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Energy Economic Development in Europe

Edited by
José Alberto Fuinhas, Matheus Koengkan and
Nuno Miguel Barateiro Gonçalves Silva

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About the Editors

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Professor José Alberto Fuinhas is a renowned expert in the field of economics, holding a Ph.D. in economics and serving as a professor of Monetary Economics and Intermediate Econometrics at the Faculty of Economics of the University of Coimbra in Portugal. With years of experience in his field, Professor Fuinhas is also an accomplished Macroeconomics, Energy Economics, and Environmental Economics researcher. He is affiliated with the prestigious CeBER (Centre for Business and Economics Research), where he conducts ground-breaking research and contributes to developing new theories and practices in his field.

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Preface to "Energy Economic Development in Europe"

Renewable energy has emerged as a promising alternative to fossil fuels, owing to the need to reduce carbon dioxide emissions and enhance energy security. Europe has been a frontrunner in this transition, with a rapid increase in the installed capacity of new renewable energies. However, as the region strives to meet the Paris Agreement goals and attain energy independence, it confronts numerous challenges that require strategic policies and actions to overcome.

This Special Issue aims to address the primary challenges faced by Europe in this transition process and the policies and actions it can undertake to foster renewable energy growth while ensuring energy security. The collection of 10 articles presented in this Special Issue delves into a range of issues, including the intermittency problem of solar and wind energy sources, the role of energy policies in promoting renewable energy sources, and the integration of energy grids and markets. Technological progress and investment barriers to renewable energy development are also discussed.

The papers cover a wide range of topics across various countries and sectors, including the acceptance of electromobility in Portugal, greenfield investments as a catalyst for green economic growth, and financial incentives for eco-friendly housing in the Lisbon metropolitan area. The collection also includes studies on the history and benefits of district heating in Denmark, the optimization of coal supply in Ukraine, and the impact of energy policies on residential energy efficiency in Portugal. The impact of natural gas, oil, and renewables consumption on carbon dioxide emissions in Europe, as well as the nexus between financial development, FDI, and CO_2 emissions, are also analyzed. Furthermore, the impact of fossil fuel and biofuel boilers in Ukraine on the levelized cost of heat and the development of renewable energy markets and public awareness in Poland and Lithuania are also examined.

Overall, this collection of empirical and analytical papers aims to provide insights into the current state of renewable energy in Europe, its challenges, and the policies and actions that can be implemented to achieve a sustainable energy future. We hope that this Special Issue Reprint will serve as a valuable resource for policymakers, academics, and practitioners working in the field of renewable energy.

José Alberto Fuinhas, Matheus Koengkan, and Nuno Miguel Barateiro Gonçalves Silva
Editors

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Article

Assessment of Selected Determinants Affecting the Acceptance of the Development of Electromobility by the Private and Business Sectors—A Case Study in Portugal

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Abstract: The energy transition requires widespread electrification of the transport sector. To promote the penetration of electric vehicles (EVs), it is essential to understand consumers' perceptions and behavior, particularly regarding the main determinants of EV purchase and the acceptance of electric mobility (EM). With this aim, we focused on an industrialized city in Portugal, addressing the differences between the effective ownership of an EV and the acceptability of EM and between the domestic sector (DS) and the business sector (BS) through questionnaires. Our results indicate that sociodemographic variables are the main determinants of the purchase of EVs and the acceptance of EM in the DS. Men and higher income individuals are more likely to own an EV. On the other hand, younger generations are more likely to have high EM acceptance. Individuals who already own an EV are the ones that have the desire and economic means to do so, regardless of any incentives. Still, widespread market penetration of EVs requires incentives for individuals who desire to own one of these vehicles but do not have the economic power to do so. Additionally, the DS and the BS behave differently; hence, specially designed policies are needed.

Keywords: electromobility; development conditions; market sectors; data analysis; statistical methods

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1. Introduction

Climate change and its impact on the planet are issues of utmost importance for both society and policy makers. In view of the rapid evolution of these changes, various large-scale impacts are anticipated, such as changes in the disposition of communities, the deterioration of the health and safety of current and future generations, the rise in the average seawater level [1], deforestation [2], and catastrophic events [3–5].

Over the years, several Synthesis Reports of the Intergovernmental Panel on Climate Change (IPCC) have indicated that, in order to ensure an increase in global temperature below 2 °C compared to the pre-industrial period, a departure from the business-as-usual scenario (BAU) [6] is urgently needed, with major changes in current business models, the restructuring of different sectors of the economy, and the implementation of the concepts of innovation and sustainability. Additionally, the later the intervention, the higher the associated costs and technological, economic, social, and institutional challenges [7].

The energy sector accounts for about two-thirds of total greenhouse gas (GHG) emissions at the global level [8], to which fossil fuels are the main contributors. It is, therefore, necessary to restructure this sector, focusing mainly on the production of electricity through renewable energy sources (RES) [9]. In turn, the transport sector accounts for one-quarter of energy-related GHG emissions, of which 70% are related to road transport [10–12]. Passenger cars account for about half of the transport sector's global energy use [8]. In Europe, these account for 83.4% of domestic transport and contribute to about two-thirds of total road emissions. On the other hand, commercial, light, and heavy vehicles represent about 13% of the total vehicles of the European continent and account for one-third of the total emissions of the transport sector [13]. Thus, the substitution of fossil fuels by greener and more efficient alternatives in the transport sector is essential, particularly through electrical vehicles (EVs) [14].

The technological advance of electric mobility (EM), its applicability, energy management, and energy storage systems represent crucial factors for the development of the energy transition [13,15], contributing to reductions in GHG emissions and energy consumption and improvements in countries' energy security [8]. In addition, public health will benefit from the reduction in air pollution [15]. Several countries are planning to discontinue sales of traditional vehicles between 2025 and 2050 [16]. According to Hawkins [17], the combination of EVs with a European energy mix more based on RES will provide a 10–20% reduction in global warming potential. For the transport of goods, if electrification is possible, it could have a major environmental impact. In addition, companies will be able to benefit from greater economic benefits (offsetting the high initial costs with lower operating costs) and image improvements [13]. Still, currently, electric vehicles have higher purchase costs than traditional ones essentially due to the high costs of batteries and the electric drive train [18]. Despite this factor, EVs are increasingly popular among consumers, which is likely related to other factors besides the cost.

Considering the data provided and studied by Associação de Utilizadores de Veículos Elétricos (www.uve.pt), it is possible to simulate the operating cost of driving 100 Km for different types of cars. In Table 1, we present some cost simulations of traveling 100 Km for different types of vehicles.

Table 1. Operational costs of traveling 100 Km for different types of vehicles.

Type of Vehicle	Average Consumption	Average Price	Average Cost for 100 Km
Diesel vehicle	7l/100 Km	1.953 €	13.67 €
Gasoline Vehicle	6l/100 Km	1.808 €	10.85 €
EV (domestic charge)	16 kWh/100 Km	0.400 €	6.40 €
EV (FCS 50 kW)	16 kWh/100 Km	0.220 €	3.52 €

Regarding the price of gasoline and diesel, the average prices of the different types of fossil fuels were used and their average was calculated. For the price of kWh for electric mobility, the cost of charging in the public charging network in Portugal (50 kW fast charging station (FCS)) was used. For the price of kWh for domestic electricity, the regulated market price was used (Last Resource Supplier—SU Eletricidade).

It is possible to observe in Table 1 that the operational cost of traveling 100 Km is substantially lower for the EV. However, it is important to note that the calculated values may change due to several variables, such as:

- Electricity supplier tariff;
- The chosen charging station, and the available power;
- The battery charge level at the time of charging;
- The temperature and the battery itself.

What we intended to show is that for normal and current use, considering the average fuel prices and the reference prices indicated by electricity suppliers, it will always be more economical to use an electric vehicle.

The European Commission has set a series of targets which include the elimination of atmospheric emissions from passenger transport by 2050 and from urban freight transport by 2030. Several European legislations have been put in place to promote the desired transition in the transport sector. For example, the Act on electromobility and alternative fuels, or the directive of 22 October 2014 (2014/94/EU) which imposed on European countries the obligation to transform the field of fuels [19]. Other relevant legislation includes the Euro 7 exhaust gas standards which will apply to all motor vehicles, imposing limits on the pollution arising from engine combustion. Hence, EM plays a key role in this transition, in particular through the introduction of 100% electric cars [13]. To achieve this goal, it is important to ensure public access to charging stations for EVs with an appropriate infrastructure network. Through several incentives, the use of EVs has shown rapid progress since their introduction. In 2016, about 1% of total car sales revenue corresponded to EVs [8]. In 2018, the global stock exceeded 5 million units, a 63% increase over the previous year. In 2021, 45% of electric passenger cars were in China, 24% in Europe, and 22% in the USA [20]. In addition, the number of two- and three-wheel EVs has also been increasing progressively [8]. Still, the spread of EVs in different international markets remains relatively low with very little uniformity across the globe.

The acceptability of EM is fundamental to a proper energy transition in the transport sector. This acceptability may be affected by several factors. These factors can be a combination of technological, regulatory, institutional, economic, cultural, and behavioral aspects. Consumers' behavior is key to the penetration of EVs in the market. For example, apart from differences in costs, there are specific factors, such as environmental concerns, preference for the latest technologies, and status, among others, that may lead individuals to buy EVs instead of conventional ones. Fiscal and economic incentives may also play an important role. Additionally, it is possible that acceptance factors differ among sectors, for example, for the domestic and the business sectors.

Hence, a central part of this process will be to understand the social perceptions relating to EVs [21] and the responses of consumers, their preferences, motivations, and sociodemographic characteristics. This understanding allows, for example, the design of appropriate policy measures and the possibility of finding efficient policy solutions and exploring business innovation strategies [22]. According to Sovacool et al. [21], some aspects, such as occupation and household size, related to the role of consumers in the acceptance of EVs have been ignored in the literature.

Thus, this article aims to contribute to the understanding of consumers' perception and acceptance of EVs and to the identification of factors that significantly influence their development. For a deeper analysis, we analyze and compare both the business sector (BS) and the domestic sector (DS) in Portugal in a case study conducted in the municipality of Felgueiras. We chose this municipality because it is a highly industrialized one, where it is possible to obtain a combination of responses from the DS and BS; furthermore, it has a relatively high number of EVs.

Our research questions cover the following aspects: Do sociodemographic characteristics affect the preference for EVs? What are the main incentives and hindering factors behind the preference for EVs? Do the domestic and business sectors display different behaviors?

The main expected differences between the DS and BS relate to individual preferences. The DS, composed of single individuals, may have a stronger component of personal preferences contributing to the acceptance of EM. Often, automobiles are seen as a sign of status or an extension of an individual's personality. Economic and fiscal incentives are expected to be important for both cases. Other studies (e.g., Nogueira et al. [23]) have focused on the Portuguese case but covered distinct topics. Our contribution to the literature is twofold. Firstly, we compare the results regarding the effective purchase of an EV and the acceptability of EM. This can lead to a deeper analysis of the factors explaining the fact that some individuals accept EM but have not purchased an EV yet. Secondly, we perform a comparative analysis of the domestic and business sectors. As far as we know, this is the first attempt to perform this comparison.

The structure of the article is as follows. After this introduction, Section 2 presents some important literature on the topic divided by the most common factors affecting EM. Section 3 provides details on the Portuguese case. Section 4 describes the methodology and data. Section 5 describes the results of the research. Finally, Section 6 concludes the paper with a discussion of the main results of the research, indicating their limitations and practical applications, and of the future directions of research in this field.

