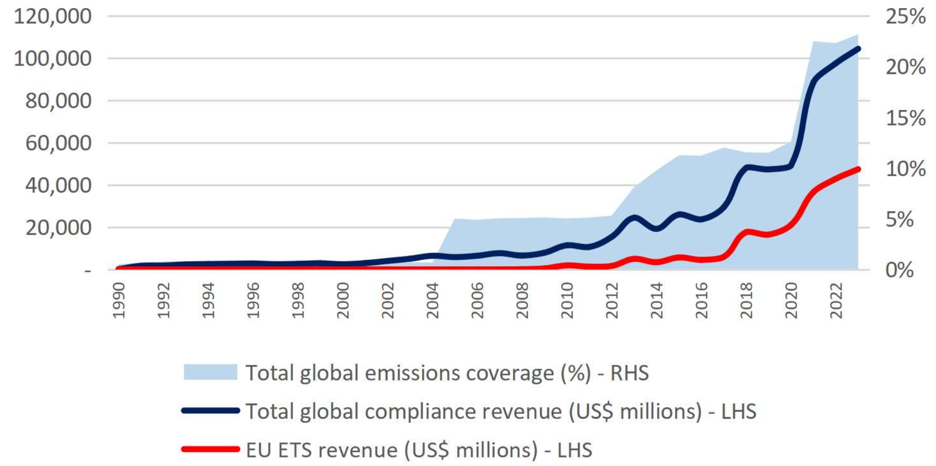
Collectively, the 111 carbon pricing mechanisms covered almost one quarter of global GHG emissions in 2024 - equivalent to 12.8 Gt of CO2 - with ETSs accounting for 19% and carbon taxes for roughly 5% of the total. For comparison, in 2014, 36 instruments covered approximately 10% of global emissions, while in 2004 only 1% of global emissions were subject solely to carbon taxation. In 2024, China’s national ETS, operational since 2021, alone accounted for 9.3% of the emissions coverage, while the EU ETS accounted for 2.6%.

The European Union Emissions Trading System (EU ETS)

The European Union (EU) ETS, established in 2005, is the oldest and one of the largest cap-and-trade systems globally. Since then, it has undergone four trading phases. The first phase (2005–2007) operated as a pilot to test system functionality ahead of the first Kyoto Protocol commitment period. Due to limited baseline data, an overallocation of allowances led to a collapse in carbon prices by 2007 (EU ETS Handbook 2015). The second phase (2008–2013), aligned with the first Kyoto commitment period, strengthened monitoring, reporting, and verification requirements and introduced links to global markets through international credits. The third phase (2013–2020) broadened sectoral coverage, tightened rules, and made auctioning the default allocation method. In 2019, the Market Stability Reserve (MSR) was introduced to address allowance surpluses and improve price stability.

Figure 4: Average carbon tax (since 1991), average ETS carbon price (since 2005) and EU ETS carbon price.





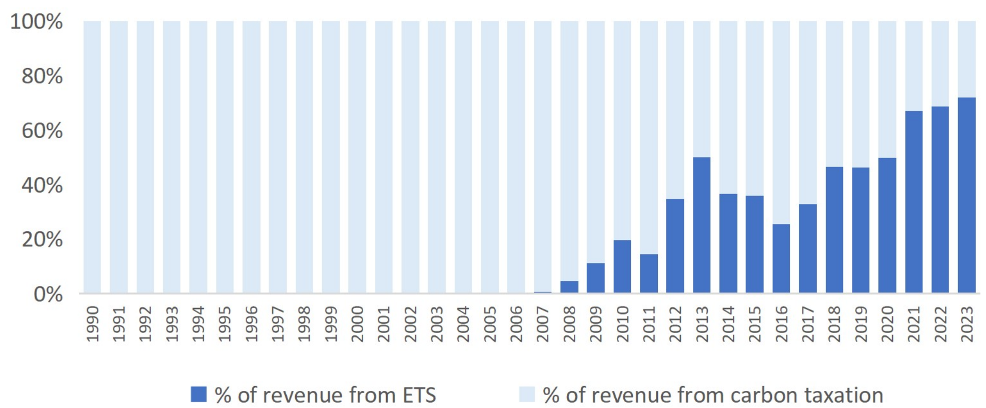
Source: processed data of World Bank (carbonpricingdashboard.worldbank.org)

The fourth trading phase (2021–2030) is currently underway. Under the broader ETS reform, a new, separate system - EU ETS2 - was established in 2023 to cover buildings, road transport, and selected small industries. ETS 2 is set to become operational in 2027 (or 2028 under persistently high energy prices). Since 2021, the annual cap under the existing EU ETS has been decreasing at a rate of 2.2%, up from 1.74% previously.

