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The Impact of Deep Decarbonization Policy on the Level of Greenhouse Gas Emissions in the European Union

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Abstract: The Green Deal, a cornerstone of the European Union's climate goals, sets out to achieve a substantial 55% reduction in greenhouse gas emissions by 2030 compared to 1990 levels. The EU's decarbonization strategies revolve around three pivotal avenues. First, there is a focus on enhancing energy efficiency and decreasing the energy intensity of economies. Second, concerted efforts are made to diminish the reliance on fossil fuels, particularly within industrial sectors. Lastly, there is a deliberate push to augment the share of renewable energy sources in the final energy consumption mix. These measures collectively aim to propel the decarbonization of EU economies, establishing EU member countries as global leaders in implementing these transformative processes. This manuscript seeks to evaluate the efficacy of three primary decarbonization strategies adopted by EU economies, namely the enhancement in energy efficiency, the promotion of renewable energy consumption and the reduction in fossil fuel consumption. The objective is to discern which strategies wield a decisive influence in achieving decarbonization goals across EU countries. The analysis encompasses all 27 member states of the European Union, spanning from 1990 to 2022, with data sourced from reputable outlets, including Eurostat, Our World in Data and the Energy Institute. Research findings underscore that, in the realm of decarbonization policies, statistically significant impacts on carbon dioxide emission reduction are attributable to the strategies of improving energy efficiency and augmenting the share of renewables in energy consumption across almost all EU countries. Conversely, the strategy with the least impact, embraced by a minority of EU member states, revolves around diminishing the share of fossil fuels in primary energy consumption. This approach, while statistically less impactful, is intricately linked with transitioning the economies toward renewable energy sources, thus playing a contributory role in the broader decarbonization landscape. The uniqueness of this research lies not only in its discernment of overarching trends but also in its fervent advocacy for a comprehensive and adaptive approach to EU decarbonization policy. It underscores the enduring significance of prioritizing energy efficiency, endorsing the integration of renewable energy and acknowledging the distinctive dynamics inherent in diverse regions. The study accentuates the necessity for nuanced, region-specific strategies, challenging the conventional wisdom of a uniform approach to decarbonization. In doing so, it accentuates the critical importance of tailoring policies to the varied energy landscapes and transition strategies evident in different EU member states.

Keywords: decarbonization; Green Deal; RES; energy efficiency; fossil fuels; European Union

Citation: Nagaj, R.; Gajdzik, B.; Wolniak, R.; Grebski, W.W. The Impact of Deep Decarbonization Policy on the Level of Greenhouse Gas Emissions in the European Union. *Energies* **2024**, *17*, 1245. https://doi.org/10.3390/en17051245

Academic Editor: Maciej Dzikuć

Received: 14 February 2024
Revised: 26 February 2024
Accepted: 29 February 2024
Published: 5 March 2024

1. Introduction

The decarbonization policy is currently a priority in the economic policy of the European Union (EU). Its significance has gained further prominence following the adoption of the European Green Deal [1] by the European Commission. As part of this deal, the EU aims for its economy to be net-zero emissions by 2050, supporting a comprehensive environmental protection policy. Within this policy framework, three types of commitments are embraced: phasing out coal—and, more broadly, fossil fuels as an energy carrier—improving energy efficiency and increasing the role of renewable energy sources (RES) in the energy mix.

Most countries have not yet specified the indicative targets for 2050, hence the focus on actions and indicative targets for 2030. Regarding energy efficiency, commitments arise from two legal acts. First, for the year 2020, Directive 2012/27/EU on energy efficiency [2] set a target of 20% energy efficiency (with the withdrawal of the United Kingdom from the EU, the target was 1312 Mtoe for primary energy consumption and 959 Mtoe for final energy consumption). Second, for 2030, an energy efficiency target of at least 32.5% was established (1124 Mtoe for primary energy consumption and 864 Mtoe for final energy consumption). As a result of the REPowerEU plan [1] in 2023, the targets for energy efficiency were revised downward by an additional 11.7% to 992.5 Mtoe for primary energy consumption and 763 Mtoe for final energy consumption, as specified in Directive 2023/1791 [3].

It is worth noting that in 2022, the final year of analysis, the final energy consumption in the EU was 1.9% below the 2020 energy target and 23.3% above the 2030 target [4]. In the realm of energy efficiency, the literature in recent years has increasingly focused on evaluating actions supporting this strategy and identifying the instruments to optimize improvements, especially in European countries [5–7].

Regarding research on renewable energy sources, the focus has mainly been on broader utilization of renewable energy sources (RES) and ways to increase their share in final and/or primary energy consumption. The literature extensively examined the impact of various instruments aimed at stimulating RES [8–10] and the potential effects of such policies on society, including fuel poverty [11]. As of 2022, the share of RES in energy consumption in the EU is 23%, but the current EU target for 2030 is 42.5%, as adopted in the 2023 Renewable Energy Directive [12], replacing the earlier target of 32%.

The third area of action in the decarbonization strategy of EU countries is reducing fossil fuels in the economy, especially in industries [13–16] but not limited to them; this also extends to other sectors, such as transportation and tourism [17–19]. In addition to actions within these three strategies, the literature also explores other supportive decarbonization measures, such as implementing efficient emission markets, integrating carbon capture technologies, promoting international cooperation [20], supporting environmentally friendly behaviors and sustainable development among current generations [21,22] and modeling scenarios for integrating sectors, which support decarbonization [23].

Reviewing the state of the art on decarbonization indicated above to date, it must be concluded that there is a research gap in the area of comprehensive impact of decarbonization strategies used to date. Therefore, the aim of this paper is to assess the impact of three priority decarbonization strategies implemented by EU economies—i.e., improving energy efficiency, increasing the consumption of renewables and reducing the consumption of fossil fuels—and to assess which of them have a decisive impact in EU countries on the achievement of decarbonization targets. Achieving this research objective will answer three research questions:

RQ1: Which of the decarbonization strategies play a decisive role in reducing greenhouse gas emissions?

RQ2: Do trends in each of these three decarbonization actions have a statistically significant impact on the reduction in greenhouse gas emissions?

RQ3: Is decarbonization and the strategies applied within this policy regionally conditioned?

The analysis will be conducted for the 27 member countries of the European Union, with the time frame of analysis determined by data availability, i.e., 1990–2022. The analysis conducted in this paper and the obtained findings will contribute to the literature in three ways. First, the research results will indicate which of the decarbonization strategies implemented in EU countries has the greatest impact on reducing carbon dioxide emissions.

As noted, the literature has extensively examined the effectiveness of instruments used by governments to enhance the efficiency of individual decarbonization strategies. However, it has not explored which of these strategies have a statistically significant, long-term impact on reducing greenhouse gas emissions, thus aiding most effectively in achieving the goals outlined in the Paris Agreement. Second, the analysis will cover all European Union countries, thus not being limited to just one country, as is commonly done in the literature. Third, a comprehensive analysis conducted for all EU member states will help determine whether there is a regional dependency in the effectiveness of implemented decarbonization strategies.

The novelty of the study lies not only in its identification of overarching trends but also in its advocacy for a comprehensive and adaptive approach to EU decarbonization policy. By employing regression analysis, the paper delves into the nuanced dynamics of key factors influencing decarbonization, including energy efficiency improvements, increased utilization of renewable energy sources and deliberate reductions in fossil fuel reliance.

What sets this research apart is its emphasis on practical implications for policymakers. Rather than limiting itself to theoretical discussions, the paper provides actionable insights. It encourages the continuation of efforts to enhance industrial processes, optimize energy use and foster technological advancements to achieve overarching energy efficiency gains. The call for creating an enabling environment for renewable energy deployment, offering financial incentives and promoting innovation underscores the tangible impact of the research on real-world policy decisions.