2. Literature Review

The development of EM can be influenced by several factors, from political and financial incentives to consumer perceptions of it. Several studies have already been devoted to the analysis of these factors. For Long and Axsen [24], anticipating demand for emerging or non-existent technologies will be one of the main challenges associated with the development of EM, as it is difficult to predict future dynamics in consumer preferences, given their instability and uncertainty. In a study for the Nordic region, Sovacool et al. [21] stated that the adoption of EVs is, in a way, similar to that of quitting smoking or the regular practice of physical exercise, as it requires the breaking and substitution of behavioral patterns, so the choice of EVs by consumers is not just a preference of the consumer but also requires adaptation to factors such as low autonomy and limited availability of charging stations. The first group of factors that may have an influence on the acceptance of EM is composed of sociodemographic ones. These also include factors directly related to the perceptions, motivations, and intentions of individuals. For example, Biresselioglu et al. [13] indicated that demographic, personal, and lifestyle factors seemed to be essential in the preference for EVs. Neves et al. [25] showed that in Europe higher levels of employability and education contributed to a higher share of EVs. Using a broader approach, Novotny et al. [16] showed the importance of cultural differences for the acceptance of EV using a sample of 21 countries. For Portugal, de Jesus et al. [26] used lessons from the adoption of vehicles powered by gas, essentially propane and butane, or natural gas, to anticipate the evolution of the EV market. The authors highlighted environmental concerns and education levels as important factors to increase the intention to purchase EVs. Hensher et al. [27] found that urbanism, ecological awareness, technophilia, and experience in car sharing are generally factors that increase the acceptance of EVs. Greater acceptance of these vehicles could be achieved by targeting individuals who move frequently and live in urban areas, especially by emphasizing the experience of sharing EVs rather than conventional vehicles. Tu and Chun [28] highlighted the importance of the energy conservation and environmental protection of vehicles for the preference of Chinese consumers regarding EVs. Using an online questionnaire with a sample of Canadian individuals over the age of 19, Long and Axsen [24] found that, generally, the use of new mobility is associated with younger ages, higher education levels, higher incomes, and males. Other factors have also shown relevance, such as travel patterns, environmental awareness, and technology-oriented lifestyles. Qian and Yin [29] identified other important factors for Chinese consumers, such as a perceived increase in self-esteem rising from the alignment between electric mobility and personal values and beliefs. Hence, public initiatives to promote EVs should take into consideration the cultural values of individuals. Policy makers can use education, media, and advertising to improve the ME strand, even facilitating communication between community members with similar principles aimed at the consumption of environmentally friendly products. Aligned with the previous studies, we investigated the following hypotheses:

Hypothesis 1 (H1). *Sociodemographic factors affect the probability of individuals owning an EV.*

Hypothesis 2 (H2). *Sociodemographic factors affect the acceptability of EM.*

Another important set of determinants of the growth in EM is the environmental, economic, and fiscal incentives. Leurent and Windisch [15] identified factors that contribute positively to the economic accessibility of this technology, such as tax incentives for the acquisition of EVs and lower use costs. The authors indicated that these types of incentives apply in the transition phase, until the technology achieves economies of scale. In this context, the role played by governments has also been identified as a key factor in the development of EM in several countries. In China, Wang et al. [30] showed that subsidies granted by central and local governments, and large non-monetary incentives such as exemption from vehicle stamp duty, represented crucial factors. However, continued sales growth was threatened by China's persistent regional protectionism, the unsustainability of large subsidies, as well as several cases of fraud by car manufacturers. Geronikolos and Potoglou [31] stated that in Greece the governmental financial incentives were an important first step to promote EVs. The authors also indicated that the incentives applied should consider the different socioeconomic situations, avoiding inequalities. Lorentzen [32] studied the case of Norway, one of the most advanced markets for EVs in the world. The author emphasized the decisive intervention of the Norwegian government, through successive incentive policies, starting in 1990 with the exclusion of taxes on the purchase of EVs. According to the author, due to these incentives, EVs have become able to compete in price in the market and can reach even better values than conventional equivalent vehicles in terms of performance and/or capacity. Zhang et al. [33] found out, through a questionnaire, that environmental benefits perceived by the population are important to sustain the adoption of EVs in the post-subsidizing period. Nevertheless, in order to enable the mass adoption of these vehicles, it will be essential to increase economic benefits through advances in technology. For South Korea, Kim et al. [34] implemented a questionnaire on the perceived value and purchase intention of EVs, concluding that respondents considered the economic benefit associated with savings in the operating cost of vehicles to be important. Environmental benefits and conduction pleasure were also factors with a positive contribution to the adoption of EVs. De Jesus et al. [26] identified low gas emissions and green energy as critical factors for the adoption of EVs for Portugal. Among the economic benefits, an additional point is raised by Wroblewski and Lewicki [19] on the residual value of vehicles in a study in Poland. If this residual value is higher for EVs, this can be seen as an advantage of these types of vehicles. Other incentives, such as free or privileged parking spaces and priority circulation with access to roads for buses and taxis, have also been pointed out in the literature, for example, by Leurent and Windisch [15] and Lorentzen [32] in Norway. Hence, we tested the following hypotheses:

Hypothesis 3 (H3). *Some incentives (such as environmental, economic, fiscal, and parking and circulation advantages) increase the probability of purchasing an EV.*

Hypothesis 4 (H4). *Some incentives (such as environmental, economic, fiscal, and parking and circulation advantages) increase the acceptance of EM.*

On the other hand, some factors may hinder the penetration of EVs in the market. Leurent and Windisch [15] highlighted uncertainties regarding future costs, future public policies, and market development, especially in view of the evolution of oil and electricity prices. Biresselioglu et al. [13] identified barriers to EM, such as lack of familiarity with the eco-friendly product market, lack of reliability, non-competitive price, lack of motivation, low availability, model limitations, and technological uncertainty. Kim et al. [34] and de Jesus et al. [26] also highlighted the difficulties arising from the high cost of buying and replacing batteries. One of the most studied factors among the possible difficulties for EM penetration is the extensive existence of charging infrastructures. For example, in a study in Europe, Neves et al. [25] found that the development of batteries and the number of charging stations available are very significant drivers. This result was confirmed by Zhang et al. [33] who indicated that to reduce risk the installation of more charging stations is necessary. Geronikolos and Potoglou [31] emphasized the need for greater allocation of resources to the public charging infrastructure with national coverage in Greece to promote EV further. Desai et al. [18] also pointed out the relevance of the existence of charging stations and infrastructures, while Tu and Chun [28] indicated that vehicle charging is the biggest concern for consumers, and Kim et al. [34] pointed out that the risk associated with charging the vehicles was a significantly negative factor in the perception of their value. Sendek-Matysiak et al. [35] showed vehicle prices and operation costs as being the most relevant impediments to EV penetration. In particular, the authors showed the importance of charging conditions for the total cost of ownership of the vehicles. EVs charged at home tended to achieve cost parity sooner than the ones charged in public stations. Regarding this topic, we tested the following hypotheses:

Hypothesis 5 (H5). *Some barriers (such as higher prices and costs, uncertainty, and technical restrictions) decrease the probability of purchasing an EV.*

Hypothesis 6 (H6). *Some barriers (such as higher prices and costs, uncertainty, and technical restrictions) decrease the acceptance of EM.*

Another topic that was put forward in the literature as a relevant factor promoting EVs was the type of energy sources available. Neves et al. [25] and de Jesus et al. [26] defend that the increase in the share of EVs is promoted by increasing renewable energy generation.

Regarding the comparison between the DS and the BS, the literature is scarce. Neves et al. [25] showed that industries demonstrate a great potential for the adoption of EVs. However, Sendek-Matysiak et al. [35] pointed out that the progress of electromobility in the commercial vehicle sector has been slower than in the domestic sector, but, at the same time, these vehicles will allow firms to implement corporate social responsibility. Regarding this topic, we have the following research hypothesis:

Hypothesis 7 (H7). *The DS and the BS have similar responses when it comes to the incentives for and barriers to the ownership of EVs or the acceptability of EM.*

3. The Portuguese Case

In Portugal, the first ME Program was approved in 2009, with the aim of making the country one of the pioneers in this area [36]. In this plan, a strategy was defined to create a pilot infrastructure of high-powered public charging stations and promote EVs mainly through financial and tax incentives but also other benefits in circulation and parking [36]. Table 2 presents the financial incentives in force in Portugal.

In Portugal, the EV share has been increasing continuously and is currently around 20% of vehicle sales according to the UVE (Association of Drivers of Electric Vehicles). Our study focuses on the municipality of Felgueiras, which is located in the northern region of Portugal in the district of Porto. It has a total area of 115.74 km^2 and a population of 58,065 people (population density of 501.7 inhabitants/km^2). Currently, despite some rurality in the region, it is highly specialized in the footwear industry.

Table 2. Incentives and tax benefits associated with 100% electric vehicles in force in Portugal [37].

Particular	Enterprises
Incentive of EUR 4000 for the acquisition or leasing of electric light passenger vehicle, whose value may not exceed EUR 62,500, including VAT, up to the limit of 1300 vehicles or EUR 5,200,000, through the Environmental Fund.	Incentive of EUR 6000 for the acquisition or leasing of light goods vehicles, up to the limit of 150 vehicles or EUR 900,000, through the Environmental Fund.
Incentive of EUR 6000 for the acquisition or leasing of light goods vehicles, up to the limit of 150 vehicles or EUR 900,000, through the Environmental Fund.	Exemption from Autonomous Taxation (Article 88(3) of the IRC Code).
Exemption from payment of ISV (Vehicle Tax) (point (a) of Article 2(2) of Annex I to the Vehicle Tax Code).	Exemption from payment of ISV (point (a) of Article 2(2) of Annex I to the Vehicle Tax Code).
Exemption from payment of the IUC (Single Movement Tax) (point (e) of Article 5(1) of Annex II to the Vehicle Tax Code). Allocation of an incentive to install EV chargers in condominiums at 80% of the purchase value of a charger, up to a maximum of EUR 800 per post, and 80% of the value of the electrical installation up to a maximum of EUR 1000 per parking place, allowing the installation of up to 10 chargers per condominium, connected to the EM network through the Environmental Fund.	Exemption from payment of IUC (point (e) of Article 5(1) of Annex II to the Vehicle Tax Code). Deduction of all VAT relating to the costs of acquisition, manufacture or import, leasing, and processing into plug-in electric or hybrid vehicles of light passenger or mixed electric or hybrid plug-in vehicles; when considering tourist vehicles, the cost of purchase cannot exceed EUR 62,500 (point (f) of Article 21(2) of the VAT Code, with the value defined by Article 1(4) of Ordinance No. 467/2010, of July 7, as amended by Law No. 82-D/2014 of December 31).
	Deduction of all VAT associated with expenditure on electricity used *in electric or hybrid plug-in vehicles* (point (h) of Article 21(2) of the VAT Code).
	Deduction of all VAT associated with expenditure on electricity used in electric or hybrid plug-in vehicles (point (h) of Article 21(2) of the VAT Code).
	Depreciation of passenger or mixed vehicles is accepted as expenses in the part corresponding to the cost of acquisition or revaluation value up to the amount of EUR 62,500 (point (e) of Article 34(1) of the IRC Code, with the value defined by Article 1(4) of Ordinance No. 467/2010, 7, amended by Law No. 82-D/2014 of December 31).

Source: Own elaboration, using the information at MOBI.E.

4. Materials and Methods

4.1. Data

The data were obtained through a quantitative cross-sectional study, based on a non-probabilistic population sample obtained by convenience, between inhabitants and companies in the municipality of Felgueiras. The following parameters were considered as inclusion criteria: being a volunteer adult, being a driver's license holder (more than 18 years old), being an inhabitant of the municipality of Felgueiras, and, in the case of the BS, that the company in question be based in the municipality. We had no additional constraints in our sample and there were no output scenarios, since we were dealing with revealed preferences. The questionnaire was implemented online through the Google Forms platform for the domestic sector and face-to-face interviews for the business sector, preserving confidentiality through data protection. The dissemination of the questionnaire was carried out through specific networks to guarantee that respondents lived in Felgueiras. The final sample obtained was 256 individuals (DS) and 56 companies (BS). In the BS, the respondent was the owner or executive director of the firm.

Both questionnaires included two sections. In the first section, questions concerning sociodemographic data were asked. In the case of the DS, the gender, age group, educational qualifications, constitution and economic situation of the household, and habits of using cars on a daily basis of the participants were identified. In the BS, the size of the firm reflected by the number of employees and the constitution of the fleet were inquired.

Section 2 focused on the respondents' opinions regarding the incentives for and barriers to the adoption of EVs, and we also inquired whether respondents owned an EV and whether they considered EM a good option.

4.2. Methodology

To test the research hypotheses, we estimated two models. These two models allowed us to assess which factors influence the actual acquisition of EVs and also which factors contribute to the acceptability of EM. These are two related questions, but they do not necessarily overlap. In the first case, we dealt with revealed preferences. In order to buy an EV, respondents need to have the means to buy a vehicle and also need to meet the monetary conditions to buy one. On the other hand, in the second case, we dealt with stated preferences. The acceptance of EM is a broader concept. Respondents may consider buying an EV in the future but have not done so yet, either because their current vehicle does not need to be replaced yet or because they may not meet the monetary conditions. Thus, we performed 2 binary logit regressions (M1 and M2) using the Stata software [38]:

$$P(Y = 1|X) = G(\beta_0 + X\beta), \tag{1}$$

where G is the function taking on values strictly between zero and one, for all real numbers Z; and in the logit model, G is the logistic function:

$$G(Z) = \frac{\exp(Z)}{[1 - \exp(Z)]} = \Lambda(Z). \tag{2}$$

Before performing logit regression, we ensured that all the assumptions of the logit model were verified, according to Wooldridge [38]:

1. Dependent variable is categorical;
2. Data are independent, which means that there is no relationship between observations;
3. Data must not show multicollinearity;
4. Linear relationship between any continuous independent variable and the logit transformation of the dependent variable;
5. There are no extreme outliers.