Allowances in the EU ETS are distributed primarily via auctioning, though free allocation remains available for sectors at risk of carbon leakage. The system regulates emissions from coal, diesel, gasoline, kerosene, jet fuel, natural gas, and other oil products, as well as selected industrial process emissions. Sectoral coverage includes electricity generation, manufacturing, heavy industry, intra-EU aviation, and more recently maritime transport (World Bank Carbon Pricing Dashboard). Some European countries, such as Germany and the United Kingdom, operate national ETSs in parallel with (or previously within) the EU ETS. Greece, which does not have a separate carbon tax, has been a participant in the EU ETS since 2005, initially covering CO2 emissions from power and heat generation and from energy-intensive industries.

EU ETS allowance prices increased sharply over the last years, from 49.8 US$/tCO2e in 2021 to 86.5 US$/tCO2e in 2022 and 96.3 US$/tCO2e in 2023, before declining to 61.3 US$/tCO2e in 2024. This volatility largely reflects the post-COVID economic recovery, the energy market disruptions triggered by Russia’s war in Ukraine, and the effects of tighter EU climate policies.

Figure 5: Shares of global revenue from carbon taxation and ETS carbon pricing.



Source: processed data of World Bank (carbonpricingdashboard.worldbank.org)

Effectiveness of Carbon Pricing Instruments

The effectiveness of carbon pricing mechanisms in curbing GHG emissions has been stated in an extensive body of literature. Although carbon pricing contributes to reductions in CO_2 emissions, total GHG emissions remain high, implying limited overall effectiveness in achieving climate neutrality (OECD 2022; IPCC 2023). Aldy and Stavins (2012) explored the effectiveness of carbon pricing mechanisms, drawing from the experience of developed countries. They argued that conventional environmental policies are not sufficient to address the ubiquity and diversity of GHG and claimed that well-designed carbon pricing policies could promote cost-effective abatement, provide incentives for innovation, and help alleviate government fiscal problems. The authors also highlighted the importance of international cooperation and careful policy design to address challenges such as competitiveness impacts and emissions leakage.

Goulder and Schein (2013) compared the relative merits of carbon taxes, cap-and-trade systems, and hybrid approaches and found that these approaches can be equivalent in many ways and yield similar incentives to emissions abatement, but also differ significantly in important dimensions. Carbon taxing or hybrid systems with exogenous emissions pricing offer several advantages over pure cap-and-trade, including the limitation of price volatility, the minimization of policy errors and interactions with other climate policies, and the prevention of large wealth transfers among countries.

Narassimhan et al. (2017) distinguished between carbon taxes and emissions trading systems (ETSs), noting that both instruments should be embedded within a broader climate policy framework. Their effectiveness in reducing emissions depends on factors such as the carbon price level, sectoral and geographic coverage, and the presence of complementary policies. The authors suggest that countries considering an ETS might first adopt a carbon tax, which entails lower administrative costs, although it does not guarantee emissions reductions. If a country adopts both carbon pricing instruments, they must ensure they are effectively coordinated and not applied to the same emissions base within the same sectors, as this could lead to unfair distributional effects and economically inefficient abatement costs. They also emphasize that while carbon pricing has generally not hindered economic growth, its impacts can be more pronounced in specific sectors, particularly in energy-intensive industries.

Moreover, Narassimhan et al. (2018) also assessed the implementation of ETS systems across various jurisdictions, including the EU. Based on certain criteria such as environmental effectiveness, economic efficiency, market management, revenue management, and stakeholder engagement, the authors concluded that even modest carbon prices can amplify the effectiveness of ETSs, leading to significant emissions reductions if the cap tightens over time and auction revenues are reinvested in other emissions-reduction activities, such as investments in clean energy and innovation. Implementing minimum and maximum price thresholds, banking and borrowing allowances, and maintaining reserve allowances can enhance market predictability and stability. They also stress the need for better understanding of how ETSs interact with other climate policies to optimize emissions reductions while minimizing administrative costs.

