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Assessing the Sectoral Impact of Renewable Energy Adoption on CO_2 Emissions in the United States

Coolin-Campbell M. Zor*, Elvis Alade, Blanche Brinda Yougang, Charles Bom

Department of Economics and Finance, University of North Dakota, Grand Forks, North Dakota, USA.
*Email: coolincampbell.zor@und.edu

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ABSTRACT

This paper presents an assessment of renewable and fossil fuel consumption on CO_2 emissions of major polluting sectors in the United States using an Autoregressive Distributed Lag Error Correction Model (ARDL-ECM). The results show that renewable energy reduces emissions in the long-run, though short-run effects vary by sector due to integration challenges. The production and consumption of fossil fuels remain a dominant driver of emissions, particularly in the industrial, transportation, and electric power sectors. Energy prices also play a critical role: while higher electricity prices promote efficiency, elevated crude oil prices are associated with sustained emissions. Industry-specific dynamics emphasize the need for targeted policies such as investments in modernizing the grid, industrial energy efficiency and adoption of electric vehicles. While the renewable transition aligns with economic growth, ensuring equitable access and adapting the technology in the face of change is a daunting task. These results also highlight the importance of adaptive sectoral approaches that help align decarbonization objectives with economic sustainability, ensuring a just and effective energy transition in the United States.

Keywords: Renewable Energy, Fossil Fuels Consumption, CO_2 Emissions, Energy Transition, Electricity Generation, Energy Pricing
JEL Classifications: Q41, Q48, Q58

1. INTRODUCTION

There have been significant changes in the global energy market driven by multiple trends of democratization of energy systems, decarbonization of energy mix and transformations within the power generation sector. These shifts are resulting in new economic, social, and political dynamics (Chilukuri et al., 2023). As CO_2 emissions continue to rise, impacting air quality and climate conditions, it has become a major responsibility for nations to address these emissions while striving for sustainable economic growth. This is why it has been necessary to replace fossil fuels with renewable energy sources like geothermal, solar power, wind power or hydropower among others in order to mitigate emissions (Bilgili et al., 2024, Zohuri, 2017). According to Shanthi and Basavaraju (2024), wind energy has become a prominent renewable source, especially in states like Iowa, due to its cost-effectiveness and low carbon emissions. Iowa's leadership in wind energy not only stems from its cost-effectiveness but also its economic benefits, including \$72 million annually in lease payments to landowners, \$60.5 million in local property tax revenue in 2022, and \$22 billion in capital investment (Iowa Environmental Council, 2024).

In recent times, renewable energy has constituted a significant paradigm shift in energy systems, which includes changes in policies, and technologies, as a way of dealing with the environmentally and economically based problems. Such improvements in the generation of sources such as solar, wind, hydroelectric and biomass, which provide fuels with lower levels of pollution have taken a leap, in both developed and developing world energy sectors (Ye et al., 2023; Ramelan et al., 2022). Renewable energy has had a significant impact on reducing greenhouse gas emissions, as it provides a cleaner alternative to fossil fuel-based power sources that are major contributors to

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CO_2 emissions (Uzondu and Lele, 2024, Bashiru et al., 2024). Although we often speak about the environmental achievements associated with renewable energy resources, there seems to be a lack of information about the positive impacts of this transition on the economy, particularly at industry level.

Advancing cleaner forms of energy has an impact on all of these: emission levels, ability to create jobs, provision of energy services and investment in energy infrastructures within an economy (Adanma and Ogunbiyi 2024). The U.S. federal government has incorporated the development of renewable energy systems as part of the country's energy policy, strongly advocating for reduction carbon emissions through various strategies, stressing the adoption of the eco-friendly energy production and consumption, and creating green energy plants with artistic improvements (IEA, 2023). Policies such as the Bipartisan Infrastructure Law (BIL) and Inflation Reduction Act of 2022 (IRA) are key drivers in financing large scale renewable projects (Wang et al., 2024). Through investors efforts, the U.S. is achieving economic growth with fewer emissions as high-emission sectors transition to low-carbon electricity sources (Zuhal and Göcen, 2024). By shifting heavily polluting industries into renewable energy sources, the United States can mitigate its emissions while supporting economic expansion (Bunnag, 2023; Golpîra et al., 2023).

According to the 2022 U.S. Greenhouse Gas (GHG) inventory, CO_2 is responsible for about 80% of all emissions in the U.S., methane emission is about 11%, nitrous oxide is around 6%, with fluorinated gases contributing 3%, showing the dominance of CO_2 as compared to other agents of climate change (EPA, 2024). The data highlights the importance of focusing all management strategies towards this pollutant in order to move towards a green economy, considering fossil fuels constituted 60% of all U.S. electricity generated in 2023 (EIA, 2024a, EIA, 2024b). As opposed to fossil fuels, renewables do not emit CO_2 during electricity production, thus offering an alternative that helps mitigate the carbon footprint of energy generation (Ustun, 2024; Paraschiv and Spiru, 2023). There is no doubt that as more renewable energy gets integrated into energy systems across the globe, they would serve as a direct pathway through which CO_2 emissions can be reduced, hence, playing an important role in supporting climate change mitigation efforts as well as aligning with national and global emission targets (Marouani, 2024; Kamau, 2024).

To overcome challenges and promote sustainable energy practices, the U.S. has implemented Renewable Portfolio Standards and carbon pricing mechanisms, alongside offering subsidies and incentives to encourage the adoption of renewable energy projects and reduce CO_2 emissions (Mudaliyar et al., 2022; Basseches, 2024). State-level Renewable Portfolio Standards (RPS) mandate utilities to source a percentage of their electricity from renewables, which has helped drive market growth in states with robust RPS targets such as Texas and California (Zhou et al., 2024; Ma and Xu, 2022). The United States consider the deployment of renewable power technologies like hydroelectricity, solar and wind power among its main objectives to promote sustainable economic growth, enhance energy security while mitigating greenhouse gas emissions (EIA, 2023).

Renewable energy has produced a great deal of electricity production in the United States in recent years. This high volume of production is also due to infrastructural expansion which is a direct outcome of technological advancement, government policies supporting clean energy development, and continual reduction of costs associated with these systems. For example, in 2023, renewables including solar, wind, hydro, and more lately, geothermal and biomass, contributed 21% of the total electricity generated in the U.S. in 2023, representing 894 billion kWh of the entire 4.18 trillion kWh produced. (US Department of Energy, 2024b, EIA, 2024c, EPA, 2024). Wind energy accounted for about 50% of this total at 10% while solar accounts for about 4% (EIA, 2024c; EIA, 2024a), and these figures are growing rapidly due to large-scale projects and residential installations. Wind power alone helped the U.S. prevent about 348 million metric tons of CO_2 emissions, an amount equal to more than 76 million vehicles kept off the road and contributed to more than 120,000 jobs across the country in 2023 (American Clean Power, 2024). The renewable energy sector is also one of the fastest-growing job markets in the U.S., with wind turbine technician positions projected to increase by 60.1% and solar photovoltaic installer roles by 48% by 2033 (US Bureau of Labor Statistics, 2024). In this context, it thereby provides an important contribution to achieving the national and international climate goals by reducing the carbon intensity of the energy sector. Transitioning to more renewables is not only an essential strategy towards lower levels of greenhouse gases but also backs up creating a more reliable and enduring power system pacing for a world characterized by lasting nature-oriented goals (Rahman et al., 2024). The successful transition to renewable energy is often hindered by regional disparities in resource availability, infrastructure readiness, and political will, which can further complicate efforts to achieve long-term sustainability goals.