All the assumptions were verified, and the Hosmer and Lemeshow tests confirmed that the model selected was appropriate, that is, fits the data well. In any case, in order to safeguard the robustness of the estimation, the models were estimated using the robust matrix for the standard errors.

In the first regression (M1), the dependent variable used was the answer to the question "Do you own an electric car?" and took the value 1 if the answer was positive and 0 otherwise, and in the second regression (M2) the dependent variable used was the answer to the question "Do you consider electric cars a good alternative to conventional vehicles?" and took the value 1 if the answer was positive and 0 otherwise.

In generic terms, and according to the model in question, where Y_i will vary according to the model used, we can express these models as follows:

$$Logit(Y_i) = \beta_0 + \sum_{j=1}^{n} \beta_j X_{ij} + e_i, \tag{3}$$

where Y_i represents EV ownership in the case of M1 or EM acceptability in the case of M2 for each individual i in the sample. β_0 is the constant term; β_j represents the natural logarithm of the odds ratio of the *j* variable; X_{ij} represents the *j* explanatory variable of the I individual, and e_i is the error term of the equation.

The explanatory variables can be divided into three groups. In the first group, we included sociodemographic and general characteristics. These corresponded to the domestic sector: gender, age, education level, type of employment, income level, and driving time. For the business sector, we considered the size of the firm and number of vehicles in the fleet. The second group of explanatory variables included, for both sectors, the importance given to incentives for EM, namely, fiscal incentives (such as tax reductions or incentives), economic incentives (such as lower operational costs), environmental benefits (lower emissions), free parking and priority circulation, the use of a new technology/modernity, and charging flexibility (the possibility to charge the vehicle at home or in urban centers). The third group of explanatory variables included, for both sectors, the importance given to potential barriers to EM, namely, non-competitive prices, higher costs (for example, maintenance of batteries), uncertainty, technical restrictions (such as low battery duration or high charging times), and unsafety. Table 3 describes the variables used in the model.

Table 3. Description of the variables used in the models.

Variable	Description	Category
Gen	Gender	0 = Male; 1 = Female
Age	Age	1 = [18–30]; 2 = [31–40]; and 3 = 41 or +
Educ	Education	0 = Undergraduate; 1 = Higher Education and/or Postgraduate
Sit_prof	Professional Situation	0 = Unemployed, Student, or Retired; 1 = Full-time employed, Part-time, or Self-employed
Income	Household Income	1 = [EUR 500–999]; 2 = [EUR 1000–1999]; 3 = [EUR 2000–3999]; and 4 = EUR 4000 or +
Driving	Driving Time	1 = less than 30 min.; 2 = [30 min.–1 h]; 3 = [1 h–2 h]; and 4 = 2 h or +
Incentive factors for the acquisition of EVs		
Fiscal	Fiscal Incentives	0 = No; 1 = Yes
Economic	Economic Incentives	0 = No; 1 = Yes
Environmental	Environmental Incentives	0 = No; 1 = Yes
Parking	Free Parking and Priority Circulation	0 = No; 1 = Yes
Tech	New Technology/Modernity	0 = No; 1 = Yes
Charging	Charging at Home and Urban Centers	0 = No; 1 = Yes
Barriers to the acquisition of EVs		
Price	Importance given to Price	0 = No; 1 = Yes
Cost	Importance given to Cost, Durability, and Maintenance	0 = No; 1 = Yes
Uncertainty	Importance given to Uncertainty/Lack of Information and Infrastructure	0 = No; 1 = Yes
Technical	Importance given to Technical Restrictions	0 = No; 1 = Yes
Unsafety	Importance given to Unsafety	0 = No; 1 = Yes

5. Results

5.1. Descriptive Analysis

In this section, we describe the responses obtained to each question concerning their frequency and number of respondents both for the DS and the BS.

Table 4 shows the sociodemographic characteristics of the respondents of the domestic sector. The majority of the participants were female (52.6%), were between 21 and 30 years old (64.3%), and had higher education (58.6%). Most participants were employees (68.9%) and had a net monthly income between EUR 1000 and 2000. About 40% had a driving time of less than 30 min per day.

Table 4. Descriptive analysis of respondents to the questionnaire related to the domestic sector.

Variable	Description	Frequency	
		n	%
Gender	Male	121	47.6
	Female	133	52.4
Age Group	18–30 years	169	66.5
	31–40 years	55	21.7
	>41 years	30	11.8
Education	Undergraduate	105	41.3
	Higher Education and/or Postgraduate	149	58.7
Professional Situation	Student/Unemployed	36	14.2
	Employee	175	68.9
	Self-employed	43	16.9
Net Monthly Income	EUR 500–999	80	31.5
	EUR 1.000–1.999	88	34.6
	EUR 2.000–3.999	74	29.1
	EUR >4.000	12	4.72
Daily Driving Time	<30 min	99	39.0
	30 min–1 h	96	37.8
	1–2 h	36	14.2
	>2 h	23	9.1
Incentive factors for the acquisition of EVs			
Fiscal Incentives	Yes	166	65.4
	No	88	34.6
Economic Benefits	Yes	188	74.0
	No	66	26.0
Environmental Benefits	Yes	187	73.6
	No	67	26.4
Free Parking and Priority Circulation	Yes	64	25.2
	No	190	75.8
New Technology/Modernity	Yes	63	24.8
	No	191	75.2
Charging at Home and Urban Centers	Yes	148	58.3
	No	106	41.7
Barriers to the acquisition of EVs			
Non-competitive price	Yes	137	53.9
	No	117	46.1
Cost, Durability, and Maintenance	Yes	161	63.4
	No	93	36.6
Uncertainty/Lack of Information and Infrastructure	Yes	163	64.2
	No	91	35.8
Technical Restrictions	Yes	140	55.1
	No	114	44.9
Lack of Security	Yes	29	11.4
	No	225	88.6

Regarding the BS, Table 5 shows the characteristics of the sample considered in the study. Most companies belong to the footwear business (42.9%), with a number of employees of less than 50 (76.8%). In terms of the formation of the business fleet, most companies contain between 1 and 5 vehicles (65.4%).

Table 5. Descriptive analysis of respondents to the questionnaire related to the BS.

		Frequency	
		n	**%**
N° of employers	1–49	43	76.8
	>50	13	23.2
Number of Fleet Vehicles	1–5	34	60.7
	>6	22	39.3

5.2. Binary Logit Regression

This section presents the results of our estimations using a binary logistic model. Table 6 shows the results for the DS.

Table 6. Binary Logit Model Results for the Domestic Sector.

Included Observations: 254 Coefficient Covariance Computed Using Observed Hessian						
	M1—Dependent Variable: Have EV			**M2—Dependent Variable: Good Option**		
Variable	**Coefficient**	**Std. Err.**	**t-Value**	**Coefficient**	**Std. Err.**	**t-Value**
Gen	−1.19 **	0.48	−2.47	0.26	0.33	0.81
Age_31_40	−0.04	0.48	−0.09	−0.90 **	0.37	−2.45
Age_41+	−0.83	−1.00	0.32	0.38	0.52	0.74
Educ	0.37	0.51	0.72	0.28	0.34	0.79
Employed	−0.01	0.69	−0.02	−0.15	0.48	−0.31
Income_500_999	−2.56 ***	0.87	−2.95	1.29 *	0.73	1.87
Income_1000_1999	−2.38 ***	0.82	−2.90	1.24 *	0.71	1.83
Income_2000_3999	−1.94 **	0.79	−2.45	1.68 **	0.72	2.42
Driving_30 min_1 h	0.83	0.53	1.58	−0.74 **	0.34	−2.16
Driving_1 h_2 h	−0.30	0.62	−0.47	−0.08	0.48	−0.17
Driving_2+	0.99	0.75	1.31	0.18	0.58	0.28
Incentive factors for the acquisition of EVs						
Fiscal	0.48	0.47	1.01	0.47	0.32	1.48
Economic	−0.91	0.48	−1.89	−0.14	0.36	−0.40
Environmental	0.50	0.50	1.00	0.08	0.35	0.20
Parking	−0.32	0.67	−0.48	1.23 ***	0.42	2.93
Tech	−0.86	0.63	−1.36	−0.16	0.36	−0.44
Charging	0.49	0.46	1.08	−0.51	0.31	−1.65
Barriers to the acquisition of EVs						
Price	0.01	0.50	0.02	−0.14	0.32	−0.47
Cost	−1.00 **	0.47	−2.15	−0.28	0.32	−0.85
Uncertainty	0.81	0.51	1.58	0.07	0.33	0.21
Technical	0.38	0.46	0.83	0.24	0.32	0.74
Unsafety	−1.78 *	1.05	−1.70	−2.09 ***	0.44	−4.79
Constant	−0.13	1.39	−0.10	−0.44	0.98	−0.45
Log-likelihood	−74.396				−141.31	
Pseudo-R^2	0.2105				0.1634	

Notes: Std. Err.: standard error; ***, **, and * represent significance at 1%, 5%, and 10%.

It is important to note that for the age variable the reference group is with ages from 18 to 30; hence, the variables presented in the table represent a comparison with this reference group. Regarding income, the reference group is the highest income (higher than EUR 4000). For driving time, the reference group is the one driving less than 30 min.

Considering the first model, where the dependent variable is owning or not owning an EV, the results obtained demonstrate that there is no statistically significant difference between the different categories of the variables of age group, educational qualifications, professional status, and driving time. On the other hand, women have a lower probability of owning an EV, which is in accordance with the literature [24]. Regarding net monthly income, it was found that, compared to individuals with incomes greater than EUR 4000, individuals with incomes of EUR 500–999, EUR 1000–1.900, and EUR 2.000–3.900 have a statistically significant lower probability of owning an EV. Furthermore, the lower the income, the lower that probability. These results confirm Hypothesis 1, that is, there are sociodemographic factors that affect the probability of owning an EV. In particular, men are more likely to own an EV, probably due to a higher desire to own the latest technologies. Individuals with higher income levels are also more likely to own an EV, which relates to the higher purchase cost of these vehicles.

Regarding the incentives for the acquisition of an EV, our results demonstrate that the variables considered do not have statistical significance. Hence, Hypothesis 3 is rejected. Despite being slightly surprising, this result is probably explained by the fact that consumers who already own an EV are those who desired one and had the economic means for its purchase, regardless of any incentives. Hence, in the current moment, actual purchases are more connected to the personal preferences of individuals. Regarding the barriers to the acquisition of EVs, the results show that only cost and security concerns are statistically significant. Hence, individuals that consider higher costs and security issues as relevant barriers have a lower probability of owning an EV. This result implied that Hypothesis 5 is accepted even though only two factors are relevant. Concerns about security are likely related to a lack of proper information dissemination. EVs are not less safe than conventional ones, but there may have been a certain image created in the media indicating that they are.

The results obtained in M2 demonstrate that there is no statistically significant difference between the different categories of the variables of gender, educational qualifications, and professional status for the acceptability of EM. On the other hand, older individuals (with ages between 31 and 40 years) are less likely to consider EM a good option when compared to younger ones (with ages between 18 and 30 years). This shows that acceptance of EM is higher for younger generations, which probably relates to behavioral aspects such as resistance to change in older generations and technological acceptance in younger ones. Regarding net monthly income, it was found that, compared to individuals with incomes greater than EUR 4000, individuals in lower income groups have a statistically significant higher probability of finding EM to be a good option. Therefore, Hypothesis 2 is accepted. This result raises an interesting observation. Contrarily to the effective purchase of an EV, the desire to own one is more connected to lower income groups. This means that richer individuals probably already own an EV if they want to. However, for lower income groups, the desire may exist but the economic availability for the purchase does not exist. Hence, promoting broader EV fiscal and economic incentives from the government is key. Some lower income individuals would buy an EV if they could afford it. The difference in results when compared to M1 may be explained by the high initial investment required to buy an EV. Hence, lower income individuals find EM to be a good option but do not effectively own an EV. It is worth keeping in mind that in M2 we are dealing with stated preferences regarding the acceptance of EM. Therefore, individuals may like the idea of having an EV but may not be able to afford one. In the case of daily driving time, individuals who drive between 30 min and 1 h show a lower acceptance of EM than those who drive less than 30 min. The perceived duration of the battery can explain such a result. Despite the fact that most EVs are currently offering sufficient driving ranges for longer distances, it is important to consider that the general population does not have proper and reliable information. This is particularly relevant because in the case of the acceptance of EM we are dealing with revealed preferences, that is, individuals do not own an EV and therefore do not know for sure their technical characteristics.

The results regarding the factors that encourage the purchase of EVs demonstrated that only the variable of free parking and priority circulation positively influence the acceptance of EM. The other variables are not statistically significant. Still, this means that Hypothesis 4 is accepted. The lack of explanatory power of the existing incentives for the acceptance of EM probably means that these incentives are not perceived as sufficient. This is in line with the idea previously presented that individuals who already own an EV are those that could afford one, but some individuals would like to own one but cannot afford it.

