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Deep Decarbonization of the Electricity Sector: The Interplay of Carbon Pricing and Complementary Policies

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Abstract

This article examines the role of carbon pricing mechanisms—specifically, carbon taxes and Emissions Trading Systems (ETS)—in driving deep decarbonization in the electricity sector. While carbon pricing effectively alters the merit order of power generation and incentivizes short-term fuel switching from coal to lower-carbon alternatives, relying solely on price signals is insufficient for achieving net-zero targets. The analysis highlights that pricing mechanisms must navigate challenges such as price volatility, carbon lock-in, and adverse distributional impacts on consumers. Furthermore, standalone pricing often fails to spur the capital-intensive investments in firm low-carbon resources required to maintain long-term grid reliability. To address these distinct market failures, the study underscores the necessity of a comprehensive policy portfolio. Integrating carbon pricing with complementary measures—including targeted technology subsidies, energy efficiency standards, revenue recycling, and infrastructure investments—provides the most robust, equitable, and cost-effective pathway for the structural transformation of the power sector.

Keywords: Carbon Pricing; Emission Trading System (ETS); Carbon Tax; Deep Decarbonization; Electricity Sector; Fuel Switching; Energy Policy

1. Introduction

Carbon pricing is based on the principle of making polluters pay for the environmental costs (externalities) created by greenhouse gas emissions into the atmosphere. Two main carbon pricing tools stand out: a carbon tax and an emissions trading system. A carbon tax imposes a fixed cost per unit of carbon dioxide (CO_2) or an equivalent amount of another greenhouse gas emitted. In this system, the price is fixed, but the amount of emissions reduction achieved varies with market dynamics. In contrast, the emissions trading system (ETS) operates with a "cap-and-trade" mechanism. A total emission limit is set for specific sectors, and quotas are allocated to businesses. Businesses can buy and sell these quotas on the market according to their needs. A carbon tax is a system in which the government sets a fixed price (tax rate) for each ton of greenhouse gas emissions (usually measured in CO_2-equivalent) released into the atmosphere. Its theoretical foundation is based on economist Arthur Pigou's idea of taxing negative externalities (Pigovian tax) (Pigou, 1920).

Price Setting: The regulatory authority (the government) legally sets the price of one ton of carbon emissions (e.g., $50 per ton).

Point of Regulation: The tax is typically levied upstream (on fossil fuel producers or importers) or directly on large industrial facilities that generate emissions. Because the emissions from burning a specific fuel are known, the tax can be calculated based on the fuel's carbon content.

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Company Response: A company facing a carbon tax must choose between continuing to pay the tax and investing in measures to reduce emissions (such as renewable energy or energy efficiency). If the cost of reducing emissions is lower than the tax rate, the company will rationally choose to reduce its emissions (Stavins, 2001). Under a carbon tax, the cost (price) is certain, but because the level of reduction depends on market conditions and company decisions, the exact amount of emission reduction (the environmental outcome) is uncertain.

Emission Trading System (ETS) is a market-based approach commonly referred to as "cap-and-trade." It was first conceptualized by John Dales (1968) as a system of transferable property rights for pollution.

Setting the Cap: The government establishes a maximum limit (the cap) on the total greenhouse gases that include sectors (such as electricity, steel, and cement) can emit within a set period (like a year). This cap is gradually reduced over time to meet climate targets.

Allowance Distribution: The overall cap is divided into "emission allowances" or "permits," each allowing the emission of exactly 1 ton of CO_2. These allowances are either granted to companies for free or sold at auctions (World Bank, 2022).

Trading: By the end of the compliance period, all companies must surrender enough allowances to cover their emissions. Companies that cut emissions can sell their surplus allowances for profit on the carbon market. Those emitting more than their allowance must buy additional permits or face hefty fines if they fail to do so.

In an ETS, the total amount of emissions is certain (guaranteed by the cap), but because the price per ton of carbon is determined by market supply and demand, it is uncertain and can fluctuate (Aldy & Stavins, 2012).

Pişkin (2022) states that the ETS offers a more definite framework for achieving the emission reduction target than a carbon tax, as it sets a restrictive upper limit based on production, whereas the carbon tax, although it provides price stability, has an uncertain impact on emission levels.

1.1. Emission Trading Systems (ETS): Mechanics and Volatility

An Emissions Trading System (ETS) promotes decarbonization by imposing a strict cap on total emissions and allowing allowances to be traded. This setup generates a market-based price signal that indicates permit scarcity and the strictness of the cap. Gradually tightening the cap raises prices and accelerates emissions reductions, but prices can become highly volatile due to cap changes, banking and borrowing rules, and shifting market expectations. This volatility may discourage capital-heavy investments since firms find it difficult to predict long-term costs. To improve predictability and ensure policy credibility, ETS frameworks often include tools like price floors or long-term contracts (Pedersen et al., 2023; Vernon, 2023; Farrukh et al., 2023). When well-designed and aligned with 1.5–2°C climate pathways, ETS price signals can promote the early deployment of low-carbon technologies.