The U.S. transport sector was the highest emitter of greenhouse gas emissions in 2022 with 28%, closely followed by the electric power sector with 25%, the industrial sector emitting 23%, residential and commercial sectors combined emitted 13%, while the agricultural sector accounted for 10% - all these sectors together accounted for 6,343.2 million metric tons of CO_2 equivalent (EPA, 2024). This breakdown only serves to emphasize the overwhelming influence that both the transportation and electric power sectors have on generating U.S. greenhouse gas emissions, with the two sectors accounting for over half the entire emitted gases (53%). Most CO_2 emissions in the transportation sector are produced through direct combustion of gasoline and fossil fuels (Traver et al., 2022; Sperling et al., 2020; Long et al., 2022). Reduction in emissions of greenhouse gases in these sectors will be made possible by a shift mainly to clean energy, such as electric cars fueled by renewable sources and a larger network of renewable energy; making dependence on fossil fuels that contribute to CO_2 levels decrease (Woodle et al., 2024; Michaelides et al., 2023). Consequently, in order to drive through, the Bi-partisan Infrastructure Law (BIL) has seen a huge investment from the federal government towards projects on electric vehicle charging systems, making the grid current and expanding alternative sources of power, paving way for cleaner and more shock-resistant energy in future years.

Different economic, technological and regulatory issues slow down the development of renewable energy around the world. The immense costs of renewable energy infrastructure, such as wind turbines, solar panels as well as battery storage systems, are a major challenge especially to communities without structured means of funding (Uzondu and Lele, 2024; Agrawal et al., 2024; Rehman et al., 2024). Although federal tax credits provide some relief, their varying magnitudes across states create disparities in energy access, particularly in rural and low-income regions. Solar and wind power require better energy storage and grid modernization to compete nationally. However, limited domestic rare earth elements, essential for energy storage and efficiency, increase reliance on China, especially for photovoltaic cells (Kumar and Rathore, 2023; Painuly and Wohlgemuth, 2021). Additionally, there is the issue of "Not In My Back Yard" (NIMBY) sentiment, with locals resistance against initiatives like wind turbine projects that include transmission lines on account of their aesthetics, noise or environmental pollution levels (Muzho, 2024; Juszczyk et al., 2022; Azarpour et al., 2022).

The current U.S. grid was not intended to deal with distributed renewables at a large scale, which poses challenges both logistically and financially in extending it to remote areas with abundance of renewable resources (Singh and Singh, 2024; Valova and Brown, 2022). Most times, green power projects experience long periods of stoppage due to complex permitting procedures and divergent regulations from one state to another whereas constant changes in federal assistance influence how doable the project is (Barceló et al., 2023). This is achievable through removing bureaucratic barriers and fostering innovation in technology around renewables as is done presently. Streamlining of policies; strategic investments; and innovative technology are crucial to transition from fossil fuels to cleaner renewable forms of electricity production and emissions reduction at large (Hammed et al., 2024).

CO_2 emissions and economic growth have a complicated and mutually-dependent relationship, with rapid industrial and economic growth usually resulting in increased energy usage as well as fossil fuel combustion that increases greenhouse gases (Utomo et al., 2024; Gbadeyan et al., 2024). Emissions pose threats to economic prosperity because they accelerate global warming hence causing more severe weather patterns, higher healthcare expenditure and possible interruptions in power generation and distribution systems. In addition, impacts on economy related to weather resulting from climate change on destruction of infrastructure, crop failure or increased insurance premiums may stretch financial resources of government and business organizations thereby leading to possible deceleration of the overall economic growth rate (Topa, 2024; Fu, 2023).

While there has been considerable analysis of the relationship between energy use and CO_2 emissions, sector-level analysis, both in the U.S. and worldwide, remains sorely lacking. Most studies do not consider how the consumption of different kinds of renewable and fossil fuels differ in their impact on emissions across sectors with different energy needs and pathways of transition, aside from general economy-wide trends (Efe-Onakpojeruo et al., 2024; Mehedintu and Soava, 2024; Xuan, 2024; Jie and Khan, 2024; Caldera et al., 2024). Such lack of disaggregated analysis breeches the question of how and how much each policy should be tailored in order to optimize emissions reductions and minimize economic disruptions. Filling this gap, this study provides a comprehensive sectoral analysis of the energy emissions nexus to understand in what ways renewable energy sources and fossil fuels shape the emissions dynamics across energy sectors. Sector-specific approaches will also be key to establishing evidence-based policies that truly balance economic stability and environmental sustainability.

This study investigates how renewable and fossil fuel consumption affect CO_2 emissions across sectors in the United States, with an emphasis on their broader implications for the entire economy. Although transportation and electric power generation have been the primary sources of emissions for decades due to their heavy reliance on fossil fuels, most studies have been concerned with aggregate trends, instead of what's happening in different sectors. This gap makes it harder to develop targeted strategies for reducing greenhouse gases like CO_2, particularly in sectors that contribute the most to emissions. This paper also considers the effect of renewable energy on economic variables such as fuel prices and competitiveness in markets (OPEC[1] and domestic crude oil markets), which are crucial factors in shaping a sustainable energy transition. As the world transitions away from non-renewable resources such as coal and crude oil and embraces new technologies such as carbon capture and storage (CCS), this study contributes to existing literature by showing how renewables can drive emissions reductions and strengthen economic resilience across sectors.

2. DATA AND METHODOLOGY

We sourced the data for this study from the U.S. Energy Information Administration[2] (EIA), except for Real GDP data, which was obtained from S&P Global Market Intelligence's Monthly GDP Index[3] database. The analysis utilizes monthly time series data from January 1992 to August 2024 across all sectors (392 observations), except for the transportation sector, which spans January 1992 to March 2022 due to missing or unrecorded variables, resulting in 363 observations. This dataset covers energy consumption, CO_2 emissions, and energy prices across renewable and fossil fuel sources in various sectors. With 392 observations per variable for most sectors, the dataset offers a strong temporal foundation, enhancing the reliability of the findings. The selected variables provide a detailed assessment of sectoral energy consumption patterns, long-term emission trends, and the economic effects of renewable energy adoption within the U.S. energy landscape.

1 The Organization of the Petroleum Exporting Countries
2 https://www.eia.gov/totalenergy/data/browser/
3 https://cdn.ihsmarkit.com/www/default/1020/US-Monthly-GDP-History-Data.xlsx

The study considered variables related to energy consumption, CO_2 emissions, and energy prices, as they are fundamental to understanding the relationship between energy use, economic activity, and environmental outcomes. Energy use, being largely captured by the quantities of renewable and fossil fuel consumption, provides a view of primary energy demands and transition towards cleaner energy. CO_2 emissions, as the dependent variable, measure the environmental effects of energy consumption and provide a direct instrument for evaluation. To capture the impact of energy price variation on emissions and energy consumption choices, we integrate various energy price indicators, that is, energy prices are important for understanding how economic factors affect energy consumption patterns, fuel substitution, and the adoption of renewable technologies. These variables form a strong foundation for analyzing sector-specific factors influencing CO_2 emissions. U.S. Gross Domestic Product (GDP) is included as a key measure of economic activity but is only applied in the analysis of the entire economy. It provides a macroeconomic context for energy consumption and emissions trends, helping to assess how economic performance affects overall energy use and emissions. By incorporating GDP, the model captures the broader economic implications of renewable energy adoption at the national level.

The Autoregressive Distributed Lag Error Correction Model (ARDL-ECM) technique is employed as the variables exhibit variable exhibit mixed integration order with some stationary at level *I(0)* while others are non-stationary at *I(1)*, with none are *I(2)*. The ARDL-ECM framework effectively captures both short-term fluctuations and long-term equilibrium relationships, making it suitable for assessing how renewable energy adoption, fossil fuel consumption, economic activity, and crude oil prices influence CO_2 emissions. Recognizing that emissions do not react instantaneously to changes in energy and economic determinants, the model includes an error correction term (ECM) to assess the speed of return to convergence of emissions after a given shock. This captures both immediate and gradual effects of energy policies, renewable energy growth, and fossil fuel changes by including lagged variables. This allows ARDL-ECM to be an appropriate framework for modeling both the short-run and long-run effects of energy utilization on emissions.