Regarding the barriers to the acquisition of EVs, the results showed once again that most variables are not statistically significant. Only security concerns led individuals to have a lower acceptance of EM. Still, this result validates Hypothesis 6. As before, it also shows the importance of providing reliable information to consumers, since EVs are not less safe than conventional ones, but there seems to be a general perception that this is the case. De Jesus et al. [25] had already called attention to the relevance of reliable information in informing potential buyers, influencing the decision-making process. It is interesting to note that concerns regarding the charging stations were not found to be relevant for our sample. This is contrary to the most common literature (e.g., [25,31,33]).

Given that most independent variables included in the models were not statistically significant, we re-estimated the models considering only statistically significant independent variables. The results are presented in Table 7.

Table 7. Binary logit model results using only statistically significant independent variables for the Domestic Sector.

Included Observations: 254 Coefficient Covariance Computed Using Observed Hessian						
M1—Dependent Variable: Have EV				**M2—Dependent Variable: Good Option**		
Variable	**Coefficient**	**Std. Err.**	**t-Value**	**Coefficient**	**Std. Err.**	**t-Value**
Gen	−0.71 *	0.39	−1.81	-	-	-
Age_31_40	-	-	-	−0.98 ***	0.34	−2.90
Income_500_999	−1.89 **	0.78	−2.43	1.00	0.69	1.46
Income_1000_1999	−1.73 **	0.76	−2.27	1.05	0.68	1.46
Income_2000_3999	−1.25 **	0.72	−1.73	1.46 **	0.70	2.08
Driving_30 min_1 h	-	-	-	−0.71 **	0.29	−2.42
Incentive factors for the acquisition of EVs						
Parking	-	-	-	1.01 ***	0.39	2.60
Barriers to the acquisition of EVs						
Cost	−0.91 **	0.40	−2.27	-	-	-
Unsafety	−1.46 *	1.00	−1.47	−2.09 ***	0.44	−4.79
Constant	−0.44	0.71	0.62	−0.11	0.65	−0.17
Log-likelihood	−83.94			−145.74		
Pseudo-R^2	0.1092			0.1372		

Notes: Std. Err.: standard error; ***, **, and * represent significance at 1%, 5%, and 10%.

Analyzing the results in Table 7, it is possible to see that most variables continued to be statistically significant, except in Model 2 where two of the variables related to family income became statistically insignificant at 10%. This shows that a more complete model, with more variables, even if not statistically significant has a higher explanatory power. This is also visible by the decrease in the value of Pseudo-R^2.

Similarly, two binary logistic regressions were estimated for the BS, considering the same dependent variables as in the DS (in M1 and M2), and the Hosmer and Lemeshow tests also confirmed that the model selected was appropriate.

As before, in the first regression (M3) the dependent variable used was the answer to the question "Do you own an electric car?" and in the second regression (M4) the dependent variable used was the answer to the question "Do you consider electric cars a good alternative to conventional vehicles?" Table 8 shows the results of the models for the BS.

Table 8. Binary Logit Model Results for the Business Sector.

Included Observations: 56 Coefficient Covariance Computed Using Observed Hessian						
M3—Dependent Variable: Have EV				**M4—Dependent Variable: Good Option**		
Variable	**Coefficient**	**Std. Err.**	**t-Value**	**Coefficient**	**Std. Err.**	**t-Value**
Workers_49	−0.28	1.27	−0.22	−2.21	1.82	−1.22
Cars_5	−0.66	1.22	−0.54	1.84	1.59	1.16
Incentive factors for the acquisition of EVs						
Fiscal_Incentives	1.17	0.77	1.51	0.20	0.95	0.21
Economic_Incentives	1.45	0.92	1.58	−1.53	0.93	−1.64
Environmental_Incentives	0.89	1.02	0.88	2.10 **	0.93	2.25
Parking_Circulation	−0.99	0.99	−1.00	2.62 **	1.13	2.33
Technology	−1.65 *	0.92	−1.79	−1.09	1.05	−1.04
Barriers to the acquisition of EVs						
Price	−0.46	0.85	−0.54	0.51	0.89	0.58
Cost	0.16	0.78	0.21	0.90	0.76	1.19
Uncertainty	−0.66	0.74	−0.88	−0.53	0.90	−0.58
Technical_Restrition	−0.24	0.78	−0.31	−1.63 *	0.83	−1.96
Unsafety				−1.01	1.57	−0.64
Constant	−1.80	1.35	−1.33	0.65	1.66	0.39
Log-likelihood		−27.54			−27.84	
Pseudo-R^2		0.1514			0.2580	

Notes: Std. Err.: standard error; ** and * represent significance at 5%, and 10%.

The results demonstrated that, in both models, the number of employees and the number of vehicles in the fleet are not statistically significant.

In the first model, the results regarding incentives for the purchase of na EV demonstrate that only the variable of new technology and driving pleasure is statistically significant. However, the negative sign associated with this variable is a surprising result and is not easily explained. Simultaneously, none of the barriers to the purchase of EVs is statistically significant.

In the second model, only environmental benefits and the variable of free parking and priority circulation positively influence the acceptance of EM. Regarding the barriers to the purchase of EVs, we find two of them to be statistically significant. Companies that considered technical restrictions and unsafety important factors showed a lower acceptance of EM in comparison to those who did not consider these variables important. Overall, our results lead to the rejection of Hypothesis 7. Hence, the DS and BS present different behaviors regarding the purchase of EVs and the acceptance of EM. This result indicates the need to design and implement differentiated policies for each of these sectors.

To maintain the consistency of the analysis, and since it was also verified that most of the independent variables included in the model were not statistically significant, we also re-estimated the models for the BS, including only statistically significant independent variables. The results are presented in Table 9.

Table 9. Binary logit model results using only statistically significant independent variables for the Business Sector.

Included Observations: 56 Coefficient Covariance Computed Using Observed Hessian						
	M3-Dependent Variable: Have EV			**M4-Dependent Variable: Good Option**		
Variable	**Coefficient**	**Std. Err.**	**t-Value**	**Coefficient**	**Std. Err.**	**t-Value**
Incentive factors for the acquisition of EVs						
Environmental_Incentives	-	-	-	1.40 *	0.77	1.81
Parking_Circulation	-	-	-	1.64	1.16	1.42
Technology	−0.71	0.85	−0.83	-	-	-
Barriers to the acquisition of EVs						
Technical_Restrition	-	-	-	−1.43 *	0.74	−1.92
Constant	−0.79	0.32	−2.45	0.17	0.61	0.29
Log-likelihood		−33.22			−33.34	
Pseudo-R^2		0.0226			0.1115	

Notes: Std. Err.: standard error; * represent significance at 10%.

As in the DS, here we can also see the necessity of considering other variables in the regression to obtain more comprehensive conclusions.

6. Discussion and Conclusions

Climate change has been leading the planet towards a potentially irreversible situation [39]. We are currently seeing an increase in the occurrence of phenomena such as heat waves and floods and increased mortality, which even the most pessimistic climatologists expected would only occur within two decades. Undoubtedly, EVs represent a better alternative in environmental terms than conventional vehicles. EV sales continue to break records, and some manufacturers plan to electrify their fleets even before the targets set in the applicable legislation [40]. However, the route to the electrification of the transport sector appears long and we are only at the beginning. Among other factors, consumers' preferences will be essential for this process [41].

Hence, understanding consumers' perceptions of EVs and acceptance of EM is essential. In this article, we studied the Portuguese case, focusing on the comparison between the domestic and business sectors. We explored research hypotheses regarding the influence of sociodemographic factors, incentives, and barriers on the purchase of an EV and on the acceptance of EM. We estimated two models where the first explored the determinants of the effective purchase of EVs while the second focused on the determinants of the acceptance of EM.

Our results showed that that sociodemographic characteristics were the main drivers for EV purchases. Males were more likely to own an EV, which is in accordance with the literature [24]. Additionally, consumers with higher income were also more likely to own an EV. In the domestic sector, use and maintenance costs were found to be significant in reducing the likelihood of owning an EV, as well as concerns with security. This concern could be explained by the lack of consumer information on the safety of the electrical circuit, as lithium-ion batteries have already been shown to have a much lower risk of explosion than conventional petrol vehicles. Our results highlight the need to reduce EV costs in order to accelerate their market penetration. Simultaneously, it is key to provide consumers with comprehensive and reliable information to decrease uncertainty. The current lack of information may be responsible for the fact that most factors in the model were not statistically significant. For instance, individuals may not be aware of the fiscal incentives available for the purchase of EVs [13,33]. This observation is a relatively new result in the literature. Additionally, most people do not yet own an EV, which may relate to the lack of a need to replace their current vehicle, lack of monetary power to purchase an EV, lack of information, or the natural tendency of humans to resist change.

In the business sector, only technology-related topics seemed to be relevant. Costs and security are important for domestic buyers but not for business ones. Hence, the BS and DS display distinct behaviors. This result implies that policies directed at each sector need to be differentiated.

Regarding the determinants of the acceptability of EM, for domestic buyers we observed that younger generations (with ages between 18 and 30) are more likely to consider EV a good option than older consumers. This factor highlights the importance of time in the energy transition process. It is going to take some years for consumers to get used to the new technologies and surpass the habitual resistance to change and new technologies. One interesting observation was that consumers with lower income levels seem to find EVs appealing, even though they do not effectively own one. This indicates the importance of the price barrier, although price was not found to be statistically significant in the explanation of the acceptance of EM. This result can only indicate the difference between revealed and stated preferences. Consumers do not think or want to admit that price is a barrier to the purchase of an EV. However, they indicate that EVs are a good option but do not effectively buy one or at least have not yet bought one. This result also highlights the importance of providing broader fiscal and economic incentives if a proper transition in the transport sector is desired. This would allow consumers with lower income levels, who have good acceptance of EM, to effectively buy an EV. Furthermore, consumers with driving times between 30 min and 1 h are less likely to consider EVs a good option than consumers who drive less than 30 min. This can be explained by the concerns related to the battery autonomy [42]. Facilities regarding free parking spaces also seemed to increase the acceptability of EM, while concerns regarding security decreased that acceptability in the domestic sector. This result shows the importance of providing reliable information to consumers, since EVs are not less safe than conventional ones, but there seems to be a general perception that this is the case.

When it comes to the business sector, environmental incentives appeared as a statistically significant variable that increased EM acceptability. Here, we note that respondents were answering the questionnaire in person and on behalf of the firm they were representing. Hence, environmental concerns may be important for the image of the company. So, this variable may not only represent a real concern with the environment, which still may exist, but also a form of "warm glowing". Additionally, as in the domestic sector, parking facilities increase the acceptability of EM. On the other hand, technical restrictions decrease this acceptability. These restrictions may include, for instance, low battery duration, which is an understandable concern when we are talking about commercial, likely long-distance, transport. Once again, the comparison between the domestic and business sectors is very limited since only parking facilities appear relevant for both sectors. Most explanatory variables are not statistically significant in the two models.

One surprising result of our models is the lack of statistical significance of fiscal incentives. These have been identified as important in the literature [30–32]. This result can be explained by a general lack of information regarding the existing incentives or by the fact that EVs are already purchased by richer consumers. Another possible explanation is that individuals who already own an EV are the ones that had the desire and economic means to do so, regardless of any incentives. Simultaneously, for lower income consumers, the incentives may not be enough for them to buy an EV. In fact, obtaining these incentives is not immediate for consumers and depends on meeting eligibility criteria [43], reinforcing the fact that an individual wishing to acquire an EV must have the financial power to do so. Still, it is surprising that even for the acceptance of EM these incentives do not have explanatory power. This result can be explained by the lack of available information or by the differences found in stated preferences when compared to revealed ones. Another surprising result was the lack of explanatory power of the variables related to charging the vehicles. This has been an important factor in the literature [13]. This result is probably explained by the low number of respondents with EVs and therefore a low level of information regarding this topic. Another aspect worth mentioning is the lack of relevance of environmental concerns for the domestic sector, both for the effective purchase of the EV and for the acceptability of EM. Once again, this aspect reveals a strong need to increase information and education among the general public.

Overall, our results show a relatively small penetration of EV but higher acceptability of EM. There seems to be a need for greater economic support for consumers with lower income levels that do not own an EV but consider it a good option. Hence, improved tax and economic incentives would be required. Additionally, a larger amount of information seems to be advisable since some consumers are resistant to change due to concerns, such as security, that are not justified. The environmental benefits of EVs also need to be emphasized. Finally, younger generations will probably adopt EM more easily; hence, in a few years, EV penetration will be much more visible.