The structure of the work will be as follows. After an introductory section presenting the current state of the literature on the studied topic, a literature review on decarbonization policies applied in the European Union will be conducted. The subsequent part of this paper will consist of the methodology and results, followed by a discussion, and the entire work will conclude with conclusions.

2. Literature Review

The exploration of decarbonization policies for economies and industries is a recurring theme in numerous scholarly papers and research studies. Scholars, while aligning with the frameworks of global, European or national decarbonization policies, engage in the development of transformation models, which address diverse facets of change.

These models serve as structured frameworks for the assumptions identified by experts, offering a detailed exploration of various technologies and sectors. They aim to elucidate policy implementation challenges and account for intricate interactions and potential unintended consequences across different decarbonization levels [24]. The breadth of studies forming the foundation for these models spans from global perspectives to national and sectoral scales, encompassing analyses of individual countries, communities or entire continents [25–27].

Researchers often center their attention on the decarbonization processes of national economies. For instance, Capros et al. (2012) [25] scrutinized the decarbonization trajectory of the European economy, presenting a model projecting its decarbonization until 2050. In a subsequent publication (2014) [26], the same author, in collaboration with an extended team, delineated the path of decarbonization under alternative technological and political scenarios. Pye and Bataille (2016) [27] delved into modeling the requisite changes to facilitate deep decarbonization paths for multiple countries. Their analysis encompassed a review of existing models, such as bottom-up, hybrid, linked, top-down or integrated models, evaluating their strengths, weaknesses and areas necessitating improvement.

National deep decarbonization pathways—informed by studies on decarbonization in policy documents spanning global, EU and national levels—have been a focal point for more than a decade [28–30]. These pathways provide detailed descriptions of changes in physical infrastructure, technology deployment, sectoral investments and associated behavioral patterns necessary for achieving deep decarbonization over time. The diversity of deep decarbonization models and pathways—varying across sectors, companies and global to local levels—underscores the model-agnostic nature of the deep decarbonization approach. Different model approaches are considered valuable based on the central questions posed in a country's analysis. Consequently, multiple models may be available for each country, with the overarching goal of informing stakeholders and policymakers, fostering discussion and decision making, and building the requisite political consensus for effective policy implementation. Decarbonization pathways are used to develop scenarios for transformation to net zero. The studies address technological, technological–economic, physical scenarios. Scenarios are built for economies [31–34]—both powerful economies (China, Japan, US) [35–38] and smaller ones [39–42]. From a broad macroeconomic approach, from the national or regional level, one moves to sectoral pathways of decarbonization. The authors focus on heavy and carbon-intensive industries. Heavy industry manufactures products, which are central to our modern way of life, but it is also responsible for nearly 40% of global carbon dioxide (CO_2) emissions. Steel, cement and chemicals are the top three emitting industries and are among the most difficult to decarbonize owing to technical factors, such as the need for very high heat and process emissions of carbon dioxide, and economic factors, including low profit margins, capital intensity, long asset life and trade exposure [43]. Gajdzik et al. [44,45] presented technology replacement scenarios for the steel sector—a sectoral approach. The sectoral approach to building models and/or decarbonization scenarios is also present in publications [42,46–61].

In Table 1, there is a description of approaches used in selected industries in the decarbonization process.

Table 1. The approaches used in the implementation of decarbonization in selected industries.

Industry	Literature Positions	Description
Energy	[62]	Shift from fossil fuels to renewable sources, such as solar, wind and hydropower. Implement energy storage solutions, smart grids, and enhance energy efficiency in production and distribution. Upgrade and modernize power infrastructure to accommodate decentralized and clean energy systems.
Transportation	[63–65]	Transition to electric vehicles (EVs), invest in sustainable public transportation and develop infrastructure for EV charging. Improve fuel efficiency in traditional vehicles and explore alternative fuels, such as hydrogen and biofuels. Adopt intelligent transportation systems to optimize traffic flow and reduce emissions.
Manufacturing	[66–68]	Adopt sustainable and circular economy practices. Optimize manufacturing processes for energy efficiency and reduce resource consumption. Incorporate green materials, design for recyclability and implement closed-loop production systems. Embrace digital technologies, such as IoT and AI, for predictive maintenance and resource optimization.
Construction	[69–71]	Embrace green building standards, prioritize energy-efficient designs and use sustainable materials. Incorporate renewable energy solutions, such as solar panels and geothermal systems, in construction projects. Implement smart building technologies for energy management and monitoring. Adopt circular economy principles in construction waste management.
Agriculture	[72,73]	Implement precision farming techniques, reduce reliance on synthetic fertilizers and promote sustainable land management practices. Invest in agroecology and regenerative agriculture to enhance soil health and carbon sequestration. Utilize technology for data-driven decision making in crop management and irrigation. Adopt sustainable supply chain practices in agriculture.

Table 1. *Cont.*

Industry	Literature Positions	Description
Chemical	[74–76]	Transition to green chemistry practices, reduce emissions in chemical production processes and develop sustainable alternatives for chemical manufacturing. Invest in research and innovation for greener chemical technologies. Adopt circular economy principles in chemical waste management. Collaborate with stakeholders to establish industry-wide sustainability standards. Promote transparency in the supply chain to ensure responsible sourcing of raw materials.
Technology	[77]	Improve energy efficiency in data centers and IT infrastructure. Develop and promote energy-efficient electronic devices. Implement sustainable design practices for hardware and software. Incorporate eco-friendly materials in manufacturing electronic components. Promote responsible e-waste management and recycling. Support and invest in research and development of green technologies.
Finance and Insurance	[78,79]	Integrate environmental, social and governance (ESG) criteria into investment decisions. Provide financial incentives for sustainable and low-carbon projects. Develop and offer green financial products and services. Encourage transparency in reporting and disclosure of climate-related risks. Support initiatives and innovations, which contribute to a sustainable and low-carbon economy.
Tourism and Hospitality	[18,80–83]	Promote eco-friendly tourism practices, develop sustainable accommodations and minimize the environmental impact of travel-related activities. Implement energy-efficient technologies in hospitality facilities. Encourage sustainable tourism through education and awareness campaigns. Support local communities and biodiversity conservation in tourist destinations. Invest in low-carbon transportation options for travelers.
Healthcare	[84]	Enhance energy efficiency in healthcare facilities, promote sustainable practices in waste management and adopt green building standards. Integrate environmentally friendly technologies and materials in medical equipment. Implement telemedicine solutions to reduce the need for physical travel. Foster sustainability in the healthcare supply chain, from pharmaceuticals to medical devices.
Retail	[85–87]	Implement sustainable sourcing practices, reduce packaging waste and promote eco-friendly products. Adopt circular economy principles in supply chain management. Invest in technology to optimize inventory management and reduce overstock. Educate and engage consumers in sustainable consumption practices. Support and collaborate with suppliers committed to environmental and social responsibility.

Source: Authors' own work on the basis of Refs. [62–87].

When one moves from the macro level of decarbonization to the micro level—that is, from the level of economies to the level of companies—the problems increase. Companies in many sectors write deep decarbonization goals into their strategies. The problem arises when the provisions in the strategies should be implemented; from the strategic level, one has to move to the implementation of technological investments. Additionally, some authors wonder why companies engage in climate change policies (e.g., Amran et al., 2016; Buettner et al., 2022; Finke et al., 2016; Sullivan and Gouldson, 2017) [88–91] or what motivates them to be active in decarbonization [92], which seems obvious, given the primacy of government policies over business, as well as market motives [91]. Deep decarbonization requires greater corporate social responsibility. Are companies under pressure to be socially responsible [93]? Can the market withstand the radicality of change [94]? These questions are just examples of the dilemmas. Deep decarbonization is a strategy for many decision-making dilemmas, which escalate from the macro level to the micro level, i.e., companies [95,96].