To determine the appropriate lag length for the ARDL-ECM model, the study employs the VAR Lag Order Selection Criteria (VARSOC), which evaluates optimal lag lengths based on multiple statistical criteria, including the Akaike Information Criterion (AIC), Schwarz Bayesian Criterion (SBIC), and Hannan-Quinn Criterion (HQIC). While VARSOC offers a guide for lag selection, as during the prior step, the final lag structure in each sectoral analysis was not strictly reliant on the recommendations provided by VARSOC. Diagnostic problems such as heteroskedasticity, serial correlation, model misspecification or omitted variable bias would sometimes occur when the proposed lag length was used. In such cases, different lag structures were tested to make sure of "strong" estimation of the model, and the specification selected was the one that passed the relevant diagnostic tests but remained consistent with economic theory. This adaptive method made the most accurate estimation of the influence of renewable and fossil fuel consumption on CO_2 emissions in various sectors.

The ARDL-ECM framework used in this study is represented by the following equations, capturing both the long-run equilibrium (1) and short-run dynamics with error correction (2):

$$lnCO_{2,t} = a_0 + \sum d_j X_t + e_t \tag{1}$$

$$\Delta lnCO_{2,t} = a_0 + \sum_{i=1}^{p} \beta_i \Delta lnCO_{2,t-i} + \sum_{j=0}^{q} \gamma_j \Delta X_{t-j} + \lambda ECM_{t-1} + \varepsilon_t \tag{2}$$

where $InCO_{2,t}$ is the natural logarithm of CO_2 emissions at time *t*, serving as the dependent variable in both long-run and short-run equations; X_t includes log of key independent variables such as renewable energy consumption and fossil fuel consumption; δ_j. represents the long-run elasticities; $\Delta InCO_{2,t}$ represents the change in log of total CO_2 emissions; $\Delta InCO_{2,t-1}$ denotes the log of the first-differenced dependent variable, CO_2 emissions, lagged by *i* periods, capturing short-run fluctuations in emissions over time; ΔX_{t-j} represents the log of first-differenced explanatory variables at time *t-j*, capturing short-run changes in renewable energy consumption, fossil fuel consumption, energy prices, economic activity, and other sector-specific factors; α_0 is the intercept term; β_i and γ_j capture short-run effects of CO_2 emissions and explanatory variables; λ is negati and significant, indicating the presence of long-run equilibrium correction; ECM_{t-1} is the error correction term, showing how fast emissions return to equilibrium after a shock; and ε_t is the error term.

This ARDL-ECM model is applied consistently across all sectors to analyze the determinants of CO_2 emissions. While the fundamental framework remains unchanged, the specific variables included vary by sector to capture the unique energy consumption patterns, price dynamics, and economic activities driving emissions in each case.

Table 1 outlines the key explanatory variables used to analyze CO_2 emissions across sectors, capturing differences in energy consumption, pricing, and economic factors. Each sector has unique drivers, such as seasonal energy demand in residential and commercial sectors, electricity generation in the electric power sector, and fuel prices in transportation and industry. This breakdown supports a detailed examination of how energy use impacts emissions in each sector.

3. RESULTS AND DISCUSSIONS

Table 2 shows summary statistics of CO_2 emissions, energy consumption and price-related characteristics for each sector in the U.S. As expected, the highest CO_2 emissions are apparent in the transport (5.023) and electric power (5.103) sectors due to their dependence on fossil fuels. Residential (4.472) and commercial (4.337) have lower emissions, due to greater reliance on electricity, consistent with findings in Nejat et al., 2015. The highest renewable energy consumption rate is seen in the industrial (5.155) and electric power (5.038) sectors, with lower adoption in the commercial (2.502) and transportation (3.558) sectors, which rely heavily on

Table 1: Sector-Specific Variables in the ARDL-ECM Model

Sector	Key explanatory variables
All Sectors (Entire Economy)	CO_2 Emission Total, Renewable Energy Consumption Total, Fossil Fuel Consumption Total, Real GDP, Electricity Price Total, Domestic Crude Oil Cost.
Residential	CO_2 Emission, Renewable Energy Consumption, Fossil Fuel Consumption, Average Electricity Price, Price of Natural Gas, Heating Degree Days, Cooling Degree Days.
Commercial	CO_2 Emission, Renewable Energy Consumption, Fossil Fuel Consumption, Average Electricity Price, Price of Natural Gas, Heating Degree Days, Cooling Degree Days.
Electric Power	CO_2 Emission, Renewable Energy Consumption, Fossil Fuel Consumption, Net Generation of Electricity, Natural Gas Receipts at the Electric Generating Plants, Price of Natural Gas at the Electric Generating Plants, Electricity Sales.
Industrial	CO_2 Emission, Renewable Energy Consumption, Fossil Fuel Consumption (Linear & Squared), Net Generation of Electricity, Average Electricity Price, Price of Natural Gas.
Transportation	CO_2 Emission, Renewable Energy Consumption, Fossil Fuel Consumption, Domestic Crude Oil Cost, OPEC Crude Oil Cost, Non-OPEC Crude Oil Cost, Price of Motor Gas, Price of Diesel Fuel.

The variables listed are specific to each sector and are included based on their relevance to the CO_2 emissions dynamics within that sector. Units of measurement are provided in Appendix A1

Table 2: Summary statistics of key variables

Variable	All sectors	Residential	Commercial	Electric power	Industrial	Transportation
CO_2 Emissions Total	6.110 (0.097)	4.472 (0.243)	4.337 (0.148)	5.103 (0.205)	4.879 (0.112)	5.023 (0 0.079)
Renewable Energy Consumption Total	6. 100 (0.283)	3.854 (0.167)	2.502 (0.285)	5.038 (0.320)	5.155 (0.158)	3.558 (1.139)
Fossil Fuel Consumption Total	8.802 (0.080)	6.010 (0.689)	5.729 (0.437)	7.605 (0.167)	7.404 (0.066)	7.663 (0.076)
Real GDP	9.684 (0.222)	-	-	-	-	-
Electricity Price Total	2.174 (0.212)	2.362 (0.219)	2.227 (0.174)	-	1.782 (0.200)	-
Crude Oil Cost, Domestic	3.669 (0.711)	-	-	-	-	3.611 (0 0.706)
Crude Oil Cost, OPEC	-	-	-	-	-	3.682 (0.700)
Crude Oil Cost, Non-OPEC	-	-	-	-	-	3.628 (0.653)
Natural Gas Price	-	2.379 (0.356)	2.070 (0.287)	1.373 (0.444)	1.497 (0.371)	-
Heating Degree Days	-	5.039 (1.676)	-	-	-	-
Cooling Degree Days	-	3.933 (1.392)	-	-	-	-
Electricity Net Generation	-	-	0.206 (2.300)	5.732 (0.133)	2.501 (0.070)	-
Natural Gas Receipts at the Electric Generating Plant	-	-	-	1.344 (0.440)	-	-
Electric Sales Total	-	-	-	5.680 (0.131)	-	-
Price of Motor Gas	-	-	-	-	-	0 0.673 (0 0.436)
Price of Diesel Fuel	-	-	-	-	-	0 0.243 (0 0.644)

The table reports mean values with standard deviations in parentheses for key variables across U.S. sectors. CO_2 emissions, energy consumption, and pricing trends vary significantly, reflecting sector-specific energy dependencies. The data highlights differences in fossil fuel reliance, renewable energy adoption, and electricity pricing, underscoring the need for targeted energy policies.

infrastructure and fuel. Fossil fuel consumption remains prevalent in transportation (7.663), electric power (7.605), and industry (7.404), with more stable usage patterns across sectors.