It is important to note the limitations of this study, namely, the short sampling of respondents related to the difficulties in disseminating the questionnaires, especially in the business sector. This low representativity requires caution in extrapolating the results. Hence, our results are dependent on the sample and the methodology used, which is also a limitation of our work. Another important limitation of our study is that it is based on stated preferences, which can be biased. In future research, it would be interesting to test other methodologies and broaden our sample to test the results obtained.

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Abbreviations

BS	Business Sector
DS	Domestic Sector
EM	Electric Mobility
EV	Electric Vehicle
FCS	Fast Charging Station
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
RES	Renewable Energy Sources

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Article

Greenfield Investment as a Catalyst of Green Economic Growth

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Abstract: The intensification of countries' growth causes the depletion of natural resources, biodiversity degradation, ecological imbalances, damage, and disasters. The aggravation of ecological issues requires the development of mechanisms for simultaneous achievement of economic, social, and ecological goals. The energy sector is the core direction of economic decarbonization. Therefore, green economic growth requires economic development due to the extension of innovative technologies for renewable energies and relevant investment for that. The study aims to test the hypothesis on the impact of green field investment on green economic growth. The object of the research was countries in the European Union (EU) for 2006–2020. This study applied the Malmquist-Luenberger Global Productivity Index to estimate green economic growth. It considers the resources available for the production process in the country (labor, capital, energy), the desired outcome (gross domestic product) and undesirable results (emissions to the environment) of this process. The study applied the Tobit model to test the hypothesis. The findings confirm the spatial heterogeneity of green economic growth among the EU countries. The asymmetry in technological efficiency and progress limits the efficacy of green innovations. At the same time, the obtained data confirm the research hypothesis. It is shown that along with green investments, economic openness and the efficiency of public governance have a positive effect on the green economic growth of countries. The findings highlight the importance of attracting green investments to increase green innovations in renewable energy, which boost green economic growth. This study explored the linear and direct effects of green investment on the green economic growth while eliminating the transmission impact of other mediating factors. It should be noted that further research should analyze the nonlinear impact of green investment on the green economic growth and the mediating effect, which could be caused by other variables (corruption, governance efficiency, green innovations, etc.).

Keywords: sustainable development; green investment; green growth; green energy; renewable energy

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1. Introduction

Within the paradigm of sustainable development goals, countries in the European Union (EU) have accepted the green deal policy, which aims to decarbonize economic growth by 2050 [1,2]. Thus, the EU will become the first region with carbon-free economic development. However, although countries in the EU provide coherent policies, the EU has disparities and gaps in reducing carbon emissions and consequently achieving sustainable development goals (SDGs) [3–5].

The concept of "green economic growth" is linked to the paradigm of sustainable development and reflects economic growth considering the rational use of natural capital, prevents and reduces pollution and developed opportunities to improve social well-being due to providing carbon-neutral economy [6–8]. The concept of "greenfield investment" is wider and complex definitions, the scholars [9] define it as the investment on environmental, social and governance projects which aims to achieve sustainable development goals in long-term. Based on the methodology of experts from the Division on Investment and

Enterprise of UNCTAD [10], within this study the green field investment is the value of announced greenfield foreign direct investment projects.

It should be noted that the transition to green economic growth requires green innovations and technologies that reduce environmental degradation, particularly carbon emissions. Scholars [11–15] confirm that green innovations have a statistically significant impact on declining carbon dioxide emissions and boost the achievement of SDGs. At the same time, past studies [16] emphasize that countries with strong institutions and effective implementation of sustainable development principles have higher capabilities for extending green innovations. In addition, new innovations and technologies require additional resources (financial, labor, etc.). Prior studies [17,18] have highlighted the crucial role of greenfield investment in boosting green innovations and technologies. Adeel-Farooq et al. [19] confirmed that greenfield investment negatively affects environmental performance in Asia countries. At the same time, economic growth positively affects environmental performance. However, Neto et al. [20] concludes that economic growth boosts the greenfield investment, however the reverse effect is not confirmed. At the same time, they showed that greenfield investment could have indirect effects on countries economic growth in developed and developing countries. Bayar Y. [21] also showed that greenfield investment promotes the economic growth in EU countries. At the same time, the countries have disparities in attracting external and allocating internal green investment [22]. Consequently, it could restrict the green economic growth of the country. On the other hand, countries with a high level of green economic growth are more attractive for investors. In this case, it is relevant to indicate if the greenfield investment has the direct effect on green economic growth. It should be noted that the scientific community has not accepted universal approaches for assessing green economic growth: (1) approaches based on the world indexes SDG Index, Global Sustainable Competitiveness Index, and Global Green Economy Index [23–26]; (2) approaches based on green GDP [27,28]; and (3) approaches based on desirable and undesirable outcomes [29,30]. This study bridges the theoretical gap in green economic growth by developing an approach that (1) assesses the green economic growth of the EU countries based on the Malmquist-Luenberger Global Productivity Index. It allows considering the input (labor, capital, energy), desirable (gross domestic product) and undesirable output (emissions to the environment); (2) to measure the impact of greenfield investment on green economic growth by using the Tobit model. The novelty of this study is developed approach of assesses the green economic growth, and how greenfield investment effect on which unlike the existing ones consider the desirable and undesirable outputs and based on Malmquist-Luenberger Global Productivity Index and Tobit model. The past studies [31–33] which used the Malmquist-Luenberger Global Productivity Index focused on indicators of the sustainability of individual sectors or industries for the territory and the impact of environmental regulation and green economic growth achievement. While the overall analysis for EU member states and the EU as a whole union are not often investigated. At the existence studies did not consider key indicators for achieving a carbon-neutral economy and the Sustainable Development Goals: emissions to the environment and a share of renewable energy in primary energy consumption. Furthermore, for a deeper understanding of the countries' green growth progress, this study evaluates the effectiveness of the relevant policies of EU countries. The findings of Tobit model are basis for policies suggestions within increasing green growth in the EU.

This study has the following structure: the Literature Review analyses the theoretical landscape of green economic growth and its core dimensions; the Materials and Methods section explains the variables and sources, methods and instruments to test the hypothesis of the research; the Results explain the empirical results of hypothesis testing; the Discussion and Conclusion summarize the findings, compare the analysis of the obtained results with the previous studies, limitations and further directions for investigations.

2. Literature Review

2.1. Assessment of Green Economic Growth

The results of the theoretical background on green economic growth show that most authors analyze it as a synergistic effect on simultaneous economic and ecological development [11,15,28–33]. Scholars [31] use SO_2, wastewater and smoke–dust emissions to measure green economic growth. At the same time, they confirm that innovations could boost green economic growth. The study [32] applies energy efficiency and stochastic frontier techniques to estimate green economic growth. Based on these findings, they conclude that reforms in Chinese energy sectors were effective and caused an increase in energy efficiency, which boosted green economic growth. Dizon K. E and Norona M. [34] confirm that a country's green economic growth depends on SMEs' green development. Thus, using the structural equation model, they define green economic growth as the latent variable with the following constructs: intra- and intergenerational equity; equity and inclusiveness; job creation and economic diversification; environmental integrity; efficiency; and green technological advancement [34]. Considering the findings, they conclude that environmental integrity has the highest statistically significant load on green economic growth. At the same time, scholars [34] emphasize that initialization plays the core role in providing green economic growth. Gao X. [35] applies spatial clustering and blockchain techniques to identify the abnormal and pic points of green economic growth of the country, and based on the findings, the scholarly cluster region depends on green economic growth. It should be noted that green economic growth is analyzed within the productivity of green factors and the efficiency of green economies. A similar approach to estimate green economic growth is used by [33]. Thus, scholars apply the green total productivity factor as a long-term reference-point to achieve sustainable development goals. Guo S. and Diao Y. [36] estimate the green economic growth of regions of the Yangtze River economic belt. They construct an integrated index that consists of economic quality, green growth, green industry, and green benefits. Based on the entropy method, scholars conclude that the Pan-Yangtze River Delta urban agglomeration has the highest value of green economic growth, which is caused by coherent ecological and economic policies. Kuang Y. and Lin B. [37] applied the quasi-difference–in-difference method for the assessment of green economic growth. Scholars [37,38] used an integrated index constructed from energy efficiency, economic productivity, and emissions reduction. A previous study [39] developed an index to estimate green economic growth that merges three dimensions: environmental efficiency (wastewater, SO_2 and industrial smoke emissions), resource efficiency (water and electricity consumption) and governance capacity (scale of greening, recycling of domestic waste, and cost for eliminating industrial pollution). Contrary to the abovementioned research, scholars [40] calculate green economic growth based not only on economic (GDP, GDP per capita, and share of tertiary industry in GDP) and ecological (green urban area, forest area, and green park) indicators but also on social (population growth rate, unemployment rate, and income per capita) indicators.

2.2. Greenfield Investment and Green Economic Growth

The results of the analysis of the theoretical landscape of green economic growth show that researchers have identified a vast range of indicators that catalyze green economic growth: fiscal decentralization [41,42]; digitalization and artificial intelligence [43–47]; good governance [48]; green innovations [49–53]; environmental regulation [54–57]; green finance [58–61]; renewable energy [62–68]; green consciousness, education and awareness [69–76]; and investment and business climate [77–82].

Scholars [33] applied FMOLS and DOLS techniques to empirically justify the statistically significant impact of innovations, green policies, government efficacy, and renewable energy consumption on green economic growth. In addition, they highlight that the implementation of green innovations requires greenfield investment. Studies [41,42] show that in China, fiscal decentralization could differentially impact green economic growth depending on the efficacy of environmental regulations and green innovation implementation. At the same time, researchers [43] confirmed that Big Data, cloud computing, and artificial intelligence could enhance green economic growth in China. However, they confirm that the government should actively develop digital infrastructure and improve the country's digital capabilities. Prior studies [47,48,52] prove that digital technologies positively affect enhancing green economic growth. However, the innovation effect on green economic growth is not statistically significant in China. Furthermore, green economic growth is positively conducive to innovation in the long term, and this effect is not confirmed in the long term. Controversial conclusions have been confirmed by researchers [83]. Considering the results of two-step GMM techniques, they conclude that R&D expenditures positively promote green economic growth in the long term, and this impact does not conform in the short term.

Green finance is a core determinant of greenhouse gas emissions, which is the core dimension of green economic growth [59,60,63,81] Studies [59,60,63,81] confirm that green finance promotes innovation and technologies that allow the decline of environmental degradation, a safe economic growth rate and the achievement of green development. The pool of researchers [74,76,82] proves the positive statistically significant effect of renewable energies on green economic growth. However, scholars [83] confirm the inverted N-shaped relationship between renewable energies and green economic growth for 27 EU members from 2008 to 2017. Thus, based on the results of the SBM-GML technique, researchers show that the growth of renewable energy in the interval of 0.67%–10.87% is conducive to green economic growth; in other cases (less than 0.675 or higher than 10.87%), it causes a decline [83]. In addition, they use the following control variables: population density, government expenditure and unemployment rate. Based on the meta-analysis of the investigation on green finance and green economic growth, Desalegn G. and Tangl A. [84] theoretically justify that green investment promotes a country's green economic growth. The authors of [85] applied the ARDL model to check the long- and short-term effects of green investment on green economic growth. Considering the findings for Asian countries, scholars indicate that green investment positively impacts green economic growth in the long term. It should be emphasized that the accepted agreement between China and the EU on the Comprehensive Agreement on Investment [85] allows for achieving the common goals of decoupling carbon emissions and intensifying green economic growth. This is also confirmed by previous studies [86–88]. Furthermore, scholars [88] underline that green investment could be effective if the government provides effective environmental policies and planning and control mechanisms for environmental investments, expenditure, and projects. Past studies [89–98] have analyzed the impact of green investment at the local or company level. Based on empirical findings, scholars [89–98] show that green investment is conducive to a company's green performance, which is the core element for a country's green economic growth.

Considering the abovementioned analysis of the theoretical framework of green economic growth and core dimensions, this study aims to test the following hypothesis:

Hypothesis: *Greenfield investment positively affects the green economic growth of the country.*

3. Materials and Methods

3.1. Assessment of the Green Economic Growth

Similar to prior studies [99–101], green economic development is estimated by the Malmquist-Luenberger productivity index, which is based on the nonparametric method of data envelopment analysis (DEA) [102,103]. This approach allows exploring the cost efficiency of the EU countries for green economic development. One of the advantages of DEA is that there is no need to establish a functional relationship between explanatory and dependent variables. It eliminates inadequate results due to the application of an irregular form of the function. Moreover, compared withthe traditional approaches for assessment of green economic growth, the Malmquist-Luenberger productivity index compares countries by transmissibility and cyclical accumulation of the index during the analysis.