Baranzini et al. (2017) highlighted the cost-effectiveness of carbon pricing for reducing emissions when combined with other technology and innovation policies, enhancing overall effectiveness in climate policy. Köppl and Schratzenstaller (2022) provide a thorough review of the empirical effects of carbon taxation across several key dimensions. Carbon taxes were shown to be effective in reducing CO_2 emissions or slowing their growth and do not negatively affect economic growth, competitiveness, or employment. The authors show that countries with higher carbon tax rates exhibit greater reduction in carbon emissions, although their impact depends on the type and height of the tax rate, the exemptions, and the broader environmental policies.

Haites (2018) argues that both carbon taxes and carbon trading have reduced emissions, but from a ``business as usual" perspective. Achieving reductions in actual emissions is often influenced by other mitigation policies or external factors, such as changes in fossil fuel prices and economic conditions. ETS allowance prices are generally lower than carbon tax rates, and many carbon tax rates are falling short of the necessary levels to achieve climate goals. The author claims that few jurisdictions regularly adjust their tax rates or ETS caps and implement measures in case of allowance surpluses, such as annual reductions in emissions caps.

Studies have also commented on the presence of speculative trends within emissions trading systems, suggesting that entities other than compliance firms who actually emit, such as investment firms, brokers, and banks, hold shares of carbon allowances and enter the carbon market primarily for profit. This can have a distortionary effect on price signals, which are primarily intended to incentivize emissions reductions (Isah et al., 2025). Speculation is a strong predictor of carbon prices, rendering the ETS an attractive investment opportunity for non-emitters and consequently, ignoring speculative behavior can lead to misjudgments regarding the effectiveness of carbon pricing and therefore contribute to increased long-term carbon price volatility (Isah et al., 2024). However, the investigation of the dramatic surge in European Emissions Allowance prices between 2018 and 2022 concluded that although speculation exists and to some extent can amplify price movements, these surges reflected primarily factors such as energy demand and supply, or gas-coal switching, rather than purely speculative impacts (ECB, 2022).

Carbon taxes can also have distributional implications, as their impact on income groups varies depending on how revenues are used. For instance, lump-sum transfers tend to benefit lower-income households (Köppl and Schratzenstaller 2022). To mitigate the distributional effects and enhance public acceptance, recycling carbon tax revenues, such as through reductions in social security contributions or labor taxes, but also channeling a portion into environmental projects, can lead to a ``double dividend," with economic and environmental benefits (Köppl and Schratzenstaller 2022). As argued by Hepburn et al. (2020), carbon pricing is just one, although very crucial, part of a broader structural transformation strategy for reducing GHG emissions and meeting climate targets. Necessary to achieve net-zero emissions is also the encouragement of positive motivation through direct regulation and public investment in clean technologies.

5. CONCLUSIONS

Restructuring the energy system towards cleaner alternatives remains a multifaceted challenge. The scheduled lignite phase-out in Greece by 2028 represents an ambitious structural reform, requiring a comprehensive transformation that balances economic requirements, environmental imperatives, and social considerations, particularly in regions where fossil fuels have historically served as economic pillars.

In this regard, both Greece and the EU-27 have achieved substantial emission reductions through delignification and a fundamental energy mix transformation. This is especially evident in electricity generation, where Renewable Energy Sources (RES) now dominate the landscape, signaling a decisive shift away from solid fuels. The National Energy and Climate Plan (NECP) and the Just Transition Program (JTP) have provided the essential framework and necessary social safeguards for Greece, utilizing a robustly funded mechanism to manage the transition fairly, while repurposing former lignite regions into new RES and technology hubs.

However, it is crucial to recognize that while regulatory measures constitute the structural backbone of decarbonization—establishing targets and mandates—they are often insufficient on their own to ensure cost-effectiveness or to stimulate continuous abatement across all sectors. Consequently, the policy framework increasingly relies on complementary market-based instruments. Tools such as the EU ETS reinforce national regulatory efforts by providing clear financial signals that optimize abatement costs and accelerate the transition to cleaner alternatives.

Ultimately, neither regulation nor carbon pricing is sufficient in isolation; a synergistic approach is required. While regulations establish the foundational architecture and binding targets, market tools provide the incentives and flexibility to ensure economic efficiency. Furthermore, the transition demands large-scale investments in RES technologies alongside energy efficiency solutions, such as smart grids and advanced carbon capture, to supplement the existing regulatory and pricing mechanisms.

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