Residential sector electricity prices are highest (2.362), while they are lowest for industrial users (1.782), reflecting cost structures and consumption patterns. The electric power sector ranks first in both electricity generation (5.732) and sales (5.680). Prices for crude oil and natural gas vary sector by sector, but we see natural gas prices on the higher end in residential sector (2.379) and lower in electric power sector (1.373).

In Table 3, we provide the ARDL-ECM estimates of CO_2 emissions across all sectors using two distinct model specifications, with model 2 including an interaction term between renewable energy consumption and real gross domestic product (GDP). The long-run renewable energy consumption coefficient has a negative value (-0.154) in model 1, indicating that increasing renewable energy

Table 3: ARDL-ECM estimates for CO_2 emissions across all sectors (entire economy)

Variables	(1)		(2)	
	Short Run	Long Run	Short Run	Long Run
Renewable Energy Consumption	0.010**	−0.154***		3.648***
	(0.005)	(0.056)		(0.630)
Fossil Fuel Consumption	0.919***	−2.202	0.780***	−0.260
	(0.015)	(1.466)	(0.052)	(0.488)
Real GDP		0.1989		2.357***
		(0.140)		(0.396)
Electricity Price Total, All Sectors		−19.011**	−0.611**	−7.221***
		(7.86)	(0.256)	(2.418)
Crude Oil Cost, Domestic	0.006**	5.285**	0.174**	2.044***
	(0.003)	(2.042)	(0.075)	(0.633)
Interaction between Fossil Fuel Consumption &		−0.593**	−0.019**	−0.229***
Domestic Crude Oil Cost		(0.231)	(0.009)	(0.072)
Interaction between Fossil Fuel Consumption &	0.018***	2.112**	0.087***	0.809***
Electricity Price	(0.001)	(0.877)	(0.029)	(0.272)
Interaction between Renewable Energy Consumption &			0.001*	−0.387***
Real GDP			(0.000)	(0.064)
Error Correction Term (ECM_{t-1})	−0.045***		−0.107***	
	(0.015)		(0. 024)	
Constant	1.106***		−1.464**	
	(0.345)		(0.726)	
Bounds Test (F-Test)	10.935 (0.000)		10.039 (0.000)	
Breusch–Godfrey LM Test	0.621 (0.431)		0.556 (0.456)	
Breusch–Pagan Test	2.320 (0.128)		2.310 (0.129)	
Ramsey RESET Test	2.070 (0.103)		1.940 (0.122)	
Observations	390		391	
Adjusted R^2	0.995		0.995	

The two models (1) and (2) represent different specifications of the ARDL-ECM framework. Statistical significance is denoted as follows: ***Significant at the 1% level, **Significant at the 5% level, *Significant at the 10% level

consumption leads to emissions reduction as evidenced in its negative correlation with CO_2 emissions (−0.499) in Appendix A2 however, in model 2, where the interaction term is added, the long-run coefficient of renewable energy becomes statistically significant and positive at 3.648, suggesting that lower emissions from renewables can only be determined after controlling for GDP effects. This change indicates that the mitigation effect of renewables is dependent on economic growth. Notably, GDP is not significant in model 1 but is a main driver of emissions in model 2 where a 1% increase in GDP increases emissions by 2.36%, which corroborates the energy-consuming nature of economic growth. Fossil fuel consumption remains a dominant emissions driver in the short run, increasing CO_2 emissions by 0.92% and 0.78% in both models, which aligns with its strong positive correlation with emissions (0.910) in Appendix A2, but their long-run effects are not statistically significant.

Energy price dynamics also shape emissions trends. The results indicate that electricity prices have a strong impact on emissions, with a 1% increase in electricity price resulting in 19.01% and 7.22% reduction in emissions in both models, reflecting demand-side adjustments. The impact of U.S. crude oil prices domestically on emissions, however, is notable, as a 1% increase in crude oil prices led to a 5.29% and 2.04% increase in emissions across both models, indicating that higher crude prices may not necessarily curb emissions, possibly due to continued reliance on fossil fuel-based energy sources or shifts to alternative high-emission fuels. The long run effect of interaction between fossil fuel consumption and domestic crude oil prices has been found to be negative (-0.593 and -0.229), suggesting that as crude prices increase, fossil fuel usage decreases, thereby decreasing emissions. On the other hand, the interaction between fossil fuel use and electricity prices is positive (2.112% and 0.809%) in both models, indicating that higher electricity costs could lead to higher emissions as a constraint of production. Notably, the interaction between renewable energy consumption and GDP in model 2 is negative and statistically significant (−0.387), suggestive of better emission reduction outcomes at higher rates of economic growth, with possibly more efficient provisions of renewables through improvements in the level of technology. The ECM terms highlights a 4.5% and 10.7% correction of short-run imbalances per period. Diagnostics confirm model validity, with no serial correlation, heteroscedasticity, or specification errors at the 1% level. Results suggest renewable energy's emissions-reducing impact strengthens with economic growth, implying the need for balanced energy policies.

Table 4 presents ARDL-ECM estimates for CO_2 emissions in the residential sector in two models. Over the short run, a 1% increase in fossil fuel consumption leads to rises in CO_2 emissions of 0.80% in model 1 and 0.77% in model 2, providing further support for fossil fuel consumption as the primary driver of emissions, , which confirms its moderate positive correlation with emissions (0.611) in Appendix A3; however, it has no significant long-run effect, indicating that long-run changes in energy consumption patterns may limit its impact. The long-run coefficient for renewable energy in model 2 (6.856) is counterintuitive, indicating that at lower rates of adoption renewables do not effectively displace fossil fuels, possibly due to integration inefficiencies or dependence on backup energy sources, however, the squared term for renewable

Table 4: ARDL-ECM Estimates for CO_2 Emissions in the Residential Sector

Variables	(1)		(2)	
	Short Run	Long Run	Short Run	Long Run
Renewable Energy Consumption	0.042	0.020	0.044	6.856***
	(0.052)	(0.091)	(0.053)	(2.289)
Renewable Energy Consumption Squared				-0.885***
				(0.296)
Fossil Fuel Consumption	0.801***	−0.196	0.765***	−0.054
	(0.038)	(0.138)	(0.039)	(0.104)
Average Electricity Price	−1.023***	−0.956***	−0.986***	−0.929***
	(0.182)	(0.117)	(0.185)	(0.099)
Price of Natural Gas	0.470***	0.558***	0.460***	0.557***
	(0.069)	(0.069)	(0.068)	(0.059)
Heating Degree Days	−0.181***	0.355***	−0.165***	0.264***
	(0.010)	(0.080)	(0.010)	(0.060)
Coolin Degree Days		0.099**		0.065*
		(0.042)		(0.034)
Error Correction Term (ECM_{t-1})	−0.268***		−0.313***	
	(0.028)		(0.030)	
Constant	1.159***		−2.870**	
	(0.212)		(1.403)	
Bounds Test (F-Test)	34.728 (0.000)		29.617 (0.000)	
Breusch–Godfrey LM Test	0.115 (0.735)		1.295 (0.255)	
Breusch–Pagan Test	0.160 (0.686)		0.500 (0.479)	
Ramsey RESET Test	0.950 (0.414)		0.400 (0.751)	
Observations	389		389	
Adjusted R^2	0.936		0.937	

The two models (1) and (2) represent different specifications of the ARDL-ECM framework. Statistical significance is denoted as follows: ***Significant at the 1% level, **Significant at the 5% level, *Significant at the 10% level

energy consumption is highly significant and negative (-0.885), meaning that emissions will fall faster over time as you consume more renewable energy, corresponding to its negative correlation (−0.392) with CO_2 emissions in Appendix A3. In the short run, it does not matter how much renewable energy is consumed, but in model 2, the squared term for the consumption is highly significant and negative (-0.885), implying that emissions will fall faster over time as we consume more renewable energy.