Considering this approach, each decision-making unit (DMU) consumes the input resources to achieve the targeted goals. Specifically, according to neoclassical theory, the maximum volume of the manufactured product in a country (Y) depends on the production costs associated with the purchase of production factors:

$$Y_i(t) = F_i(K_i(t)L_i(t)) \tag{1}$$

where F is a function that reveals the maximum volume of GDP that i-country could produce for a relevant combination of input resources: labor force (L) and gross capital formation (K).

The sustainable social–economic development of the country is the core dimension of the world economy. The European Union also analyses these issues as priority tasks to overcome issues on declining the heterogeneity of the development between member states. The EU has already accepted strategic documents that contain general and specific goals of sustainable social-economic development and relevant mechanisms. Furthermore, it aims to decrease CO_2 emissions and enhance the consumption of renewable energy [104,105]. Thus, EU countries aim to reduce CO_2 emissions by 80–95% until 2050 compared to 1990 [2,45,46,106]. The energy sector is the core generator of CO_2 emissions. Thus, the achievement of the declared goal on decarbonizing countries' development could result in a huge pressure on the energy sector [45,46,106]. In this case, energy consumption from renewable energy is the core determinant for improving people's well-being and the country's competitiveness. In addition, it could be a driver for the transition to carbon-free development and sustainable development. The green economy concept, as the pragmatic approach for achieving sustainable development, is conducive to the country's well-being simultaneously with providing effective use of available resources and reducing environmental degradation. Considering the factors mentioned above, the study applies the following parameters of the model for the assessment of green economic growth:

- Input variables (x^t): labor force (L), gross capital formation (K), share of renewable energy in primary energy consumption (E);
- Output variable (y^t) GDP per capita;
- Undesirable consequences from production in countries that should be minimized (b^t): carbon dioxide emissions CO_2:

$$Ged_t^{t+1} = \left[\frac{1 + D_i^G(x^t, y^t,\ b^t)}{1 + D_i^t(x^t, y^t,\ b^t)} \times \frac{1 + D_i^{t+1}(x^{t+1}, y^{t+1},\ b^{t+1})}{1 + D_i^G(x^{t+1}, y^{t+1},\ b^{t+1})}\right] \times \frac{1 + D_i^t(x^t, y^t,\ b^t)}{1 + D_i^{t+1}(x^{t+1}, y^{t+1},\ b^{t+1})} \tag{2}$$

where D_i^t and D_i^{t+1} are the distance functions of the decision-making units at times t and t + 1 in country i, respectively.

The study applies Equation (3) to estimate the efficacy of the policy for green economic growth provided by the EU countries compared with other determinants (share of renewable energy in primary energy consumption and carbon dioxide emissions):

$$Ef_t^{t+1} = \frac{\left[\frac{1+D_i^G(x^t, y^t,\ b^t)}{1+D_i^t(x^t, y^t,\ b^t)} \times \frac{1+D_i^{t+1}(x^{t+1}, y^{t+1},\ b^{t+1})}{1+D_i^G(x^{t+1}, y^{t+1},\ b^{t+1})}\right] \times \frac{1+D_i^t(x^t, y^t,\ b^t)}{1+D_i^{t+1}(x^{t+1}, y^{t+1},\ b^{t+1})}}{\frac{D_i^{t+1}(w^{t+1}, y^{t+1})}{D_i^t(w^t, y^t)}} \tag{3}$$

where w^t, w^{t+1}—the input parameters (labor force (L), gross capital formation (K)) of the production function (without consideration of ecological parameters of production) in country i at times t and t + 1, respectively.

The assessment of green economic growth involves three closely interrelated aspects: economic, social, and environmental. Thus, if Equation (3) is higher than one, it means that countries provide an effective policy based on a new paradigm of social and economic development grounded in two core postulates: fixed capital (and labor for production development is interchangeable and complementary; protection of ecosystems and natural resources plays a core significant role in green economic growth and provides equality between generations. From an ecological point of view, demand for human capital and productive and natural resources should be quantitatively limited, whereas ecosystem integrity and species diversification should be maintained. In this study, the countries are classified into three groups depending on the green economic growth:

1. High level (Green group)—$\mathrm{Ef}_{\mathrm{t}}^{\mathrm{t+1}} < \overline{\mathrm{Ef}_{it}^{\mathrm{t+1}}} + S_{\mathrm{Ef}_{\mathrm{t}}^{\mathrm{t+1}}}$, where $\mathrm{Ef}_{it}^{\mathrm{t+1}}$ is the average value of green economic growth and $S_{\mathrm{Ef}_{\mathrm{t}}^{\mathrm{t+1}}}$ is the standard deviation.
2. Average level (Yellow group)—$\overline{\mathrm{Ef}_{it}^{\mathrm{t+1}}} - S_{\mathrm{Ef}_{\mathrm{t}}^{\mathrm{t+1}}} \leq \mathrm{Ef}_{\mathrm{t}}^{\mathrm{t+1}} < \overline{\mathrm{Ef}_{it}^{\mathrm{t+1}}} + S_{\mathrm{Ef}_{\mathrm{t}}^{\mathrm{t+1}}}$.
3. Low level (Red group)—$\mathrm{Ef}_{\mathrm{t}}^{\mathrm{t+1}} < \overline{\mathrm{Ef}_{it}^{\mathrm{t+1}}} - S_{\mathrm{Ef}_{\mathrm{t}}^{\mathrm{t+1}}}$.

3.2. Assessment of the Greenfield Investment Effect on the Green Economic Growth

Compared with the FMOL, DOLS, GMM and SBL-GML methods, which were used by [33,83–86,98] to estimate the greenfield investment effect on green economic growth, within this investigation, the truncated regression method Tobit model with the random effect are applied as the observed range of the dependent variable ($\mathrm{Ged}_{\mathrm{t}}^{\mathrm{t+1}}$) is censored.

$$\begin{aligned} Ged_{it}^{*} &= \beta_1 GI_{it} + \beta_2 X_{it} + v_i + \varepsilon_i \\ Ged_{it} &= \begin{cases} Ged_{it}^{*},\ Ged_{it}^{*} > 0 \\ 0,\ Ged_{it}^{*} \leq 0 \end{cases} \end{aligned} \tag{4}$$

where $\alpha_0,\ \beta_1,\ \beta_2$ are the searching parameters of the model; GI_{it} is greenfield investment in a country i at time t; Ged_{it}^{*} – latent variable that is subject to truncation; X_{it} is a range of the control variables; v_i is a between-entity error; ε_i is a within-entity error.

Compared with the fixed effect model (which is biased and inconsistent), the Tobit model with the random effect allows the consideration of the marginal effects. In addition, the study applies the control variables that relate to the institutional and economic climate in the countries. The control variables are included because effective institutes are conducive to economic development [107,108], particularly within attracting investment [109–111]. From this point of view, the economic openness and effectiveness of government institutions are added to the model.

3.3. Data and Source

The object of research is the EU countries for 2006–2020. The data are compiled from open statistical databases and analytical reports from the World Data Bank [112], the United Nations Conference on Trade and Development (UNCTAD) [10] and Eurostat [113]. The variables, symbols, sources, and descriptive statistics of the selected variables are presented in Table 1.

The panel data for analysis contain 405 observations, and all panel data are logarithmic.

Table 1. Variables, source, and descriptive statistics.

Variables	Symbols	Source	Obs.	Max	Min	Mean	Std. Dev.
Input parameters:							
Labor	L	World Data Bank [112]	405	4.44×10^7	165,493	7,892,890	1.04×10^7
Capital	K		405	8.41×10^{11}	1.52×10^9	1.17×10^{11}	1.82×10^{11}
A share of renewable energy in primary energy consumption	E		405	242,094.8	0	28,102.99	41,039.27
Output parameters:							
Gross Domestic product per capita	GDP	World Data Bank [112]	405	123,678.7	4523.051	33,172.39	22,536.45
CO_2 emissions	CO_2	Eurostat [113]	405	814,410	1350	114,751.3	164,862

Table 1. *Cont.*

Variables	Symbols	Source	Obs.	Max	Min	Mean	Std. Dev.
Influential factor:							
Greenfield investment	GI	UNCTAD [10]	405	84,826	3	9216.23	15,693.69
Control variables:							
Economic openness	TO	World Data Bank [112]	405	380.104	45.419	125.820	65.641
Effectiveness of government institutions	WGI		405	1.889	0.087	1.036	0.488

4. Results

Considering the empirical results (Table 2) among EU countries, the highest values of green economic growth were found in the following countries: Cyprus—in 2012, the value was 1.072; Ireland—1.0527 in 2015; Luxembourg—1.0456 in 2006. The lowest value is in Malta —0.7419 in 2015 (Table 2). In addition, Cyprus and Malta have the most uneven values of green economic growth among all the analyzed countries. The coefficients of the variation *Ged* for Cyprus and Malta are 0.10 and 0.08, respectively.

Table 2. The empirical results of *Ged* and Ef.

Variables	Ged						Mean		CV		Level
	2006	2009	2012	2015	2018	2020	Ged	Ef	Ged	Ef	
Austria	0.999	0.984	0.987	0.972	1.013	0.981	1.000	1.012	0.01	0.03	Green
Belgium	1.003	0.982	0.988	0.975	1.013	0.981	1.000	1.008	0.01	0.03	Yellow
Bulgaria	1.003	0.999	0.998	0.996	1.005	0.999	1.002	0.980	0.00	0.09	Red
Croatia	1.006	0.992	0.993	0.992	1.007	0.992	1.001	0.991	0.01	0.06	Yellow
Cyprus	1.000	0.862	1.072	1.022	1.017	0.988	0.968	0.981	0.10	0.13	Red
Czech Republic	1.009	0.985	0.990	0.991	1.012	0.991	1.002	1.004	0.01	0.04	Yellow
Denmark	1.017	0.972	0.980	0.959	1.014	0.972	0.999	1.012	0.02	0.06	Green
Estonia	1.012	0.977	0.998	0.980	1.013	0.988	1.003	1.006	0.01	0.13	Yellow
Finland	1.017	0.979	0.982	0.978	1.013	1.000	1.001	1.012	0.02	0.04	Green
France	1.006	0.983	0.988	0.975	1.010	0.993	1.000	1.010	0.01	0.03	Yellow
Germany	1.007	0.982	0.989	0.973	1.011	0.996	1.002	1.013	0.01	0.02	Green
Greece	1.010	0.989	0.986	0.983	1.005	0.988	0.998	0.968	0.01	0.11	Red
Hungary	1.001	0.989	0.995	0.994	1.006	0.995	1.001	1.009	0.01	0.08	Yellow
Ireland	0.984	0.899	0.990	1.051	0.977	0.820	0.985	0.979	0.06	0.15	Yellow
Italy	1.006	0.983	0.986	0.980	1.008	0.987	0.999	0.995	0.01	0.03	Yellow
Latvia	1.011	0.981	1.002	0.991	1.011	0.994	1.003	0.986	0.01	0.14	Yellow
Lithuania	1.007	0.985	1.000	0.989	1.011	0.997	1.004	0.992	0.01	0.11	Yellow
Luxembourg	1.046	0.979	0.965	0.957	1.038	0.972	0.994	1.002	0.03	0.03	Yellow
Malta	1.020	1.000	0.974	0.742	0.995	0.974	0.994	0.999	0.08	0.06	Red
Netherlands	1.010	0.978	0.982	0.971	1.014	0.982	1.001	1.012	0.02	0.08	Green
Poland	1.005	0.989	0.996	0.993	1.007	0.997	1.002	0.995	0.01	0.07	Yellow
Portugal	1.004	0.992	0.991	0.988	1.007	0.989	1.001	0.990	0.01	0.06	Yellow
Romania	1.005	0.991	0.998	0.996	1.007	0.998	1.002	1.005	0.01	0.13	Yellow
Slovak Republic	1.007	0.990	0.995	0.989	1.008	0.998	1.002	0.987	0.01	0.08	Yellow
Slovenia	1.008	0.984	0.987	0.984	1.012	0.990	1.002	0.988	0.01	0.07	Yellow
Spain	1.007	0.985	0.986	0.986	1.009	0.983	0.999	0.990	0.01	0.06	Yellow
Sweden	1.010	0.966	0.989	0.971	1.002	0.994	1.001	1.019	0.02	0.04	Green

In 2010, the EU countries identified five goals of the development policy: employment, innovation, education, social inclusion, and climate change/energy. Within each goal, all countries have accepted the national indicative targets. Considering the findings of *Ged* and Ef, the following countries are involved in the Green Group: Austria, Denmark, Finland Germany, Netherlands, and Sweden. Countries from the Green Group provide an effective policy on the reduction in CO_2 emissions, increasing energy from renewable sources and improving social and economic development. The Yellow Group includes Belgium, Croatia, the Czech Republic, Estonia, France, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Poland, Portugal, Romania, the Slovak Republic, Slovenia, and Spain. The Red Group contains Bulgaria, Cyprus, Greece, and Malta. It should be noted that countries from the Red Group are far from the achievement of the national indicative targets, particularly SDG7: Affordable and Clean Energy (CO_2 emissions from fuel combustion per total electricity output), SDG12: Responsible Consumption and Production (electronic waste, production-based SO_2 emissions, SO_2 emissions embodied in imports), and SDG13: Climate Action (CO_2 emissions from fossil fuel combustion and cement production, CO_2 emissions embodied in imports, CO_2 emissions embodied in fossil fuel exports).