Companies, which replace high-carbon technology with low-carbon technology, face high transition costs. Large companies need to make changes and replace technologies with low-carbon ones to maintain their market leadership. In addition, decarbonization can be an opportunity for them to enter new markets. However, will the MSE sector be able to face the costs of new investments? This is where the problem arises, as the costs of decarbonization may be difficult for them to bear. Industrial decarbonization and energy processing involve high fixed costs and have the potential for significant energy efficiency and organizational economies of scale, resulting in large-scale processing plants, which require high upfront costs [97]. High fixed costs have to pay for themselves in cyclical markets with large fluctuations in prices and profit margins [98]. Investment cycles for large-scale reinvestments can typically range from 20 to 40 years, but in practice, the actual duration can vary widely [99]. Installations are renewed more frequently to increase productivity and improve energy efficiency. These cycles vary for different technologies, from 4–6 years for chemical facilities to 10–15 years for glass tanks [100] and blast furnaces [101]. Sectors with high-emission technologies used additional investments, and the result was the emergence of, for example, investments in steel, reducing the energy intensity of steel production [102,103]. To overcome misdirection and enable the long-term direction of technology development, low-carbon-scenario visioning and pathway processes are important tools to coordinate, guide, legitimize and learn about transitions [104]. The topic of the costs of this radical decarbonization is an important area of research; here are sample publications [105,106] in which the authors try to answer the question: Will industries bear the costs of deep decarbonization [107,108]?

Many authors also point to decarbonization barriers, including economic ones [8]. In Ref. [8], the authors summarized the barriers to implementing the RES policy (analysis based on respondents and a literature review). The barriers are not only economic but also emotional [109].

Balancing the various challenges of decarbonization will be a major challenge, and managing the transition will require a level of expertise in the changing institutional framework, which shapes innovation, state aid, trade and activities governed by the goals or challenges of ongoing decarbonization [110].

The process of transformation of countries, regions and industries is dynamic [110]. There are no ready-made rules; each country, each industry and each enterprise must develop its own path of changes. Co-opetition at the level of businesses and supply chains [111], as well as green entrepreneurship [112], may be helpful. In addition, a new market for energy consumption (RES) and awareness of green energy and energy efficiency must be developed [113–115], including in forms, which are not yet popular in many countries, such as energy cooperatives [116].

3. Methods and Materials

The research process, outlined in Figure 1, will be utilized to address these research questions.

The first step of the research process is the identification of the research problem, research gap and the current state of the literature concerning decarbonization policy. Within this stage, research questions will be formulated, and the contribution to the literature will be presented. In the subsequent stage, the authors will conduct a critical literature review on the decarbonization policy in the EU. As part of this stage, the authors will analyze the past actions taken in the European Union and the three main models for implementing decarbonization policy, namely improving energy efficiency (which is reflected in the use of less energy to achieve the same result), increasing the share of renewable energy sources in energy consumption and reducing the use of fossil fuels in the economy, primarily in industry.

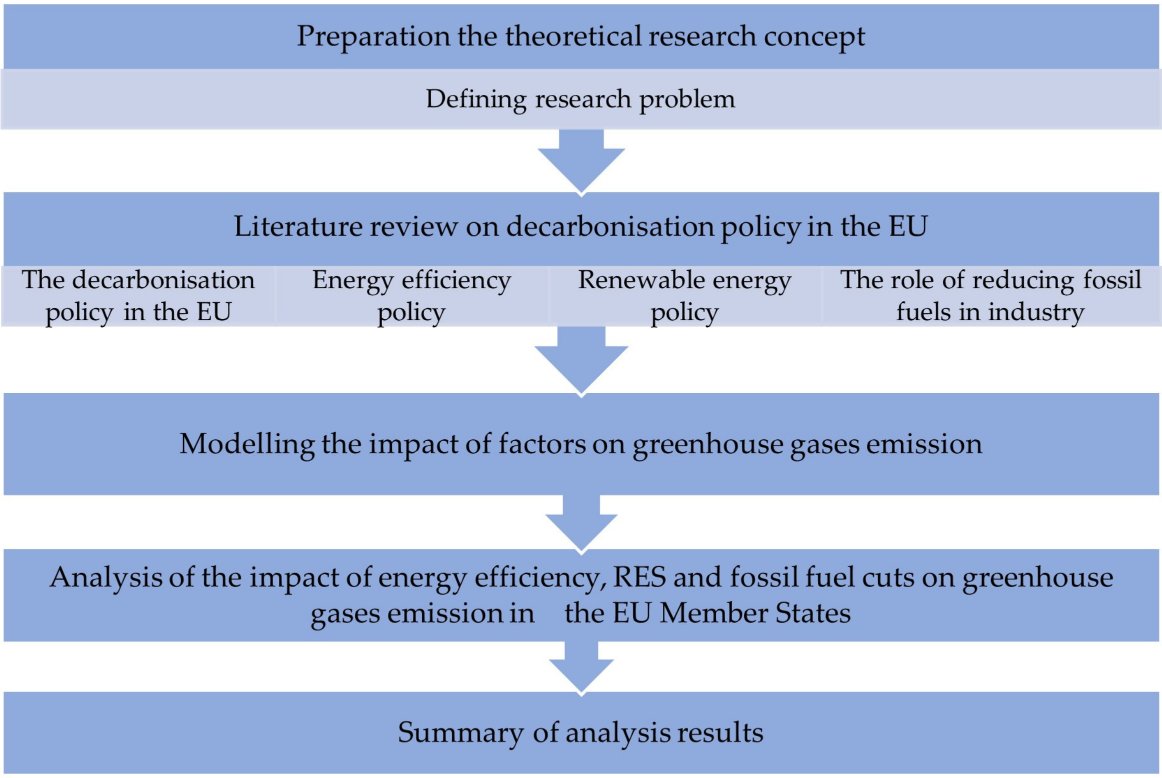

Figure 1. Stages of the research process.

The next stage of the research process involves creating an econometric model to assess which of the decarbonization models applied in the European Union influences the reduction in greenhouse gas emissions. As there are three approaches to decarbonizing economies in the EU, and thereby achieving Green Deal goals, the impact of three variables—energy efficiency, the share of renewables and fossil fuels—on greenhouse gas emissions will be evaluated. Figure 2 presents the model for analyzing the impact of these factors on greenhouse gas emissions in the EU.

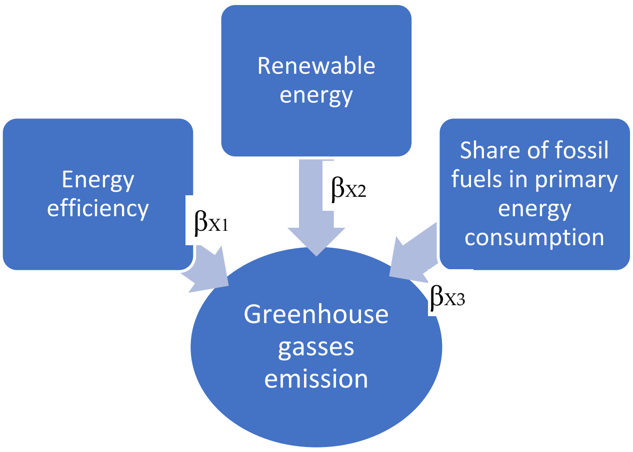

Figure 2. Model for analyzing the impact of factors on greenhouse gas emissions in the EU.

Based on the proposed model and the proposed independent variables, a multiple regression equation was constructed:

$$Y_i = a + \beta_{1i} \cdot X1 + \beta_{2i} \cdot X2 + \beta_{3i} \cdot X3 \quad (1)$$

where

Y_i—total level of greenhouse gas emissions in the i-th country (in CO_2 equivalent);
a_i, β_{1i}, β_{2i}, β_{3i}—parameters and coefficients of the regression function in the i-th country;
X1—energy efficiency of the energy in the i-th country (in million tonnes of oil equivalent);
X2—share of primary energy consumption, which comes from renewables in the i-th country (in %);
X3—share of primary energy consumption, which comes from fossil fuels in the i-th country (in %);
i = 1, . . ., 27—the EU member states.