Energy pricing is another crucial factor. A 1% increase in the price of electricity causes emissions to decrease by 1% in both models for the short run, with similar effects in the long run, suggesting that higher prices for electricity promote conservation and efficiency. On the other hand, a 1% increase in the price of natural gas results in emissions increases of 0.47% and 0.46% in the short run and approximately 0.56% in the long run, demonstrating fuel-switching effects where households switch to more carbon-intensive alternatives. Temperature fluctuations also play a key role in energy consumption — heating degree days have a significant positive effect on emissions with 0.35% and 0.26% in the long run in both models but reduces emissions in the short run in both models by 0.18% and 0.17%, reflecting the higher energy demand in colder months; cooling degree days have a significant positive effect as well, but the effect has a smaller positive impact in the long run across both models. The ECM□□□ is negative and confirms a stable long-run relationship, with 26.8% to 31.3% of short-run deviations corrected each period. A series of diagnostic tests demonstrates that the models are well specified, and there are no signs of serial correlation, heteroscedasticity or omitted variables.

In the commercial sector (Table 5), renewable energy use has a mixed impact on CO_2 emissions. In model 1, a 1% increase in renewable energy consumption will decrease emissions by 0.25% in the long run, further underscoring its emissions mitigation capacity as reflected in its negative correlation with CO_2 emissions (−0.495) in Appendix A4, but then, increases emissions by 0.52% in the short run. However, in model 2, the inclusion of the squared term of renewable energy consumption results in renewable energy raising emissions by 2.37% whiles the squared term reduces CO_2 emissions by 0.50%, indicating that while early-stage adoption may contribute to emissions, expanded use eventually offsets this impact. Consumption of fossil fuels is a significant emissions driver, with a 1% increase leading to an increase of 0.38% and 0.37% emissions in the short run and 0.21% and 0.19% emissions in the long run across both models, reinforcing the sector's dependence on fossil fuels, consistent with its positive correlation (0.279) with emissions in Appendix A4. Electricity prices show two sided effects, leading to increased emissions in the short run and a decrease in the long run by 0.29% and 0.36% respectively, meaning strengthening efficiency or consuming less due to cost increase. Higher natural gas prices are also associated with higher emissions over the long term, implying a shift toward environmentally unfriendly energy substitutes.

The corresponding ECM terms are shown to correct 36.7% and 44% of the imbalances in the short-run per period, an intermediate speed of adjustment towards equilibrium. Three tests (the Durban Watson test, Breusch-Pagan test, and Ramsey RESET test) for the model stability confirms that it is stable and not subject to serial correlation, heteroscedasticity or model misspecification. Such findings underscore the importance of policies to facilitate the integration of renewable energy and reduce the commercial sector's reliance on fossil fuels.

Table 5: ARDL-ECM Estimates for CO_2 Emissions in the Commercial Sector

Variables	(1)		(2)	
	Short Run	Long Run	Short Run	Long Run
Renewable Energy Consumption	0.521***	−0.252***		2.372***
	(0.052)	(0.055)		(0.406)
Renewable Energy Consumption Squared			0.100***	−0.497***
			(0.010)	(0.076)
Fossil Fuel Consumption	0.378***	0.207***	0.365***	0.186***
	(0.020)	(0.033)	(0.019)	(0.026)
Average Electricity Price	0.945***	−0.293**	0.937***	−0.364***
	(0.172)	(0.118)	(0.164)	(0.096)
Price of Natural Gas		0.301***		0.339***
		(0.042)		(0.034)
Error Correction Term (ECM_{t-1})	−0.367***		−0.440***	
	(0.031)		(0.032)	
Constant	1.395***		0.263	
	(0.155)		(0.240)	
Bounds Test (F-Test)	36.332 (0.000)		38.695 (0.000)	
Breusch–Godfrey LM Test	1.425 (0.233)		0.122 (0.726)	
Breusch–Pagan Test	0.050 (0.824)		0.190 (0.667)	
Ramsey RESET Test	1.200 (0.310)		1.790 (0.148)	
Observations	390		390	
Adjusted R^2	0.708		0.735	

The two models (1) and (2) represent different specifications of the ARDL-ECM framework. Statistical significance is denoted as follows: ***Significant at the 1% level, **Significant at the 5% level, *Significant at the 10% level.

Table 6: ARDL-ECM Estimates for CO_2 Emissions in the Electric Power Sector

Variables	(1)		(2)	
	Short Run	Long Run	Short Run	Long Run
Renewable Energy Consumption	0.028***	−0.088**	−0.281**	0.545
	(0.008)	(0.040)	(0.109)	(0.364)
Renewable Energy Consumption Squared			0.031***	−0.064*
			(0.011)	(0.038)
Fossil Fuel Consumption	0.846***	1.403***	0.827***	1.330***
	(0.021)	(0.095)	(0.023)	(0.102)
Net Generation of Electricity		−1.364***		−1.207***
		(0.258)		(0.235)
Natural Gas Receipts at the Electric Generating Plants	0.028***	0.035	0.029***	0.143
	(0.003)	(0.259)	(0.003)	(0.229)
Price of Natural Gas at the Electric Generating Plants		−0.019		−0.124
		(0.259)		(0.229)
Electricity Sales		0.797***		0.702***
		(0.231)		(0.197)
Error Correction Term (ECM_{t-1})	−0.162***		−0.188***	
	(0.020)		(0.024)	
Constant	−0.301***		−0.607***	
	(0.067)		(0.194)	
Bounds Test (F-Test)	15.978 (0.000)		15.030 (0.000)	
Breusch–Godfrey LM Test	1.285 (0.257)		0.657 (0.418)	
Breusch–Pagan Test	1.370 (0.242)		0.940 (0.333)	
Ramsey RESET Test	1.670 (0.173)		1.760 (0.154)	
Observations	390		390	
Adjusted R^2	0.994		0.994	

The two models (1) and (2) represent different specifications of the ARDL-ECM framework. Statistical significance is denoted as follows: ***Significant at the 1% level, **Significant at the 5% level, *Significant at the 10% level

Table 6 shows ARDL-ECM estimates for CO_2 emissions in the electric power sector for two models. The heavy dependence on fossil fuels in the sector is also reflected in both the short and long term, where in the short run, a 1% increase in fossil fuel consumption leads to a 0.85% and 0.83% increase in CO_2 emissions, whereas a 1% increase in fossil fuel consumption yields an increase in CO_2 emissions by 1.33% and 1.40% in the long run, which is strongly affirmed by its very high correlation with emissions (0.929) in Appendix A5. Renewable energy consumption has a mixed impact. Model 1 demonstrates a positive effect, as a 1% rise in renewables leads to a short-run increase of 0.028% in emissions, yet a long-run decrease of 0.088%, aligning with the negative correlation between renewables and CO_2 emissions (−0.662) in Appendix A5, hence, suggesting transitional inefficiencies prior to the reductions having an effect. In contrast, in model 2, we observe a short-term emissions decrease of 0.28%, while the long-run effect turns statistically insignificant, implying renewables capacity to reduce emissions depend on integration into the grid and the disruption of other sectors. The square term of renewable energy in model 2 indicates 'diminished' returns in the short-run (0.031), but rather 'increased' returns in the long-run (-0.064).