1.2. Carbon Taxes: Predictability and Political Realities

In contrast, a carbon tax imposes a direct, frictionless price on emissions, independent of permit markets. This approach provides a transparent, predictable price trajectory that is highly effective at spurring long-horizon investments in low-carbon generation and demand-side responses, provided the tax framework is credible and supported by stable regulation. However, carbon taxes can be politically sensitive. To address distributional impacts and maintain public support, policymakers often rely on revenue recycling to fund complementary decarbonization initiatives. Furthermore, if the established tax rate remains too low, the expected pace of decarbonization may fall short of climate targets unless bolstered by additional sector-specific policies (Jordan et al., 2025; Yan et al., 2022; Wiser et al., 2021).

Ultimately, both pricing instruments are most effective when integrated into a broader portfolio of non-price policies. Economic models consistently show that pairing carbon pricing with targeted demand-side measures—such as Minimum Energy Performance Standards (MEPS), building codes, energy-efficiency mandates, and demand-response flexibility programs—delivers significantly faster and more cost-effective decarbonization in the electricity sector than pricing alone. Combining demand-side measures, supply-side innovation, and robust pricing forms the comprehensive strategy required for deep emissions cuts (Mundaca et al., 2018; Hannula & Reiner, 2019; Mani et al., 2024; Liu et al., 2024; Bistline et al., 2022; Ampah et al., 2024).

2. Literature Review

2.1. The Electricity Sector as the Primary Locus of Carbon Tax Impact

There is broad agreement across modeling exercises that the electricity sector bears the majority of emissions reductions under carbon pricing. The EMF 32 study of U.S. carbon tax scenarios found that "across all models, carbon prices lead to significant reductions in CO_2 emissions and conventional pollutants, with the vast majority of the reductions occurring in the electricity sector" (Alzate & González, 2019). This is because "economic dispatch of power plants and retirements provide relatively fast ways to achieve emissions reductions, as well as in the medium term as there are lower or zero carbon generation options that are cost-competitive with high carbon generation" (Alzate & González, 2019). Empirical evidence from the UK corroborates this: carbon pricing in the electricity sector resulted in "emissions in the electricity sector falling by 58%" in four years (Lozano et al., 2023). Similarly, empirical models examining the EU and UK find that "most abatement occurring in the electricity and heat sector" (Dávila & Dávila, 2022).

The responsiveness of the electricity sector is also evident in developing countries. In Indonesia, carbon tax simulations indicate a "significant decrease in coal consumption" along with a notable rise in renewable energy use, aligning with plans to shut down coal plants and boost renewable capacity (Polo, 2022). Meanwhile, in China, CGE models show that carbon taxes increase fossil fuel prices and raise production costs. Technological advances in clean electricity help "accelerate the transition of the electricity infrastructure, reduce thermal power's share, and better support emission reductions" (Albertoni et al., 2022).

Kaplan Dönmez's (2024) panel data analysis of OECD countries shows that carbon taxes have a statistically significant positive effect on long-term CO_2 emissions.

Furthermore, macroeconomic modeling studies by Acar, Aşıcı, and Yeldan (2021) emphasize the importance of channeling public revenues from a carbon tax in Türkiye into a fund to support renewable energy investments. Directing tax revenues toward clean technology and energy-efficiency projects accelerates structural transformation in the electricity sector while offsetting potential losses in economic growth.

2.2. The Role of Emissions Pricing and Fuel Switching

Carbon pricing instruments explicitly alter the merit order of electricity generation by penalizing high-emission technologies. Research shows that a robust carbon price fundamentally restructures power markets, making coal generation economically uncompetitive compared with natural gas and renewable energy sources. For instance, the United Kingdom's Carbon Price Support (CPS)—a domestic tax that serves as a carbon price floor—led to a rapid, dramatic phase-out of coal in favor of natural gas. This policy intervention demonstrated that targeted, stable pricing signals are highly effective at triggering immediate fuel switching in the power sector, leading to unprecedented declines in national greenhouse gas emissions (Abrell et al., 2019; Dolphin et al., 2020).

The transition away from carbon-heavy fuels depends greatly on how carbon prices interact with underlying commodity markets. Studies of European electricity markets show that applying carbon pricing often proves more cost-effective for cutting immediate emissions—particularly through coal-to-gas switching—compared to simply subsidizing renewable energy. The specific carbon price needed to trigger this shift is largely influenced by the relative cost difference between coal and natural gas. For instance, when natural gas is inexpensive, even a low carbon price can push coal out of the market. Conversely, if gas is costly, a significantly higher carbon tax is necessary to achieve the same switching effect (Cullen & Mansur, 2014; Gugler et al., 2021).