The source of data regarding the level of greenhouse gas emissions and energy efficiency is Eurostat [4,117]. Data regarding the level of renewable energy sources (RES) in primary energy consumption were obtained from Our World in Data [118], while data indicating the share of fossil fuels in primary energy consumption come from the Energy Institute [119]. Based on the available data, a multiple regression analysis will be conducted for each of the 27 member countries of the European Union. The time frame of the analysis is determined by data availability, covering the years 1990–2022.

The research results should indicate which of the three factors—namely the measures taken in the decarbonization policy in EU countries—statistically significantly impact the level of carbon dioxide emissions, i.e., its reduction. The analysis aims to assess whether, given the observed trends, the Green Deal goal for 2030 is realistically achievable. A significance level of 0.05 was adopted for the study.

4. Results

Embarking on the analysis of decarbonization strategies, the first step involved examining the progress of European Union member countries in reducing greenhouse gas emissions since 1990. Figure 3 presents the change in greenhouse gas emissions in the EU member states in 2022 compared to 1990.

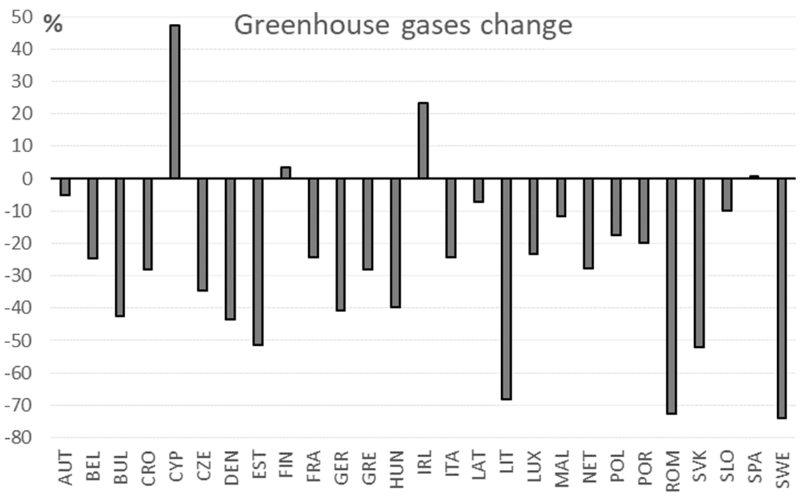

Figure 3. Change in greenhouse gas emissions in 2022 compared to 1990 in EU member states [4].

The analysis indicated that in 2022, 23 out of the 27 current member countries of the European Union emitted fewer greenhouse gases than in 1990. Among them, five countries had already reduced their emission levels by at least half, with three countries—Lithuania, Romania and Sweden—having already achieved the goal of a 55% reduction in greenhouse gas emissions by 2030. In the case of four countries, an increase in emissions was observed compared to 1990; however, it should be noted that in no country in 2022 was the maximum emission level recorded. This implies that the peak occurred several years ago, and currently, the emission levels are decreasing.

The correlation analysis (Table 2) indicated that the majority of member states show an average or high correlation with each independent variable. On average, the highest level of correlation pertains to energy efficiency (with an average level of 0.58 for EU countries), while the lowest level of correlation relates to the share of fossil fuels in primary energy consumption (0.53). However, it can be observed that a decrease in greenhouse gas emissions is accompanied by a lower share of fossil fuels, an increase in the share of renewables in primary energy consumption and a lower level of energy efficiency (measured in kilowatt-hours used per million tonnes of oil equivalent).

Table 2. Results of correlation analysis of the dependent variable with independent variables at a significance level of 0.05.

Country	Independent Variables				
	Efficiency of Final Energy	Efficiency of Primary Energy	RES	Fossil Fuels	RES vs. Fossil Fuels
Austria	0.66	0.67	0.14 *	−0.14 *	−1.00
Belgium	0.20 *	0.61	−0.96	0.75	−0.77
Bulgaria	0.87	0.87	−0.43	0.79	−0.81
Croatia	0.84	0.92	−0.37	0.37	−1.00
Cyprus	0.98	0.98	−0.61	n.a. **	n.a. **
Czech Republic	0.93	0.73	−0.79	0.83	−0.93
Denmark	0.56	0.90	−0.97	0.97	−1.00
Estonia	0.91	0.93	−0.09	0.09 *	−1.00
Finland	0.56	0.56	−0.09	0.13 *	−0.99
France	0.40	0.14 *	−0.89	0.88	−0.72
Germany	0.84	0.89	−0.94	0.97	−0.98
Greece	0.83	0.91	−0.80	0.80	−1.00
Hungary	−0.07 *	0.67	−0.87	0.93	−0.94
Ireland	0.71	0.77	−0.12 *	0.12 *	−1.00
Italy	0.65	0.69	−0.95	0.95	−1.00
Latvia	0.45	0.34 *	0.17 *	−0.17 *	−1.00
Lithuania	0.85	0.96	−0.43	−0.27 *	0.81
Luxembourg	0.60	0.67	−0.25 *	0.25 *	−1.00
Malta	−0.57	0.72	−0.88	n.a. **	n.a. **
The Netherlands	0.61	0.55	−0.95	0.95	−1.00
Poland	−0.02 *	0.48	−0.48	0.48	−1.00
Portugal	0.66	0.78	−0.66	0.66	−1.00
Romania	0.80	0.96	−0.91	0.95	−0.97
Slovakia	0.80	0.88	−0.89	0.85	−0.88
Slovenia	0.21 *	0.10 *	0.31 *	−0.35	−0.95
Spain	0.75	0.75	−0.41	0.67	−0.95
Sweden	0.72	0.60	−0.86	0.81	−0.94

* Cases below 0.35 are statistically insignificant (at $p < 0.05$); ** n.a.—data not available.

For Poland and Hungary, in the case of energy efficiency, there is a positive correlation with primary energy rather than final energy. This is because these countries rely on coal as a significant energy source for energy consumption not only in industry but also for end users, mainly households. In France, a significant share is contributed by nuclear energy, which is primarily used by industry (not in buildings or transport). However, in most EU member countries, the correlation for energy efficiency of final energy and primary energy is similar, indicating that energy efficiency applies to all sectors of the economy, including industry, transport and end users.

Finally, it is worth noting that in the majority of countries (20 out of 27), there is a very high correlation between the increase in the share of renewables in energy consumption and the decrease in the share of fossil fuels in energy consumption. This suggests that the reduction in primary energy consumption coming from fossil fuels is entirely covered by renewable energy sources.

Next, a regression analysis was conducted for each country for the three examined independent variables (n = 33, significance level = 0.05). The results of this analysis are presented in Table 3.

Table 3. Results of regression analysis for EU member states.