An increase in net electricity generation of 1% decreases emissions in model 1 (-1.36%) and model 2 (-1.21%), representing improvements in efficiency or a cleaner energy mix. On the other hand, electricity sales lead to long-term emissions, considering a 1% increase in electricity sales results in a 0.70% and 0.80% increase in CO_2 emission due to the increased electricity demand being met by fossil fuel sources. An increase in natural gas receipts at power plants raises emissions somewhat in the short-run, while gas prices have no significant effect. The long-run adjustment is confirmed by negative error correction terms (-0.162 and -0.188), implying corrections of 16.2% to 18.8% per period. The reliability of the model is confirmed by diagnostic tests which reveal no serial correlation, heteroscedasticity or omission of variables.

Table 7 displays ARDL-ECM estimates for the industrial sector's CO_2 emissions across two models. In both models, fossil fuel consumption is a key CO_2 emissions contributor in the long run with a 1% increase leading to a 5.98% and 6.46% increase in CO_2 emissions in both models, which detracts from the sector dependency status in conventional energy sources, a relationship as shown in its positive correlation with CO_2 emissions (0.501) in Appendix A6. Regarding renewable energy consumption, there is no short-run significant impact, but in both models a 1% increase in the use of renewable energy leads to emissions reduction in long-run by 0.25% to 4.16%, illustrating its potential role in decarbonization of CO_2 emissions, as observed in its negative correlation with CO_2 emissions (−0.562) in Appendix A6. The second model adds a squared term for renewables, which is positive but not statistically significant, implying that emissions-reduction benefits do not accelerate at very high levels of adoption in the industrial sector.

Electricity prices are characterized by sizeable, short-run and long-run effects. A 1% increase in the price of electricity decreases emissions by about 3.04% to 3.06% in the short run, which we attribute to demand-side reductions or efficiency improvements. Over time, higher prices correlated with 23.63% to 25.58% higher emissions, reflecting industries transitioning to alternative high-carbon energy sources. The interaction between electricity prices and fossil fuel consumption is also significant: A 1% increase in electricity prices increases fossil fuel consumption by 0.44% in the short run (in both models) but decreases CO_2 emissions by 3.23% to 3.49% in the long run, indicating a lag in the transition to cleaner alternatives. The error correction term varies from -0.087 to -0.090, indicating that 8.7% to 9.0% of disequilibrium is corrected in each period, reflecting a moderate rate of adjustment toward equilibrium. Robust estimates are confirmed through diagnostic tests that indicate no model stability issues, such as serial correlation, heteroscedasticity, or specification errors (at least, at 5% significance level).

Table 8 shows results from ARDL-ECM for CO_2 emissions in the transportation sector. In the short run, both models show that a 1% increase in the consumption of renewable energy leads to an increase in the emissions by 0.17%, which indicate that short-term dependence on biofuels or transitional inefficiencies increase emissions, a finding that mirrors the moderate positive correlation (0.305) between renewable energy use and emissions reported in Appendix A7. In the long run, however, renewable energy has

Table 7: ARDL-ECM estimates for CO_2 emissions in the industrial sector

Variables	(1)		(2)	
	Short Run	Long Run	Short Run	Long Run
Renewable Energy Consumption		−0.253**		−4.158
		(0.124)		(3.624)
Renewable Energy Consumption Squared				0.384
				(0.355)
Fossil Fuel Consumption		5.975**		6.464***
		(2.399)		(2.448)
Net Generation of Electricity	0.112***	0.307	0.113***	0.338
	(0.022)	(0.242)	(0.022)	(0.237)
Average Electricity Price	−3.056***	23.625**	−3.035***	25.581***
	(0.122)	(9.572)	(0.124)	(9.775)
Price of Natural Gas	0.033***	0.045	0.032***	0.059*
	(0.009)	(0.034)	(0.009)	(0.038)
Interaction between Electricity Price & Fossil Fuel Consumption	0.442***	−3.226**	0.438***	−3.491***
	(0.018)	(1.283)	(0.018)	(1.312)
Error Correction Term (ECM_{t-1})	−0.087***		−0.090***	
	(0.024)		(0.024)	
Constant	−3.363**		−2.888**	
	(1.331)		(1.398)	
Bounds Test (F−Test)	3.183 (0.110)		2.939 (0.144)	
Breusch–Godfrey LM Test	0.394 (0.530)		0.199 (0.656)	
Breusch–Pagan Test	1.290 (0.256)		1.340 (0.247)	
Ramsey RESET Test	2.500 (0.059)		2.460 (0.062)	
Observations	390		390	
Adjusted R^2	0.881		0.882	

The two models (1) and (2) represent different specifications of the ARDL−ECM framework. Statistical significance is denoted as follows: ***Significant at the 1% level, **Significant at the 5% level, *Significant at the 10% level

Table 8: ARDL−ECM Estimates for CO_2 Emissions in the Transportation Sector

Variables	(1)		(2)	
	Short Run	Long Run	Short Run	Long Run
Renewable Energy Consumption	0.166***	0.010	0.168***	−0.008
	(0.020)	(0.015)	(0.020)	(0.015)
Price of Motor Gas		0.491***		0.529***
		(0.129)		(0.118)
Price of Diesel Fuel		−7.542***		−6.894***
		(1.495)		(1.340)
Crude Oil Cost, Domestic		0.911***		0.912***
		(0.132)		(0.119)
Crude Oil Cost, OPEC	0.121***	−0.746***	0.117***	−0.484***
	(0.034)	(0.140)	(0.034)	(0.155)
Interaction between Fossil Fuel Consumption & Price of Diesel Fuel		0.921***		0.845***
		(0.188)		(0.169)
Interaction between Cost of Domestic Crude Oil & Cost of OPEC Crude Oil				−0.045***
				(0.017)
Error Correction Term (ECM_{t-1})	−0.318***		−0.350***	
	(0.037)		(0.039)	
Constant	1.338***		1.357***	
	(0.214)		(0.212)	
Bounds Test (F−Test)	16.222 (0.000)		15.234 (0.000)	
Breusch–Godfrey LM Test	0.021 (0.884)		0.097 (0.755)	
Breusch–Pagan Test	0.010 (0.913)		0.000 (0.986)	
Ramsey RESET Test	3.430 (0.017)		2.560 (0.055)	
Observations	361		361	
Adjusted R^2	0.520		0.528	

The two models (1) and (2) represent different specifications of the ARDL−ECM framework. Statistical significance is denoted as follows: ***Significant at the 1% level, **Significant at the 5% level, *Significant at the 10% level

no significant effect in both models, implying that the impact of renewables on emissions may be neutral over extended periods. The price of domestic crude oil is a major contributor to emissions in both models, as a 1% increase in crude oil prices raises CO_2 emissions by 0.91%, thereby being consistent with the heavy reliance of this sector on petroleum a relationship also in line with its positive correlation with emissions (0.426) in Appendix A7. OPEC crude oil prices exhibit heterogeneous effects on emissions, a 1% increases emissions by 0.12% in the short run but reduces them by 0.75% and 0.48% in the long run, suggesting that higher OPEC prices drive long-term efficiency improvements. Long-run emissions are also significantly increased through motor gasoline prices, which implies indirect cost pass-through effects that sustain fuel consumption. In contrast, higher diesel fuel prices have a strong and negative effect on emissions, decreasing emissions by 7.54% and 6.89% in both models for a 1% increase in price, likely due to less diesel consumption or higher fuel efficiency.

The error correction term is negative and statistically significant, suggesting that 32% to 35% of any short-run deviations from long-run equilibrium are corrected per period. The model is confirmed by robust diagnostic tests indicating serial correlation and heteroscedasticity absence, while the Ramsey RESET test hints at potential specification issues at 5% significance level, however, no such concerns arise at the 10% level.