While carbon pricing effectively encourages short-term fuel switching, relying on it alone risks leading to "carbon lock-in"—a situation where energy systems become heavily reliant on transitional fossil fuels like natural gas instead of shifting entirely to zero-carbon alternatives. To achieve comprehensive decarbonization and long-term net-zero goals, structural changes are necessary that go beyond simply improving existing power plants. Consequently, energy modelers stress that carbon pricing should be supplemented with targeted technology policies, R&D subsidies, and large-scale infrastructure investments—such as grid upgrades and energy storage—to ensure a smooth and secure transition to renewables and zero-carbon solutions (Bertram et al., 2015).

Taranto et al. (2021) reported in their study that increasing the share of renewable energy and reducing emissions during the transformation of Türkiye's electricity system would increase social welfare and reduce health externalities.

However, caution is advised when assessing the macroeconomic impacts of ETS. Bolat et al. (2023), in their study of the EU ETS, highlight a macroeconomic "carbon rebound" effect. Although ETS encourages energy efficiency and enhances economic performance at the sector level, their findings suggest that increased long-term economic output may lead to greater-than-expected energy demand, potentially slowing emission reductions. Therefore, Türkiye's electricity sector ETS should incorporate strict control measures and gradually tighten emission limits.

2.3. Electricity Price Pass-Through and Distributional Consequences

Carbon taxes influence the electricity sector not just by altering supply but also by passing costs to consumers. The tax "tends to be transferred from the upstream to the end-users through the carbon-integrated locational marginal electricity price," leading to a situation where "generators lose incentives to develop sustainable technologies," while consumers shoulder the costs (Peña et al., 2021). This transfer has important implications for how costs are distributed.

Shang notes that in some jurisdictions, like South Africa, the impact of the carbon tax scheme on electricity prices will be minimal in the initial phase due to regulatory design. In contrast, in China, because electricity tariffs are regulated, pass-through effects are limited (Padilla, 2023). Pereira et al. point out that the primary cause of regressivity in carbon taxes is the increase in prices of carbon-intensive goods such as electricity, heating, and food, which often have subsistence levels (Basterra et al., 2020). Pigato also observes that sectors heavily reliant on electricity—particularly in production—would experience higher costs due to tax-induced electricity price increases. Firms operating in more electricity-intensive sectors would face even greater negative impacts (Basterra, 2021).

In addition to meeting environmental goals, carbon pricing offers significant health benefits by lowering local air pollution and related health damages. Nonetheless, studies on distributional effects indicate that these mechanisms may unfairly impact disadvantaged and low-income groups. To promote a fair transition and avoid increasing inequality, it is essential to incorporate strong equity measures alongside carbon pricing. This can involve targeted policies like revenue recycling or directing strategic investments to vulnerable and low-income areas (Luo et al., 2022).

2.4. The Necessity of Complementary Policies for Deep Electricity Decarbonization

Achieving deep decarbonization in the electricity sector demands addressing multiple market failures, indicating that simply pricing carbon is not enough. While carbon pricing targets the primary greenhouse gas externality, it does not address other key barriers such as infrastructure lock-in, behavioral rigidities, and financial hurdles. The "Three Domains" framework of climate policy highlights that effective mitigation requires a strategic mix of actions: standards and engagement to modify behaviors, carbon pricing to enhance market efficiency, and targeted investments to promote innovation and infrastructure. Relying solely on a carbon tax or an ETS overlooks the systemic, coordinated efforts required to develop a resilient, zero-carbon power grid (Grubb et al., 2014).

Economic modeling consistently shows that the most cost-effective way to achieve climate mitigation is through a combination of policy tools rather than relying on a single price signal. Early-stage low-carbon technologies face considerable "knowledge spillovers," meaning innovators cannot fully capture the economic benefits of their R&D efforts. Consequently, a carbon price alone is insufficient to incentivize private investment in clean energy R&D. A well-rounded policy approach that combines emission pricing with technology-specific measures—such as R&D subsidies and renewable energy mandates—can notably reduce the overall economic costs of decarbonization. These targeted policies promote faster commercialization of key grid technologies, like utility-scale storage, which a carbon price alone might be too slow to incentivize adequately to meet climate goals (Fischer & Newell, 2008).