	Coefficients	Standard Error	t-Statistic	p-Value
Austria	Regression statistics: $R = 0.6694$; $R^2 = 0.4481$; Adjusted $R^2 = 0.4303$; $F(1;31) = 25.1679$; $p < 0.0000$			
Constant	28.4022	15.3664	1.8483	0.0741
Variable X1	2.5877	0.5158	5.0168	0.0000
Belgium	Regression statistics: $R = 0.9621$; $R^2 = 0.9256$; Adjusted $R^2 = 0.9232$; $F(1;31) = 385.7955$; $p < 0.0000$			
Constant	103.1022	0.6693	154.0465	0.0000
Variable X2	−2.8137	0.1433	−19.6417	0.0000
Bulgaria	Regression statistics: $R = 0.9396$; $R^2 = 0.8829$; Adjusted $R^2 = 0.8707$; $F(1;31) = 72.8606$; $p < 0.0000$			
Constant	−113.9376	18.3515	−6.2086	0.0000
Variable X1	2.7450	0.4831	5.6819	0.0000
Variable X2	1.2444	0.2867	4.3401	0.0002
Variable X3	1.5462	0.2841	5.4428	0.0000
Croatia	Regression statistics: $R = 0.9377$; $R^2 = 0.8793$; Adjusted $R^2 = 0.8712$; $F(2;30) = 109.2555$; $p < 0.0000$			
Constant	−30.5880	9.7897	−3.1245	0.0039
Variable X1	14.0833	1.0354	13.6012	0.0000
Variable X2	−0.3945	0.1608	−2.4525	0.0202
Cyprus	Regression statistics: $R = 0.9776$; $R^2 = 0.9556$; Adjusted $R^2 = 0.9542$; $F(1;31) = 667.9116$; $p < 0.0000$			
Constant	15.9418	5.0103	3.1818	0.0033
Variable X1	55.3942	2.1434	25.8440	0.0000
Czech Republic	Regression statistics: $R = 0.9620$; $R^2 = 0.9255$; Adjusted $R^2 = 0.9178$; $F(3;29) = 120.0628$; $p < 0.0000$			
Constant	−161.0103	23.8936	−6.7386	0.0000
Variable X1	2.2585	0.2331	9.6884	0.0000
Variable X2	1.9782	0.5215	3.7937	0.0007
Variable X3	1.6004	0.2040	7.8445	0.0000
Denmark	Regression statistics: $R = 0.9836$; $R^2 = 0.9674$; Adjusted $R^2 = 0.9652$; $F(2;30) = 444.8693$; $p < 0.0000$			
Constant	35.5933	14.1092	2.5227	0.0172
Variable X1	3.7832	0.6897	5.4851	0.0000
Variable X2	−1.0436	0.0856	−12.1852	0.0000
Estonia	Regression statistics: $R = 0.9500$; $R^2 = 0.9026$; Adjusted $R^2 = 0.8961$; $F(2;30) = 138.9719$; $p < 0.0000$			
Constant	−15.7708	4.0735	−3.8715	0.0005
Variable X1	11.2258	0.6763	16.5993	0.0000
Variable X2	0.6373	0.1822	3.4984	0.0015
Finland	Regression statistics: $R = 0.6940$; $R^2 = 0.4817$; Adjusted $R^2 = 0.4281$; $F(3;29) = 8.9840$; $p < 0.0002$			
Constant	−803.0099	268.7749	−2.9877	0.0057
Variable X1	2.6313	0.7062	3.7262	0.0008
Variable X2	10.5636	3.5540	2.9723	0.0059
Variable X3	9.6741	3.1780	3.0441	0.0049
France	Regression statistics: $R = 0.8883$; $R^2 = 0.7890$; Adjusted $R^2 = 0.7822$; $F(1;31) = 115.9213$; $p < 0.0000$			
Constant	118.3223	2.5590	46.2380	0.0000
Variable X2	−3.1154	0.2894	−10.7667	0.0000
Germany	Regression statistics: $R = 0.9783$; $R^2 = 0.9570$; Adjusted $R^2 = 0.9526$; $F(3;29) = 215.1559$; $p < 0.0000$			
Constant	−250.1857	46.8220	−5.3433	0.0000
Variable X1	0.1690	0.0488	3.4634	0.0017
Variable X2	0.9676	0.3311	2.9228	0.0067
Variable X3	3.2243	0.4684	6.8835	0.0000
Greece	Regression statistics: $R = 0.9889$; $R^2 = 0.9778$; Adjusted $R^2 = 0.9764$; $F(2;30) = 661.5533$; $p < 0.0000$			
Constant	26.2233	4.6856	5.5966	0.0000
Variable X1	3.5994	0.1683	21.3821	0.0000
Variable X2	−1.4455	0.1022	−14.1451	0.0000
Hungary	Regression statistics: $R = 0.9442$; $R^2 = 0.8915$; Adjusted $R^2 = 0.8843$; $F(2;30) = 123.2797$; $p < 0.0000$			
Constant	−167.7838	16.0597	−10.4475	0.0000
Variable X1	2.1518	0.6997	3.0754	0.0045
Variable X3	2.2757	0.2070	10.9921	0.0000

Table 3. *Cont.*

	Coefficients	Standard Error	t-Statistic	*p*-Value
Ireland	Regression statistics: $R = 0.8825$; $R^2 = 0.7788$; Adjusted $R^2 = 0.7640$; $F(2;30) = 52.8103$; $p < 0.0000$			
Constant	56.6228	6.0282	9.3930	0.0000
Variable X1	4.7804	0.4697	10.1764	0.0000
Variable X2	−0.7056	0.1398	−5.0481	0.0000
Italy	Regression statistics: $R = 0.9901$; $R^2 = 0.9804$; Adjusted $R^2 = 0.9791$; $F(2;30) = 749.0428$; $p < 0.0000$			
Constant	72.7187	4.4166	16.4647	0.0000
Variable X1	0.2713	0.0256	10.6149	0.0000
Variable X2	−1.9610	0.0709	−27.6430	0.0000
Latvia	Regression statistics: $R = 0.5409$; $R^2 = 0.2925$; Adjusted $R^2 = 0.2454$; $F(2;30) = 6.2023$; $p < 0.0056$			
Constant	−173.9936	62.4125	−2.7878	0.0091
Variable X1	26.3625	7.9082	3.3335	0.0023
Variable X2	4.5193	1.6381	2.7589	0.0098
Lithuania	Regression statistics: $R = 0.9682$; $R^2 = 0.9373$; Adjusted $R^2 = 0.9331$; $F(2;30) = 224.3011$; $p < 0.0000$			
Constant	−28.7126	4.2163	−6.8099	0.0000
Variable X1	8.2778	0.4358	18.9939	0.0000
Variable X2	0.8183	0.2406	3.4006	0.0019
Luxembourg	Regression statistics: $R = 0.7972$; $R^2 = 0.6355$; Adjusted $R^2 = 0.6112$; $F(2;30) = 26.1545$; $p < 0.0000$			
Constant	22.1418	10.3433	2.1407	0.0405
Variable X1	17.8544	2.5942	6.8824	0.0000
Variable X2	−1.5068	0.3881	−3.8826	0.0005
Malta	Regression statistics: $R = 0.8781$; $R^2 = 0.7711$; Adjusted $R^2 = 0.7568$; $F(1;16) = 53.9107$; $p < 0.0000$			
Constant	119.0317	2.6468	44.9720	0.0000
Variable X2	−3.4869	0.4749	−7.3424	0.0000
The Netherlands	Regression statistics: $R = 0.9489$; $R^2 = 0.9005$; Adjusted $R^2 = 0.8973$; $F(1;31) = 280.5192$; $p < 0.0000$			
Constant	103.9937	0.7138	145.6969	0.0000
Variable X2	−2.5832	0.1542	−16.7487	0.0000
Poland	Regression statistics: $R = 0.4762$; $R^2 = 0.2268$; Adjusted $R^2 = 0.2019$; $F(1;31) = 9.0933$; $p < 0.0051$			
Constant	89.3463	1.6736	53.3868	0.0000
Variable X2	−1.2297	0.4078	−3.0155	0.0051
Portugal	Regression statistics: $R = 0.7001$; $R^2 = 0.4902$; Adjusted $R^2 = 0.4737$; $F(1;31) = 29.8048$; $p < 0.0000$			
Constant	11.6390	16.5961	0.7013	0.4883
Variable X1	4.2517	0.7788	5.4594	0.0000
Romania	Regression statistics: $R = 0.9906$; $R^2 = 0.9814$; Adjusted $R^2 = 0.9801$; $F(2;30) = 789.6766$; $p < 0.0000$			
Constant	−103.3504	6.4195	−16.0995	0.0000
Variable X1	1.3875	0.1211	11.4558	0.0000
Variable X3	1.2170	0.1179	10.3193	0.0000
Slovakia	Regression statistics: $R = 0.9622$; $R^2 = 0.9258$; Adjusted $R^2 = 0.9182$; $F(3;29) = 120.6569$; $p < 0.0000$			
Constant	−78.1099	26.0551	−2.9979	0.0055
Variable X1	5.9136	0.9041	6.5410	0.0000
Variable X2	−0.9983	0.4805	−2.0775	0.0467
Variable X3	0.6860	0.2288	2.9979	0.0055
Slovenia	Regression statistics: $R = 0.3521$; $R^2 = 0.1240$; Adjusted $R^2 = 0.0957$; $F(1;31) = 4.3867$; $p < 0.0000$			
Constant	194.8440	46.7552	4.1673	0.0002
Variable X3	−1.4662	0.7000	−2.0944	0.0445
Spain	Regression statistics: $R = 0.9830$; $R^2 = 0.9664$; Adjusted $R^2 = 0.9641$; $F(2;30) = 431.1652$; $p < 0.0000$			
Constant	30.2035	4.3188	6.9934	0.0000
Variable X1	1.0391	0.0390	26.6214	0.0000
Variable X2	−2.1294	0.1122	−18.9860	0.0000
Sweden	Regression statistics: $R = 0.8570$; $R^2 = 0.7344$; Adjusted $R^2 = 0.7258$; $F(1, 31) = 85.7162$; $p < 0.0000$			
Constant	223.9805	16.4779	13.5928	0.0000
Variable X2	−4.0123	0.4334	−9.2583	0.0000