The results derived from the economy-wide analysis (Table 3) render critical orientation for designing national policy. These findings indicate stronger co-evolution between renewable energy utilization and economic growth affirms that emissions reductions from renewables are most effective when economic expansion is supported. These findings are indicative of why policies should be directed towards creating incentives for investment in clean energy, making the economy more resilient. Such policies may include support investment in green infrastructure projects, tax credits for clean energy industries and grants for advancements in energy efficiency. As fossil fuel consumption is such a major contributor to emissions, policies need to target the phase-out of carbon-intensive forms of energy, through carbon pricing, emissions caps, and stricter environmental and regulatory standards. However, existing carbon pricing mechanisms, such as the polluter-pay principle based on the Coase theorem, appear to have been ineffective in curbing emissions, as they may inadvertently encourage pollution by allowing firms to pay for continued emissions rather than adopting cleaner technologies. The significant effect of electricity prices on emissions reduction also highlights the need for reforms in energy pricing that fosters efficiency without penalizing consumers. Policies that stabilize crude oil price volatility including diversifying energy imports and expanding domestic clean energy production help to minimize spikes in emissions associated with volatile fossil fuel markets.

Sector-specific results reflect unique policy needs. The greatest potential for emissions reductions from renewables lies in the electric power sector, but transitional inefficiencies mean that with the current grid and energy storage features, the full benefits of renewables will not be obtained. Unlike the entire economy, the residential and commercial sectors show non-linear effects of wide-scale renewables, thus, while early-stage renewables may not immediately lower emissions, sustained energy efficiency and technology integration investments will result in longer-term reductions. Unlike the entire economy, where GDP plays a significant role in emissions dynamics, these sectors are more responsive to electricity prices, suggesting the need for targeted subsidies and efficiency programs.

Emissions reduction would be harder to achieve in the industrial and transportation sectors as they depend more on fossil fuels. Industrial emissions are more sensitive to electricity prices and fossil fuel prices than across other sectors, indicating the need for incentives for industrial energy efficiency and direct renewables integration. Unlike most sectors, the industrial sector long-run emissions increase in response to electricity price increases, implying that industries can switch to higher-emission energy sources when electricity output is expensive. Hence, targeted policies to promote renewables for industrial processes, as well as financing incentives for clean manufacturing, will be critical. Since crude oil price fluctuations account for most price-driven emissions in the transportation sector, the same does not apply for the entire economy and suggests that policies in this sector must reduce petroleum reliance, mainly through the acceleration of electric vehicle (EV) adoption and clean fuel expansion. In the harshest climates of America, in states like Alaska and North Dakota, battery inefficiencies and charging limitations are two major challenges which would prevent widespread adoption of electric vehicles. This means that a comprehensive transition to EVs in these areas might be challenging, and additional policies will be needed to make battery technology more efficient and broaden low-emission alternative mobility options.

A major area of focus must also be the equitable access to renewable energy solutions over states and income groups. The transition to cleaner energy cannot, and must not, disproportionately impact low-income households or states with less developed infrastructure. Policies must involve targeted subsidies for low-income communities, support for distributed renewable energy systems like community solar programs, and financial incentives for private sector investment in rural clean energy development. Also, workforce transition programs will be essential to mitigate job displacement in fossil fuel-dependent industries, ensuring that workers have access to reskilling and employment opportunities in the renewable energy sector. Improving socio-economic inequalities will make the energy transition more equitable and politically sustainable, diminishing the resistance of communities that might otherwise be negatively affected by decarbonization.

4. CONCLUSION

In this study, we demonstrate with a sectoral focus the nuanced difference that policy approaches can make to the CO_2 mitigation strategy embodied in energy flows associated with economy-wide renewable energy adoption. Renewable energy is the key to long-term decarbonization, but its effectiveness differ substantially due to sector-specific challenges. Policies can help remove these barriers by facilitating energy storage, increasing grid flexibility, and promoting clean energy infrastructure. The cost of energy also matters greatly, with more expensive energy providing an incentive for immediate (short-term) reductions but sometimes results in a long-term shift toward carbon-intensive. That said, the reliance on historical data in the study may limit its relevance to future technological and policy developments. It also omits the sectoral spillover effects or emerging technologies like hydrogen and advanced battery storage. Understanding these factors will help policy makers define policy measures that target emissions reduction while ensuring a robust economic stability by ensuring a sustainable and resilient energy transition.

In sum, comparing across sectors highlights the varying degrees of renewable energy effectiveness in emissions reduction. Whereas the industrial sector shows the clearest benefits of renewables in terms of direct emissions savings (in the long term), other sectors require complementary interventions, including efficiency, pricing, and technology. Policies that consider dynamics within each sector yet seek to align with the larger goal of emissions reduction will be critical in achieving an energy transition in the U.S. that aligns with economic growth and environmental sustainability. A flexible and adaptive policy framework that accounts for these variations will ensure a just and effective decarbonization pathway across all sectors.

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APPENDICES

Appendix A1: Units of measurement for key variables

Variable	Unit of Measurement
CO_2 Emissions Total, Residential	Million Metric Tons of Carbon Dioxide
CO_2 Emissions Total, Commercial	Million Metric Tons of Carbon Dioxide
CO_2 Emissions Total, Electric Power	Million Metric Tons of Carbon Dioxide
CO_2 Emissions Total, Industrial	Million Metric Tons of Carbon Dioxide
CO_2 Emissions Total, Transportation	Million Metric Tons of Carbon Dioxide
CO_2 Emissions Total, All Sectors	Million Metric Tons of Carbon Dioxide
Renewable Energy Consumption, Residential	Trillion Btu
Renewable Energy Consumption, Commercial	Trillion Btu
Renewable Energy Consumption, Electric Power	Trillion Btu
Renewable Energy Consumption, Industrial	Trillion Btu
Renewable Energy Consumption, Transportation	Trillion Btu
Renewable Energy Consumption, All Sectors	Trillion Btu
Fossil Fuel Consumption, Residential	Trillion Btu
Fossil Fuel Consumption, Commercial	Trillion Btu
Fossil Fuel Consumption, Electric Power	Trillion Btu
Fossil Fuel Consumption, Industrial	Trillion Btu
Fossil Fuel Consumption, Transportation	Trillion Btu
Fossil Fuel Consumption, All Sectors	Quadrillion Btu (converted to Trillion Btu for the analysis)

(Contd...)

Appendix A1: *(Continued)*

Variable	Unit of Measurement
Real Gross Domestic Product	Trillion US Dollars
Crude Oil Cost, Domestic	US Dollars per Barrel
Crude Oil Cost, OPEC	US Dollars per Barrel
Price of Natural Gas, Residential	US Dollars per Thousand Cubic Feet
Price of Natural Gas, Commercial	US Dollars per Thousand Cubic Feet
Price of Natural Gas, Industrial	US Dollars per Thousand Cubic Feet
Price of Natural Gas, Electric Power	US Dollars per Thousand Cubic Feet
Natural Gas Receipts at the Electric Generating Plants	US Dollars per Million Btu (including Taxes)
Cooling Degree−Days	Number
Heating Degree−Days	Number
Average Electricity Price, Residential	Cents per Kilowatt−hour (including Taxes)
Average Electricity Price, Commercial	Cents per Kilowatt−hour (including Taxes)
Average Electricity Price, Industrial	Cents per Kilowatt−hour (including Taxes)
Electricity Price Total, All Sectors	Cents per Kilowatt−hour (including Taxes)
Net Generation of Electricity, Electric Power	Million Kilowatt−hours
Net Generation of Electricity, Industrial	Million Kilowatt−hours
Electricity Sales, Electric Power	Million Kilowatt−hours
Price of Motor Gas	US Dollars per Gallon (including Taxes)
Price of Diesel Fuel	US Dollars per Gallon (including Taxes)