The study applies the panel Tobit regression model with random effects to assess the dimension's impact on green economic growth. In the first stage, all data are checked for stationarity by applying Levin–Lin–Chu, Im–Pesaran–Shin, augmented Dickey–Fuller, and Harris–Tzavalis tests (Table 3).

Table 3. The finding of stationarity of the selected variables.

Variables	Levin–Lin–Chu		Im–Pesaran–Shin		Augmented Dickey–Fuller		Harris–Tzavalis	
	Statistic	***p* Value**	**Statistic**	***p* Value**	**Statistic**	***p* Value**	**Statistic**	***p* Value**
				At level				
Ged	−14.269	0.000	−7.258	0.000	216.587	0.000	0.182	0.000
GI	−7.891	0.000	−7.007	0.000	275.892	0.000	0.370	0.000
TO	−2.862	0.002	−0.853	0.197	56.876	0.369	0.796	0.328
WGI	−1.627	0.052	0.223	0.588	49.078	0.664	0.811	0.478
				At First difference				
Ged	−18.938	0.000	−10.181	0.000	489.103	0.000	−0.259	0.000
GI	−15.528	0.000	−10.551	0.000	732.726	0.000	−0.202	0.000
TO	−9.509	0.000	−7.659	0.000	250.627	0.000	−0.032	0.000
WGI	−6.845	0.000	−9.026	0.000	421.071	0.000	−0.128	0.000

The values and *p*-value (Table 3) within the Levin–Lin–Chu test show that all data are stationary. However, the findings of the Im–Pesaran–Shin, augmented Dickey–Fuller, and Harris–Tzavalis tests allow rejecting the null hypothesis on the existence of a unit root for TO and WGI, and their minimal probability (*p* value) and non-stationarity are 19.0% and 47.8%, respectively. This means that TO and WGI are non-stationary at this level. However, at the first difference, all data within all tests are stationary.

The variance inflation factor (VIF) allows for checking multicollinearity. It shows the coefficient regression's impact on standard error for all independent variables. The square root of VIF indicates how much larger the standard error is compared with if the variable were uncorrelated with all other independent variables in the regression. The findings of multicollinearity are shown in Table 4. The VIF values for all variables are less than 10, which confirms the absence of multicollinearity.

Table 4. The empirical results for the variance inflation factor (VIF).

Indicator	GI	TO	WGI	Mean VIF
VIF	2.20	2.05	1.70	1.98

The findings of the impact of greenfield investment on the green economic growth for all countries and separate groups depending on the efficacy of the policy for green economic growth are shown in Table 5. Columns (1), (3), (5) and (7) in Table 5 contain the results with 9 considering only one explanatory variable in Model (4). Columns (2), (4), (6) and (8) show the results considering all control variables. The study provides a likelihood-ratio test to identify the reliability of using the panel regression method. The *p* values for all countries and the green, yellow and red groups are less than 1%. This means that at least one of the regression coefficients in the model is not equal to zero. The impact of GI on green economic growth is positive and statistically significant for all types of samples. The addition of explanatory variables TO and WGI does not change the sign and statistical significance of the GI's effect on Ged. This shows that in the EU, the tool for green structural changes and development is the intensification of green investments aimed mainly at technologies and equipment to increase renewable energy sources and reduce environmental pollution.

Table 5. The findings of the Tobit model within the countries' group.

Variables	Total				Green				Yellow				Red			
	(1)		(2)		(3)		(4)		(5)		(6)		(7)		(8)	
	Coef	Prob	Coef	Prob	Coef	Prob	Coef	Prob	Coef	Prob	Coef	Prob	Coef	Prob	Coef	Prob
GI	0.017	0.000	0.015	0.000	0.035	0.000	0.026	0.000	0.003	0.000	0.004	0.003	0.017	0.014	0.019	0.006
TO	–	–	0.180	0.000	–	–	0.148	0.000	–	–	0.071	0.000	–	–	0.178	0.000
WGI	–	–	0.002	0.828	–	–	0.116	0.014	–	–	−0.009	0.167	–	–	0.021	0.498
sigma_u	0.871	0.000	0.085	0.000	0.667	0.002	0.032	0.002	1.020	0.000	0.634	0.000	0.888	0.005	0.103	0.022
sigma_e	0.031	0.000	0.033	0.000	0.016	0.000	0.015	0.000	0.032	0.000	0.020	0.000	0.060	0.000	0.061	0.000
rho	0.998		0.873		0.999		0.819		0.999		0.999		0.995		0.739	
Wald chi2	338.10	0.000	2702.05	0.000	5211.21	0.000	4728.29	0.000	35.55	0.000	4114.29	0.000	6.08	0.014	344.31	0.000
LR test	1476.40	0.000	414.63	0.000	209.90	0.000	99.42	0.000	1179.12	0.000	445.31	0.000	147.32	0.000	12.16	0.000

LR test—likelihood-ratio test.

Targeted energy, environmental protection, and social policies could become important stimulators of green economic transformations, providing new sources of growth due to "low carbon" technologies and developing new markets, industries, and jobs. It should be noted that the quality of institutions plays a core role in providing green economic growth due to direct and/or indirect effects. Thus, an effective government policy based on financing green transformation, spreading green technologies, enhancing research and development, and promoting green products and services is conducive to green economic growth. Considering the empirical results, WGI (quality of institutions) has had a statistically significant effect on the green economic growth for countries from the Green Group. Thus, the growth of WGI by one point led to Ged growth by 0.116. At the same time, for countries from the yellow and red groups, WGI does not have a statistically significant impact on green economic growth. In addition, trade openness has statistically significant impacts on green economic growth for all country groups. The intensification of the goods and capital movement among countries along with the corresponding targets for achieving the SDGs is a kind of incentive for changing the behavior of producers and consumers to use resources more effectively, considering the consequences for the environment. The findings of the analysis of the relationship between greenfield investment and green economic growth for each country are summarized in Table 6.

Countries within the EU have tried to improve the quality of the environment by improving renewable energy sources and extending green technology. However, the green economic growth differs from country to country. GI has a positive statistically significant impact on the green economic growth in Austria, Belgium, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Italy, Latvia, Malta, the Netherlands, Portugal, Slovakia, Slovenia, Spain and Sweden. This means that the growth of green investment develops the appropriate conditions for the green economic growth due to developing new workplaces and increasing the efficiency of production. In this case, the government of the country from the Yellow and Green Group should enlarge investment in green projects and technologies that aim at extending renewable energy. In addition, the positive statistically significant impact of trade openness on the green economic growth justifies the necessity to develop common international projects to enhance collaboration between countries in spreading renewable energy. Furthermore, it is necessary to improve the quality of institutions that allow for the development and implementation of effective strategic decisions that meet the demands in the energy sector, improving the qualifications of the workforce, update the fixed capital to reduce the anthropogenic impact and increase the competitiveness of countries.

Table 6. The findings of the Tobit model for each country.

Variables	GI		TO		WGI		LR Chi2		Group
	Coef	Prob	Coef	Prob	Coef	Prob	Coef	Prob	
Austria	0.005	0.002	0.010	0.000	0.099	0.098	71295.280	0.000	Green
Belgium	0.017	0.063	0.165	0.000	0.080	0.155	39220.780	0.000	Yellow
Bulgaria	−0.011	0.062	0.222	0.000	0.003	0.855	18817.31	0.000	Red
Croatia	0.002	0.742	0.192	0.000	−0.156	0.223	16634.88	0.000	Yellow
Cyprus	0.017	0.603	0.174	0.005	0.111	0.485	603.88	0.000	Red
Czech Republic	0.012	0.147	0.182	0.000	−0.245	0.195	16207.23	0.000	Yellow
Denmark	0.024	0.055	0.236	0.000	0.219	0.028	19680.29	0.000	Green
Estonia	0.009	0.043	0.192	0.000	−0.075	0.246	18422.69	0.000	Yellow
Finland	0.002	0.817	0.243	0.000	0.058	0.087	29022.29	0.000	Green
France	0.026	0.030	0.173	0.000	0.106	0.064	42010.36	0.000	Yellow
Germany	0.043	0.004	0.113	0.005	0.067	0.070	31905.27	0.000	Green
Greece	0.015	0.010	0.224	0.000	0.027	0.102	7924.02	0.000	Red
Hungary	0.002	0.317	0.196	0.000	0.019	0.040	114576.77	0.000	Yellow
Ireland	−0.011	0.742	0.171	0.004	0.473	0.136	1348.89	0.000	Yellow
Italy	0.027	0.001	0.200	0.000	0.113	0.010	62362.44	0.000	Yellow
Latvia	0.012	0.045	0.191	0.000	−0.107	0.152	14730.92	0.000	Yellow
Lithuania	0.002	0.668	0.197	0.000	−0.114	0.003	21083.59	0.000	Yellow
Luxembourg	−0.008	0.704	0.178	0.002	0.047	0.926	4095.12	0.000	Yellow
Malta	0.033	0.012	0.145	0.000	0.248	0.104	1452.72	0.000	Red
Netherlands	0.038	0.001	0.080	0.056	0.456	0.016	17727.70	0.000	Green
Poland	0.020	0.185	0.189	0.000	−0.015	0.706	7843.09	0.000	Yellow
Portugal	0.019	0.002	0.197	0.000	−0.077	0.321	21070.61	0.000	Yellow
Romania	0.004	0.607	0.205	0.000	0.053	0.702	11252.12	0.000	Yellow
Slovak Republic	0.005	0.027	0.201	0.000	0.171	0.000	55057.52	0.000	Yellow
Slovenia	0.010	0.041	0.192	0.000	0.151	0.178	19712.07	0.000	Yellow
Spain	0.039	0.000	0.151	0.000	0.080	0.310	41140.60	0.000	Yellow
Sweden	0.011	0.007	0.180	0.000	0.076	0.024	20277.41	0.000	Green

Note: LR chi2 is the likelihood ratio (LR) chi-squared test.

5. Discussion and Conclusions

The concept of the green economic growth is the most important element of development strategy for the EU countries. This meant promoting the most resource-effective, ecological, and competitive economy. In addition, EU countries actively consider ecological issues under industrial production, and attracting greenfield investment and renewable energy consumption are conducive to the green economic growth. At the same time, the EU countries have disparities in achieving green economic growth. On the one hand, it is caused by the differences in macroeconomic conditions (labor, capital, gross domestic product); on the other hand, it is the result of targeted implementation of the sustainable development goals.

This study contributes to the theoretical framework on green economic growth within sustainable development goals by developing an approach to estimate the green economic growth of the EU countries which are in contrast to the existing ones based on the Malmquist-Luenberger Global Productivity Index and consider the gross domestic product (as the desirable output) and emissions to the environment (as the undesirable output). Moreover, this investigation contributes to the field of green investment within the developed approach (which the Tobit model is based on) for assessment of the impact of greenfield investment on green economic growth.

The empirical findings confirm that GI, TO and WGI impact differences in achieving green economic growth, which is consistent with prior studies [27,45,48,54]. Thus, GI, TO and WGI positively affect Ged. Thus, the growth of GI, TO and WGI by one point led to an increase in Ged by 0.015%, 0.180% and 0.002%, respectively. However, despite the differences in the green economic growth, the obtained findings are similar to those of the studies referenced in [34,41,47], indicating that the universalization mechanism of green economic growth is based on a formula that includes the need to increase green investments, the quality of institutions and openness of the economy.

It should be noted that GI has a positive and statistically significant effect on the green economic growth for all types of models, considering the explanatory and control variables. From a quantitative point of view, after including the control variables and other equal conditions , the growth of GI by one point led to improvement in green economic growth by 0.026%, 0.003% and 0.019% for the green, yellow and red groups, respectively. These results are coherent with previous studies [84–86], which showed that greenified investment is conducive to green economic growth in the long term. At the same time, the obtained findings are opposite to those from past studies [19,20], which prove that greenfield investment could not lead to green economic growth.