The results of the regression analysis (Table 3) indicated that in the majority of EU countries (20 out of 27), the improvement in energy efficiency had an impact on reducing greenhouse gas emission levels between 1990 and 2022. In most countries, this positive influence primarily applied to primary energy rather than final energy, indicating that the improvement in energy efficiency and the consequent reduction in greenhouse gas emissions primarily occurred through efficiency enhancements in the industry. The regression analysis also demonstrated that renewable energy sources played a significant role in influencing the progress of decarbonization processes (Table 3). The share of renewable energy consumption increased in all countries during the study period, while the share of fossil fuels decreased, with Lithuania being the only exception (Figure 4). This statistically significant negative impact was observed in 21 out of 27 countries.

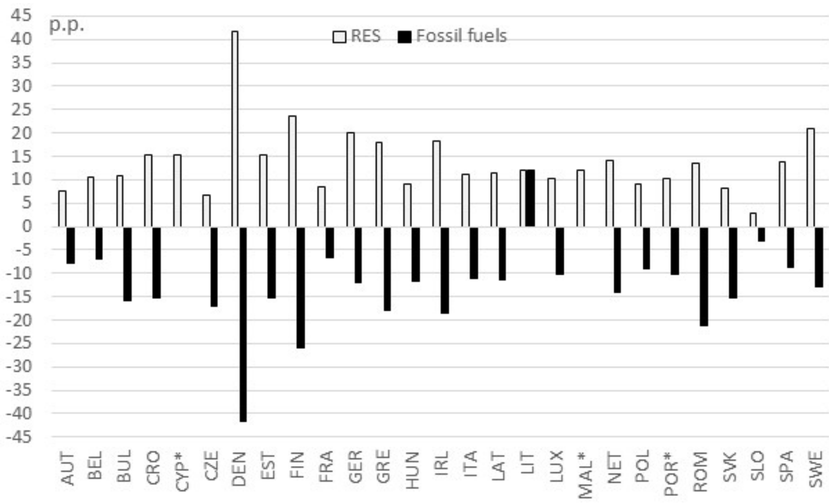

Figure 4. Change in the share of renewables and fossil fuels in primary energy consumption in 1990–2022 in the EU member states * [118,119]. * Due to data availability, the research period for Cyprus and Malta is 2002–2021, and for Portugal, it is 1996–2022.

The factor, which statistically significantly influenced the reduction in greenhouse gas emission levels in the smallest number of countries, was the reduction in primary energy consumption coming from fossil fuels. This impact was observed in eight countries. However, it is essential to note that the decrease in the share of fossil fuels in energy consumption between 1990 and 2022 occurred in all EU member states, except Lithuania. The lack of a statistically significant impact of this factor was due to the fact that it resulted from an increase in the quantity of renewable energy sources replacing the energy derived from fossil fuels.

Figure 5 illustrates which of the factors examined in the study statistically significantly influenced the level of greenhouse gas emissions in the European Union between 1990 and 2022. The impact is presented in the results shown in Table 3, while Figure 5 graphically indicates how the influence of individual factors is distributed geographically. It was found that the impact of energy efficiency mainly affected the central and eastern parts of the European Union and—with the exception of countries relying on nuclear energy or hydropower—covered the entire EU area.

It is worth noting that the influence of reducing the share of fossil fuels in energy consumption pertained to central Europe, along with countries where decarbonization primarily occurs through the efficiency of primary energy. Figure 5 also demonstrates that the increase in the share of renewable energy sources in energy consumption statistically significantly influenced the entire Europe, but most strongly, the western part of Europe and Scandinavia.

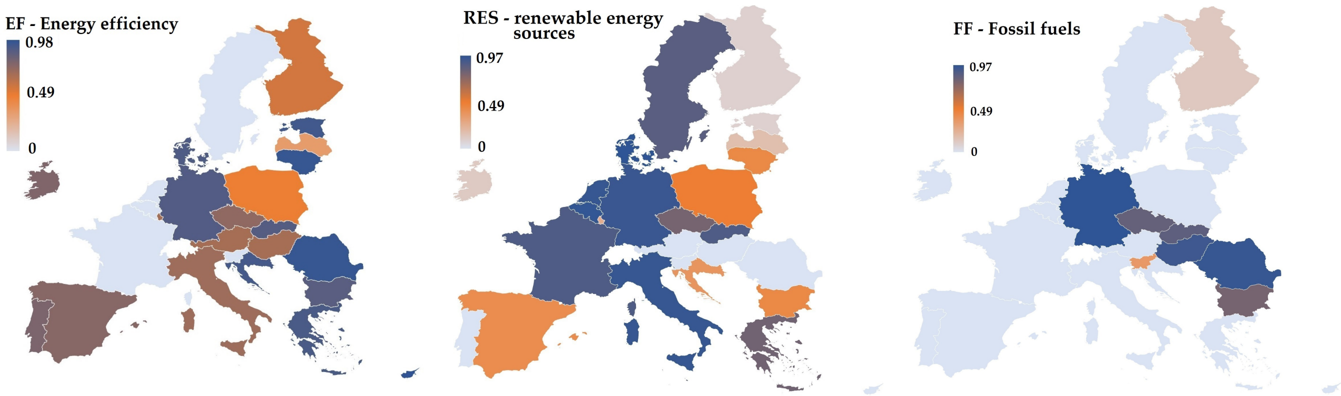

Figure 5. Factors influencing greenhouse gas emissions in EU member states.

5. Discussion

The regression analysis results offer valuable insights into the factors influencing greenhouse gas emissions in EU member states, providing a meaningful connection to the theoretical expectations in environmental economics and energy policy.

In Austria, the positive impact of energy efficiency measures on the reduction in greenhouse gas emissions has aligned with expectations [120,121]. The implementation of improved energy efficiency practices is believed to have played a significant role in lowering the overall energy consumption within the country [122]. This, in turn, has led to a consequential reduction in emissions [123]. The observed correlation between enhanced energy efficiency and the decrease in greenhouse gas emissions underscores the effectiveness of Austria's efforts to promote and implement sustainable practices in its energy sector. The success in achieving emission reductions through a focus on energy efficiency highlights the importance of such strategies in the broader context of mitigating climate change and promoting environmental sustainability.