This table presents the units of measurement for key variables used in the analysis across all sectors. Energy consumption is measured in Trillion Btu, emissions are reported in Million Metric Tons of CO_2, and prices are shown in US Dollars or Cents per respective unit. All variables are measured on a monthly basis, with fossil fuel consumption for all sectors (entire economy) converted from Quadrillion Btu to Trillion Btu for consistency

Appendix A2: Correlation matrix for the entire economy (all sectors)

Variables	CO_2 Emissions Total, All Sectors	Renewable Energy Consumption, All Sectors	Fossil Fuel Consumption, All Sectors	Real GDP	Electricity Price Total, All Sectors	Crude Oil Cost, Domestic
CO_2 Emissions Total, All Sectors	1.000					
Renewable Energy Consumption, All Sectors	−0.499	1.000				
Fossil Fuel Consumption, All Sectors	0.910	−0.183	1.000			
Real GDP	−0.302	0.854	0.005	1.000		
Electricity Price Total, All Sectors	−0.426	0.902	−0.160	0.920	1.000	
Crude Oil Cost, Domestic	−0.127	0.680	0.033	0.803	0.831	1.000

This table presents the pairwise correlation coefficients between key variables for the entire U.S. economy. The coefficients range from−1 to 1, where values closer to 1 indicate a strong positive relationship, values closer to−1 indicate a strong negative relationship, and values near 0 indicate little to no linear relationship. The variables include CO_2 emissions, energy consumption, fossil fuel consumption, real GDP, electricity use and prices, and crude oil costs (domestic and OPEC)

Appendix A3: Correlation matrix for the residential sector

Variables	CO_2 Emissions Total, Residential	Renewable Energy Consumption, Residential	Fossil Fuel Consumption, Residential	Average Electricity Price, Residential	Price of Natural Gas, Residential	Heating Degree−Days	Cooling Degree−Days
CO_2 Emissions Total, Residential	1.000						
Renewable Energy Consumption, Residential	−0.392	1.000					
Fossil Fuel Consumption, Residential	0.611	−0.256	1.000				
Average Electricity Price, Residential	−0.382	0.592	−0.264	1.000			
Price of Natural Gas, Residential	−0.272	0.286	−0.561	0.766	1.000		
Heating Degree−Days	0.326	−0.194	0.911	−0.188	−0.517	1.000	
Cooling Degree−Days	−0.553	0.226	−0.967	0.241	0.527	−0.935	1.000

This table displays the pairwise correlation coefficients between key variables in the residential sector. The coefficients range from−1 to 1, with values near 1 indicating a strong positive correlation, values near−1 indicating a strong negative correlation, and values close to 0 suggesting little to no linear relationship. Variables included are CO_2 emissions, renewable and fossil fuel consumption, average electricity and natural gas prices, and climate factors such as heating and cooling degree−days

Appendix A4: Correlation matrix for the commercial sector

Variables	CO_2 Emissions Total, Commercial	Renewable Energy Consumption, Commercial	Fossil Fuel Consumption, Commercial	Average Electricity Price, Commercial	Price of Natural Gas, Commercial
CO_2 Emissions Total, Commercial	1.000				
Renewable Energy Consumption, Commercial	−0.495	1.000			
Fossil Fuel Consumption, Commercial	0.279	0.002	1.000		
Average Electricity Price, Commercial	−0.269	0.812	−0.122	1.000	
Price of Natural Gas, Commercial	0.205	0.347	−0.070	0.695	1.000

This table presents the pairwise correlation coefficients between key variables in the commercial sector. Correlation values range from−1 to 1, where values near 1 indicate a strong positive correlation, values near−1 indicate a strong negative correlation, and values close to 0 suggest little to no linear relationship. Included variables are CO_2 emissions, renewable and fossil fuel consumption, average electricity price, net electricity generation, and natural gas prices

Appendix A5: Correlation matrix for the electric power sector

Variables	CO_2 Emissions Total, Electric Power	Renewable Energy Consumption, Electric Power	Fossil Fuel Consumption, Electric Power	Net Generation of Electricity, Electric Power	Natural Gas Receipts at the Electric Generating Plants	Price of Natural Gas, Electric Power	Electricity Sales, Electric Power
CO_2 Emissions Total, Electric Power	1.000						
Renewable Energy Consumption, Electric Power	−0.662	1.000					
Fossil Fuel Consumption, Electric Power	0.929	−0.392	1.000				
Net Generation of Electricity, Electric Power	0.353	0.390	0.659	1.000			
Natural Gas Receipts at the Electric Generating Plants	0.341	−0.105	0.369	0.375	1.000		
Price of Natural Gas, Electric Power	0.329	−0.088	0.363	0.385	0.999	1.000	
Electricity Sales, Electric Power	0.277	0.418	0.594	0.977	0.371	0.383	1.000

This table shows the pairwise correlation coefficients between key variables in the electric power sector. The correlation values range from−1 to 1, where values near 1 represent a strong positive correlation, values close to−1 signify a strong negative correlation, and values around 0 suggest little or no linear relationship. The variables include CO_2 emissions, renewable and fossil fuel consumption, net electricity generation, natural gas receipts and prices, and electricity sales, reflecting the sector's energy consumption and production dynamics

Appendix A6: Correlation matrix for the industrial sector

Variables	CO_2 Emissions Total, Industrial	Renewable Energy Consumption, Industrial	Fossil Fuel Consumption, Industrial	Net Generation of Electricity, Industrial	Average Electricity Price, Industrial	Price of Natural Gas, Industrial
CO_2 Emissions Total, Industrial	1.000					
Renewable Energy Consumption, Industrial	−0.562	1.000				
Fossil Fuel Consumption, Industrial	0.501	−0.083	1.000			
Net Generation of Electricity, Industrial	0.559	0.069	0.550	1.000		
Average Electricity Price, Industrial	−0.834	0.653	−0.447	−0.352	1.000	
Price of Natural Gas, Industrial	−0.107	0.033	−0.292	−0.217	0.391	1.000

This table presents the pairwise correlation coefficients between key variables in the industrial sector. Correlation values range from−1 to 1, where values close to 1 indicate a strong positive correlation, values near−1 indicate a strong negative correlation, and values around 0 suggest little or no linear relationship. The variables include CO_2 emissions, renewable and fossil fuel consumption, net electricity generation, average electricity price, and natural gas prices

Appendix A7: Correlation matrix for the transportation sector

Variables	CO_2 Emissions Total, Transportation	Renewable Energy Consumption, Transportation	Fossil Fuel Consumption, Transportation	Crude Oil Cost, Domestic	Crude Oil Cost, OPEC	Price of Motor Gas	Price of Diesel Fuel
CO_2 Emissions Total, Transportation	1.000						
Renewable Energy Consumption, Transportation	0.305	1.000					
Fossil Fuel Consumption, Transportation	0.999	0.324	1.000				
Crude Oil Cost, Domestic	0.426	0.851	0.431	1.000			
Crude Oil Cost, OPEC	0.387	0.866	0.393	0.996	1.000		
Price of Motor Gas	0.404	0.895	0.413	0.982	0.984	1.000	
Price of Diesel Fuel	0.398	0.873	0.405	0.992	0.992	0.989	1.000

This table presents the correlation coefficients among key transportation sector variables. The values indicate the strength and direction of the linear relationship between variables, with coefficients ranging from−1 to 1. A positive coefficient indicates a direct relationship, while a negative coefficient indicates an inverse relationship. The stronger the coefficient, the closer it is to 1 or−1. All correlations are calculated using the entire sample period, with 363 observations for the transportation sector due to data availability constraints