Beyond just economic efficiency, the political economy of decarbonization tends to favor a mixed policy strategy. Setting a high, optimal carbon price from the beginning often faces political hurdles due to opposition from established fossil-fuel interests and public worries about increased energy costs. Studies indicate that sequencing climate policies—like initially adopting renewable portfolio standards or clean energy subsidies—can build a strong "green" coalition composed of clean energy companies, workers, and other stakeholders. As these low-carbon industries expand and technology costs fall, political opposition to more aggressive, economy-wide carbon pricing lessens. This strategic order of policies creates the conditions needed for the deep reforms required to fully eliminate emissions from the power sector (Meckling et al., 2015; Pahle et al., 2018).

The World Bank's Decarbonizing Development report notes that "under an economy-wide carbon tax, a feed-in tariff promotes investment in renewable power without reducing incentives to abate in other sectors" (Rengifo, 2021).

Global and national energy-system models often analyze sector-level carbon pricing scenarios, such as carbon taxes or ETS-like price signals, to map pathways to deep decarbonization in the electricity sector. These studies consistently show that while carbon pricing is a core policy instrument, its effectiveness is significantly enhanced when paired with complementary measures. Combining pricing with policies that address specific demand- and supply-side barriers—such as energy efficiency standards, strict building codes, and direct investment incentives—creates a much more robust framework for reducing emissions than pricing alone (Mundaca et al., 2018; Hannula & Reiner, 2019; Mani et al., 2024; Liu et al., 2024).

If a policy goal is rapid decarbonization of the electricity sector with credible long-term signals, an ETS with a progressively tightening cap, complemented by firm zero-emission resource incentives and a credible price path or price floors, can be highly effective; this is especially true when paired with demand-side standards, efficiency improvements, and capacity mechanisms to ensure reliability (Pedersen et al., 2023; Keppler et al., 2022; Farrukh et al., 2023).

If policy credibility and predictability are paramount to spur investment in low-carbon capacity, a well-designed carbon tax with stable revenue recycling and sector-specific incentives (e.g., investment credits, technology-specific subsidies) can drive decarbonization while maintaining fiscal predictability; however, it should be complemented by targeted policies to avoid undermining innovation and to address potential inequities (Jordan et al., 2025; Yan et al., 2022; Wiser et al., 2021).

A hybrid approach that uses carbon pricing as the backbone and layers on sector-specific standards, efficiency policies, and capacity and reliability mechanisms is repeatedly identified across multiple studies, regions, and model frameworks as the most robust pathway to deep decarbonization of the electricity sector (Mundaca et al., 2018; Mani et al., 2024; Liu et al., 2024; Bistline et al., 2022; Ampah et al., 2024).

2.5. The Role of Firm Low-Carbon Resources in Grid Reliability

Achieving deep decarbonization while maintaining grid reliability and cost-effectiveness requires the widespread deployment of "firm" low-carbon resources. Technologies such as nuclear power, biomass with carbon capture and storage (BECCS), and fossil-fuel plants equipped with CCS provide the continuous, dispatchable generation that intermittent renewables (like wind and solar) cannot guarantee. Research indicates that a carbon price alone is often insufficient to trigger the massive, capital-intensive investments required for these firm resources. Securing these investments requires credible, long-horizon policy signals alongside robust assurances of grid reliability (Sepulveda et al., 2018; Yan et al., 2022).

Several studies emphasize the importance of state-backed low-carbon capacities such as nuclear, CCS-enabled plants, and bioenergy with CCS to support intermittent renewables. Relying solely on market prices might not attract sufficient investment in these assets if the prices don't cover fixed costs or the benefits of reliability. Therefore, market designs that account for capacity value or offer long-term contracts are crucial in ETS frameworks. Additionally, tax-based regimes can be combined with capacity mechanisms or reliability standards (Sepulveda et al., 2018; Keppler et al., 2022; Wiser et al., 2021).

3. Conclusion

Pricing mechanisms (ETS or carbon taxes) can align electricity-sector decarbonization with 1.5–2°C pathways by increasing the cost of high-emission generation and rewarding low-carbon alternatives. However, the magnitude and timing of decarbonization depend on policy design and complementary measures. An ETS requires credible, tightening caps or credible price floors to ensure price signals consistently push investment toward low- and zero-carbon generation, while mitigating potential price volatility that can deter near-term investment without stabilizers.

A carbon tax provides price certainty that can guide long-term investment in low-carbon capacity and demand response, but its effectiveness depends on setting a sufficiently ambitious price path and on using revenue recycling and supplementary policies to address equity and technology-prioritization concerns. In practice, addressing the electricity decarbonization challenge requires a combination of policies: emissions pricing; demand-side measures such as efficiency standards, MEPS, and demand response; and incentives for low-carbon technologies and grid modernization to maintain reliability and cost-effectiveness. Empirical research and modeling suggest that carbon pricing alone may fall short of achieving decarbonization or lead to unfair outcomes if sector-specific complements are absent. Therefore, additional policies are vital for managing distributional effects and harnessing co-benefits such as better health and lower local pollution.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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