Belgium's notable reduction in emissions, attributable to the increased adoption of renewable energy sources, is consistent with the underlying theoretical framework [124,125]. The premise that an elevated dependence on renewables displaces the consumption of fossil fuels, thereby resulting in a decrease in emissions, finds affirmation in the Belgian context. The negative coefficient associated with the renewable energy variable in Belgium signals a successful incorporation of renewable sources into the country's energy mix. This successful integration has evidently played a significant role in contributing to substantial reductions in overall emissions.

The observed negative impact emphasizes the effectiveness of Belgium's commitment to transitioning toward cleaner and more sustainable energy practices. The incorporation of renewable energy sources has not only diversified the energy portfolio but has also demonstrated its potential in mitigating the environmental impact associated with traditional energy sources. Belgium's experience serves as a noteworthy example of how strategic investments and policies supporting renewable energy can yield tangible benefits in terms of environmental conservation and emission reduction, aligning with broader global efforts to combat climate change [124].

The case of Bulgaria demonstrates a comprehensive approach to decarbonization [126]. The positive coefficients for energy efficiency, renewable energy and fossil fuel reduction indicate a multifaceted strategy, which has effectively contributed to reducing greenhouse gas emissions. Through a nuanced strategy, the country has successfully addressed various facets of its energy landscape, as evidenced by the positive coefficients associated with energy efficiency, renewable energy and fossil fuel reduction. These coefficients signify that Bulgaria has strategically employed a multifaceted approach, encompassing improvements in energy efficiency, increased integration of renewable energy sources and a deliberate reduction in reliance on fossil fuels [127,128].

The overall regression analysis results for the majority of EU countries—showing the positive influence of energy efficiency on emission reduction—resonate with the theoretical understanding that improvements in energy efficiency lead to a lower environmental impact. Moreover, the statistically significant impact of renewable energy sources in influencing decarbonization processes underscores the importance of transitioning toward cleaner energy alternatives.

The lack of a statistically significant impact of the reduction in primary energy consumption from fossil fuels in some countries might be explained by the intricate dynamics of energy transition. In cases where this factor did not show a significant impact, it is attributed to the increase in the quantity of renewable energy sources replacing the energy derived from fossil fuels.

The geographical distribution illustrated in Figure 5 provides a visual representation of how the impacts are distributed across the European Union. The findings further emphasize that different regions may have distinct drivers for emission reduction, aligning with their energy mix and decarbonization strategies.

The results of this study bear significant implications for shaping and refining the European Union's decarbonization policy. The positive influence of energy efficiency improvements on reducing greenhouse gas emissions across the majority of EU member states underscores the importance of prioritizing and incentivizing measures, which enhance energy efficiency. This calls for continued policy support for initiatives aimed at improving industrial processes, optimizing energy use and promoting technological advancements, which contribute to overall energy efficiency gains.

The notable impact of renewable energy sources on decarbonization, as indicated by the regression analysis results, highlights the need for sustained efforts in promoting and integrating renewables into the energy mix. Policymakers should continue to focus on creating an enabling environment for renewable energy deployment, offering financial incentives and fostering innovation to ensure a smooth transition away from fossil fuels.

The geographical distribution of impacts depicted in Figure 5 emphasizes the importance of tailoring decarbonization policies to regional characteristics. Different parts of the EU exhibit varying degrees of responsiveness to different factors, suggesting the need for nuanced, region-specific approaches. Policymakers should take into account the diverse energy landscapes and transition strategies within EU member states, allowing for flexibility in the implementation of targeted measures.

While the reduction in primary energy consumption from fossil fuels did not consistently exhibit a statistically significant impact in all countries, its overall contribution to emission reduction cannot be disregarded. The study suggests that, in specific contexts, the reduction in fossil fuel dependence may be intricately linked to the concurrent increase in renewable energy sources. Policymakers should recognize and support this dynamic, potentially by offering transitional support and incentives for renewable energy adoption.

The paper's results advocate for a comprehensive and adaptive approach to the EU decarbonization policy. Continued emphasis on energy efficiency, robust support for renewable energy integration and recognition of region-specific dynamics will be crucial for achieving the ambitious emission reduction targets set by the European Union. The findings provide actionable insights, which policymakers can leverage to fine-tune existing strategies and formulate new policies, which align with the evolving landscape of sustainable energy practices in the EU.

The results of the paper align closely with established theoretical frameworks in the field of environmental science and energy policy [56–58]. The positive correlation between improvements in energy efficiency and reduced greenhouse gas emissions, as observed in the regression analysis, resonates with the widely acknowledged principle that enhancing energy efficiency is a key driver in mitigating environmental impact. This correlation substantiates the theoretical understanding that increasing energy efficiency leads to a more sustainable and environmentally friendly energy system [61–64]. The study's identification of energy efficiency improvements as a significant factor influencing emission reduction thus reinforces and supports existing theoretical foundations.

The study's emphasis on the positive impact of renewable energy sources on decarbonization is consistent with theoretical frameworks advocating for a transition to cleaner and renewable energy alternatives [40,41]. The theory posits that a shift toward renewables contributes to a decrease in reliance on fossil fuels and, consequently, a reduction in greenhouse gas emissions [47–49]. The empirical findings of the study, showcasing the increase in the share of renewable energy consumption in all countries, affirm the theoretical underpinnings of the positive role renewables play in achieving sustainability goals. This alignment between empirical evidence and theoretical expectations strengthens the credibility of both the paper's results and the existing theoretical frameworks.

The theory emphasizing the importance of reducing the share of fossil fuels in energy consumption to mitigate climate change [129–131] also aligns closely with the study's findings. The statistically significant negative impact observed in most countries, signifying a decrease in fossil fuel usage, underscores the theoretical understanding that reducing reliance on fossil fuels is integral to achieving decarbonization targets [132,133]. The exception of Lithuania [134] (attributed to an increase in renewable energy replacing fossil fuels) supports the theory that diversifying the energy mix is crucial for effective decarbonization. This consistency between theoretical expectations and observed outcomes adds robustness to both the theoretical frameworks and the empirical findings of the study.

Additionally, the study's acknowledgment of regional variations in the impact of different factors resonates with the theoretical recognition that one-size-fits-all approaches may not be optimal. The theory acknowledges the diverse socio-economic and geographical contexts within the EU, emphasizing the need for tailored, region-specific strategies. The paper's identification of regional influences on energy efficiency and the share of renewable energy aligns with this theoretical understanding, emphasizing the importance of nuanced policy approaches. This alignment reinforces the relevance of theory in guiding policymakers to adopt flexible and adaptive policy frameworks, which consider the diverse needs and characteristics of different regions within the EU [55–61].

Several policy recommendations emerge to strengthen and optimize decarbonization efforts within the European Union. First, acknowledging the significant impact of energy efficiency improvements on reducing greenhouse gas emissions, policymakers should prioritize and incentivize initiatives aimed at enhancing energy efficiency across various sectors. This may involve implementing stringent energy efficiency standards, promoting technological innovation and fostering public–private partnerships to drive sustainable practices.

The study underscores the positive influence of renewable energy sources on decarbonization. Therefore, policymakers should continue to invest in and promote the development and integration of renewable energy technologies. This could include expanding the financial incentives, streamlining regulatory processes and fostering international collaborations to facilitate the transition toward a more sustainable energy mix.

Given the observed variation in the impact of reducing the share of fossil fuels across EU member states, tailored strategies should be developed to address the unique challenges and opportunities within each country. Policymakers could consider region-specific policies, which align with the energy landscape and socio-economic conditions, ensuring a targeted and effective approach to decarbonization.

Additionally, the paper highlights the importance of recognizing regional variations in the influence of different factors. Policymakers should take these nuances into account when designing and implementing decarbonization policies. This involves adopting a flexible and adaptive policy framework, which considers the diverse needs and characteristics of different regions within the EU.

Lastly, as the study identifies limitations in data availability and acknowledges potential gaps in capturing recent developments, policymakers should prioritize enhancing data collection and analysis capabilities. This could involve investing in comprehensive data infrastructure, fostering international collaboration for data sharing and continuously updating information to ensure that policies are informed by the latest trends and insights.

Drawing insights from the comprehensive analysis conducted in this paper, tailored recommendations for region-specific decarbonization policies emerge as imperative. Recognizing the diverse energy landscapes and transition trajectories within European Union member states, a nuanced approach is essential for effective and targeted interventions.

For countries, which have showcased a significant positive correlation between energy efficiency improvements and emission reduction, such as Germany and Sweden, policymakers are encouraged to fortify existing initiatives. This entails continued support for advancements in industrial processes, optimization of energy consumption and the promotion of technological innovations. Furthermore, these countries might benefit from fostering collaborations between industries and research institutions to accelerate the adoption of cutting-edge energy-efficient practices.

In the case of regions where the share of renewable energy sources has proven instrumental in decarbonization, such as Denmark and The Netherlands, policymakers should prioritize sustaining an enabling environment for renewables. This involves not only extending the financial incentives for renewable energy projects but also actively engaging in research and development to overcome technology-specific challenges. Tailored support for decentralized renewable energy projects and community-based initiatives can further enhance the renewable energy transition.

For those countries where the reduction in fossil fuel dependence is intricately linked with an increase in renewable energy, transitional support mechanisms become crucial. Countries such as Bulgaria, exemplified in this study, may benefit from targeted incentives for industries to shift toward renewable energy sources during the transitional phase. Policymakers should consider crafting policies, which facilitate a smooth and economically viable transition, balancing the immediate economic concerns of industries with the long-term benefits of reduced carbon emissions.

Acknowledging the variations in regional characteristics, it is paramount for policymakers to conduct in-depth assessments of local challenges and opportunities. In regions facing unique hurdles, such as Cyprus, Malta and Portugal, where data availability poses limitations, efforts should be directed toward improving data collection infrastructure. Policymakers can collaborate with relevant agencies to ensure a more accurate representation of the regional dynamics, thereby facilitating the design of tailored and effective decarbonization strategies.

6. Conclusions

This research provides valuable insights into the complex dynamics of decarbonization efforts within the EU from 1990 to 2022. The positive correlation between improvements in energy efficiency, increased utilization of renewable energy sources and a deliberate reduction in fossil fuel reliance emerges as a common thread across the majority of EU member states. The multifaceted strategy employed by countries such as Bulgaria, as exemplified in this study, underscores the effectiveness of a comprehensive approach to decarbonization.

The findings highlight the importance of prioritizing and incentivizing measures, which enhance energy efficiency. The positive influence of energy efficiency improvements on reducing greenhouse gas emissions aligns with established environmental principles, emphasizing the pivotal role of energy efficiency in mitigating the environmental impact. Policymakers are encouraged to continue supporting initiatives aimed at improving industrial processes, optimizing energy use and fostering technological advancements to achieve overall energy efficiency gains.

Renewable energy sources emerge as a significant factor influencing decarbonization, emphasizing the need for sustained efforts in promoting and integrating renewables into the energy mix. The study advocates for creating an enabling environment for renewable energy deployment, offering financial incentives and fostering innovation to ensure a smooth transition away from fossil fuels. The increase in the share of renewable energy consumption observed across all countries reinforces the theoretical underpinnings of the positive role renewables play in achieving sustainability goals.

While the reduction in primary energy consumption from fossil fuels did not consistently exhibit a statistically significant impact in all countries, its overall contribution to emission reduction cannot be disregarded. The study suggests that, in specific contexts, the reduction in fossil fuel dependence may be intricately linked to the concurrent increase in renewable energy sources. Policymakers are encouraged to recognize and support this dynamic, potentially offering transitional support and incentives for renewable energy adoption.

The results of this study advocate for a comprehensive and adaptive approach to the EU decarbonization policy. Continued emphasis on energy efficiency, robust support for renewable energy integration and recognition of region-specific dynamics will be crucial for achieving the ambitious emission reduction targets set by the EU. The findings provide actionable insights, which policymakers can leverage to fine-tune existing strategies and formulate new policies aligned with the evolving landscape of sustainable energy practices in the EU.

The observed regional variations in the impact of different factors underscore the importance of tailoring decarbonization policies to regional characteristics. Policymakers should consider the diverse energy landscapes and transition strategies within EU member states, allowing for flexibility in the implementation of targeted measures. A one-size-fits-all approach may not be optimal, and nuanced, region-specific strategies are essential for effective decarbonization.

The main scientific value of this paper lies in its comprehensive examination of decarbonization efforts within the European Union from 1990 to 2022. By employing regression analysis, the study investigates the impact of key factors, including energy efficiency, renewable energy utilization and reduction in fossil fuel dependence, across various EU member states. The paper contributes to the existing body of knowledge by highlighting the positive correlation between energy efficiency improvements and reduced greenhouse gas emissions, as well as the significant role of renewable energy sources in influencing decarbonization processes.

This paper brings a novel and in-depth perspective to the discourse on decarbonization efforts within the European Union from 1990 to 2022. Through the application of regression analysis, the study delves into the nuanced dynamics of key factors influencing decarbonization, notably energy efficiency improvements, increased utilization of renewable energy sources and deliberate reductions in fossil fuel reliance. By examining these factors across diverse EU member states, the research contributes significantly to the existing body of knowledge by elucidating a positive correlation between enhanced energy efficiency and reduced greenhouse gas emissions. Moreover, the paper sheds light on the pivotal role played by renewable energy sources in shaping the decarbonization landscape.

The novelty of this research lies not only in its identification of overarching trends but also in its advocacy for a comprehensive and adaptive approach to EU decarbonization policy. It emphasizes the continued importance of prioritizing energy efficiency, supporting renewable energy integration and recognizing the unique dynamics within different regions. The study acknowledges the need for nuanced, region-specific strategies, challenging the viability of a one-size-fits-all approach to decarbonization. In doing so, it underscores the critical role of tailoring policies to the diverse energy landscapes and transition strategies present in various EU member states.

This paper is not limited to theoretical discussions but provides actionable insights for policymakers. It encourages the continuation of efforts to enhance industrial processes, optimize energy use and foster technological advancements to achieve overarching energy efficiency gains. The call for creating an enabling environment for renewable energy deployment, offering financial incentives and promoting innovation further underscores the practical implications of the research.

Additionally, the study does not shy away from acknowledging its limitations, such as the temporal scope, which might not capture recent developments and variations in data availability for specific countries. This self-awareness positions the paper as a foundation for future research endeavors, highlighting the evolving nature of sustainable energy practices within the EU. In essence, the novelty of this paper lies not only in its substantive findings but also in its forward-looking approach, acknowledging the dynamic nature of decarbonization challenges and providing a platform for ongoing refinement of strategies and policies in pursuit of ambitious emission reduction targets.

Author Contributions: The main contributions of the team of authors can be described as follows: Conceptualization, B.G., R.W. and R.N.; methodology, R.N.; software, B.G., R.W. and R.N.; validation, B.G., R.W. and R.N.; formal analysis, B.G., R.W. and R.N.; investigation, B.G., R.W. and R.N.; resources, B.G., R.W. and R.N.; data curation, R.N.; writing—original draft preparation, B.G., R.W., R.N. and W.W.G.; writing—review and editing, B.G., R.W. and R.N.; visualization, B.G., R.W. and R.N.; supervision, B.G., R.W., R.N. and W.W.G.; funding acquisition, B.G. and R.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Silesian University of Technology: BK-264/ROZ1/2024 (13/010/BK_24/0081),(11/040/BK_24/0036), BK-204/RM4/2024.

Data Availability Statement: All the data used are contained in the paper.

Conflicts of Interest: The authors declare no conflicts of interest.

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