Considering the abovementioned results, the following policy implications could be developed:

- The EU countries should enhance the common green innovative projects which boost the sharing of the best knowledge and practices, and the development of the network of green investors. Moreover, it allows increase the openness of economy within circulation not only capital and resources but also knowledge and technologies.
- The EU commission should provide the obligatory response to publish non-financial statements at all levels (companies, local authorities, etc.). It will increase the transparency and accountability of the greenfield investment during the entire cycle.
- It should continue to provide the digitalization of state services which simplify the communication between green investors, business, and authorities during the realization of green projects. Moreover, it allows for a decline in corruption, and increased transparency and trust in the government.
- It should improve the legislation base for the circulation of green bonds, which attract new investors to the country. Consequently, it promotes the appropriate climate for developing green innovation projects which act as a catalyst for the green economic growth of the country.
- It should continue to intensify the fiscal incentives for green investors minimal loan rates, preferential taxation of green projects, etc.
- It should promote green education and implement targeted programs to promote green consciousness and awareness among green investors, businesses, local community, and government.

It should be noted that this research could be further advanced from the following aspects. First, this study explored the linear and direct effects of green investment on the green economic growth while eliminating the transmission impact of other mediating factors. Thus, further research should analyze the nonlinear impact of green investment on the green economic growth and the mediating effect, which could be caused by other variables (corruption, governance efficiency, green innovations, etc.). Second, this study focuses on the analysis of the EU countries for the period 2006–2020, which limits comparisons with other countries (the USA, China, India, etc.). In this case, the next stage of research should enlarge the number of countries for analysis. Third, it is necessary to analyze whether digitalization allows the promotion of green investment in the countries with sustainable development goals. Furthermore, past studies [45] confirmed the positive effect of crypto trading on renewable sources of energy, which is the basis of green economic growth. Moreover, crypto currency could be an additional financial resource for green innovation.

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Article

Assessing the Role of Financial Incentives in Promoting Eco-Friendly Houses in the Lisbon Metropolitan Area—Portugal

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Abstract: This article investigates the impact of fiscal and financial incentives for energy efficiency labels on eco-friendly houses (houses with high energy efficiency certificates, such as A+, A, B, and B−) in 18 municipalities in the Lisbon metropolitan region during the period 2014–2020. The empirical results indicate that the variables of fiscal incentive policies for energy efficiency labels, income per capita, credit agreements for the purchase or construction of a house, and the number of completed dwellings in new constructions for family housing encourage eco-friendly houses. In contrast, the variable number of completed reconstructions per 100 completed new constructions has a negative impact. Although this study is constrained by data limitations resulting from the short period under analysis and the moderate number of municipalities available, it advances the discussions around energy efficiency in residential properties in Portugal. Furthermore, it investigates the effectiveness of tax incentive policies for energy efficiency seals as an instrument for promoting ecological houses in the municipalities of the Lisbon metropolitan area. Thus, the need to study the Portuguese capital stands out as it is the most populous city in the country and concentrates a large part of the economic activity.

Keywords: eco-friendly houses; econometrics; energy economics; energy efficiency; incentive policies; Lisbon; Portugal; sustainability; statistical analysis

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1. Introduction

The European Union's (EU) energy policy aims to reduce total energy consumption and achieve carbon neutrality, with numerous distinctive features. A critical part of the policy is dedicated to reducing energy consumption and emissions in the residential sector, primarily because of technological advancements in the renewable energy area that can be applied in this particular sector [1]. EU established the legal framework for making buildings more energy efficient, starting in 2010 to reach decarbonized buildings by 2050. The EU residential sector is crucial for achieving EU targets in the environmental and energy areas and creating more jobs in the green sector, alleviating poverty, improving health conditions and increasing people's comfort. The residential sector's contribution to total world energy consumption is more than one third (25% in the EU), and to total pollution up to (40%) [2]. Furthermore, the EU legal framework has introduced minimum energy performance standards and released energy performance certificates to support building renovations to achieve energy efficiency goals [3].

Many EU funds are allocated for innovation in technological processes, pilot plants, and smart grids [4]. In addition, the European Investment Bank grants technical assistance to support building investments. However, EU financial support varies across EU countries, and so do the countries' performances in renewable energy use in buildings [5]. As a result, renewable energy in the building sector has increased in the EU. Nevertheless, it has increased at a slower pace than in other sectors. The most significant shares are found in Baltic countries, Balkan countries (such as Romania, Bulgaria, Slovenia, Croatia, and Greece), Scandinavian countries (such as Sweden and Finland), as well as France, Germany, and Italy [6,7].

Pollution has caused severe climate changes across the world, and buildings in Southern Europe cannot quickly adapt to these severe changes [8]. Increased heat waves during the summertime require solutions for cooling the building space in this part of Europe. The residential sector in Portugal represents a critical share (18%) of the country's total energy consumption, despite the share of total energy consumption in Southern Europe being lower than in other European countries. This situation is due to Portugal's reliance on fossil fuels (around 75% of total energy consumption) and its vulnerability to severe climate changes [9–12]. Portugal has many old buildings with low energy performance and high energy consumption [13] that require significant renovation [11,14]. However, Portugal ranks 2nd among the countries with the lowest energy consumption in the residential sector in Europe, after Malta [15]. Despite this, Portugal's programs for improving energy efficiency are not as developed or performant as those of other European countries [16]. One crucial program adopted by Portugal to achieve its 2050 targets for zero-carbon emissions is the evaluation of buildings in terms of energy efficiency and the release of green-houses certificates for houses with high energy efficiency [17]. Since 2009, all buildings in Portugal must have an energy certificate, and the legislation for this was updated in 2013 [12].

Some previous researchers have linked low energy performance to Portuguese energy poverty [18] and the high price level of electricity and gas for households compared to the EU average [19]. Portugal is also one of the first countries to release energy performance certificates for buildings [12]. In addition, some previous studies have shown that energy efficiency programs and building performance tools are crucial for reducing total energy consumption in the residential sector [20]. In contrast, others have found that financial or fiscal subsidies or incentives are more effective in achieving this goal [9,21].

Previous research has shown that fiscal and credit incentives can support building renovation, increase energy efficiency, and reduce energy consumption [9,22,23]. Fuinhas et al. [12] investigated the impact of energy policy in 19 Portuguese districts between 2014 and 2021. They found that Gross Domestic Product (GDP) per capita negatively impacted households with energy performance certificates, but the fiscal and financial incentives or credit per capita had mixed impacts on households with energy performance certificates. The income level was found to be insufficient for promoting high-efficiency energy certificates for buildings. Some studies found that fiscal and financial subsidies even impede energy-efficiency programs because of their continuous evolution and diversity [24,25]. Despite mixed results in previous studies on the impact of fiscal and financial incentives on energy-efficiency targets, the current research is essential in filling this gap. The study aims to investigate the impact of fiscal/financial incentives on energy-efficiency certificates for houses in Lisbon municipalities, using GDP per capita, credit granted for house construction or purchase, number of new houses constructions, and number of reconstructions as control variables. The study applies Ordinary Least Squares (OLS) with the fixed effects method and Method of Moments Quantile Regression (MM-QR) for 18 municipalities in the Lisbon area between 2014 and 2020.

Thus, the contribution of this research is as follows:

- It aims to investigate whether fiscal and credit incentives can support building renovations in Lisbon, where there are many old buildings, and if this can increase energy efficiency and reduce energy consumption for households;
- It aims to analyse the impact of economic growth, new dwelling constructions, and the number of reconstructions on eco-friendly houses with certificates;
- It applies 2nd generation techniques for estimations, including a detailed analysis for quantiles (MM-QR) to elaborate adequate and specific policy measures in this regard.

This research can support Portugal's goal of decreasing its total energy consumption, increasing energy efficiency, increasing the consumption of renewable energy sources, and promoting technological advancements in the residential sector to achieve carbon neutrality by 2050. It also addresses the severe effects of climate change that have significantly impacted Southern Europe, particularly in the form of significant heat waves during the last decade. This study aims to deepen the analysis carried out in previous studies on the Portugal case [11,12] by introducing new control variables into the econometric model, focusing on the municipalities of the Lisbon area, and applying new quantitative methods in this field. Previous studies have yielded mixed results on the relationship between fiscal and credit incentives and the increase in eco-friendly houses with energy efficiency certificates, including those few existing studies that have been conducted on Portugal, where the results have varied depending on the type of dwelling, with high-energy efficiency and low-energy efficiency. Fiscal and credit incentives are expected to support the increase in eco-friendly houses with energy efficiency certificates.

Section 2 presents the findings of previous studies on this topic, while Section 3 presents the applied methodology. Section 4 presents the results. Section 5 discusses the results and correlates them with the findings of previous studies. Section 6 presents the limitations and directions for future research. Finally, Section 7 presents the conclusions and some policy recommendations.

2. Literature Review

Incentive policies to increase energy efficiency in the residential sector can take different forms, including direct and indirect incentives such as subsidies, tax exemptions, direct grants, and research and development programs. Sarker et al. [26] investigated the role of financial incentives in promoting energy efficiency in the industrial sector of four Asian countries (India, Japan, China, and Indonesia). They found that market-based instruments (MBIs) like white certificates and tendering schemes significantly reduced energy intensity, while direct subsidies had limited results despite their high costs for the government. Trotta [27], for England, using the survey data "England Housing" with the probit model, found that households living in London were more likely to invest in building retrofits than in the northeast. Additionally, the results found that households that received a mortgage were more likely to invest in increasing the energy efficiency of their homes than actual owners. Finally, Trotta et al. [9] evaluated energy efficiency in the residential sector of Hungary, Finland, Italy, the United Kingdom (UK), and Spain. They found that the UK has adopted a better range of private-sector policies and initiatives.

On the other hand, Finland's lack of adequate policies led to increased energy consumption. Hungary, Spain, and Italy used attractive financial incentives. Filippini et al. [22] for the European Union (EU)-27 from 1996 to 2009 stated that the residential sector of the European Union had a high potential to reduce energy consumption caused by inefficiency. Financial incentives and performance standards also played an influential role in promoting energy efficiency.

Noailly [28], for seven European countries from 1989 to 2004, found that a (10%) increase in wall insulation standards led to a (3%) improvement in technological innovations. Additionally, the increase in Research and Development (R&D) costs positively affected energy efficiency, but the price did not significantly affect energy efficiency. Lakić et al. [29], for Slovenian households in 2017, found that energy efficiency was the second most crucial factor in property purchase after energy price. The results indicated that households paid more attention to energy efficiency when investment costs were higher. He and Chen [30] found that subsidies positively affected the development of green buildings.

Additionally, the results showed that the subsidy paid to consumers had more positive effects than the subsidy to developers, and the subsidy paid to consumers and developers brought the most benefits for developers and the highest welfare. Villca-Pozo and Gonzales-Bustos [31] found that tax incentives for energy efficiency were insufficient in a Spanish housing energy efficiency study. Bonifaci and Copiello [32] investigated the effect of tax incentive policies on energy efficiency in the residential sector in Italy. They found that incentive policies could not fully promote minimum energy standards in buildings. Neveu and Sherlock [33] found that tax credits for energy efficiency were vertically inequitable. The results showed that taxpayers in states with colder weather claimed tax credits, while taxpayers with higher electricity costs claimed more significant tax credit amounts. In a study of Kuwait's residential sector, Ameer and Krarti [34] stated that both households and the government benefited from strict energy efficiency codes even under high energy price subsidies.

Shen et al. [35] investigated the energy efficiency of buildings in seven selected countries and regions using three policy statements categories: mandatory, incentive, and voluntary implementation tools. The authors found that different policy initiatives have helped improve building efficiency. Chen and Hong [36] investigated suitable subsidy policies for green building development. The results indicated that construction policies influence subsidy policies and that removing asymmetric information can help create more green areas and fewer subsidies. In a study for Italy, Alberini and Bigano [37] addressed the effectiveness of energy efficiency incentive programs. The authors found that monetary incentives, such as tax incentives, have more significant effects on replacing heating systems with more efficient equipment than non-monetary incentives, such as potential reductions in CO_2 emissions. Charlier [38], in a study for France using a Tobit model, found that tenants have high energy costs due to energy-inefficient buildings. Because of their lower income level than homeowners, they cannot invest in energy saving. Moreover, the results indicated that the tax credit division in the tax incentives between owners and tenants was inefficient. Dubois and Allacker [39] stated that subsidies for renovating residential buildings with a partial energy increase led to worsening overall energy consumption because it locks in energy-inefficient houses. The authors found that taxes on virgin land use would have to be increased to convince people to invest in demolishing and rebuilding old homes.

Pasichnyi et al. [40] assessed the quality of energy performance certificates (EPCs) using Sweden's data quality assurance method. The authors found that EPC data could be improved by adding or revising EPC features and ensuring the interoperability of EPC datasets. Murphy et al. [24] conducted a study to improve the energy performance of the Netherlands and found that current policy instruments are unsuitable for improving the long-term energy-saving performance of existing residential buildings. Linden et al. [41] researched the residential sector of Switzerland and stated that extensive information campaigns during the oil crisis of the 1970s and energy labelling of household appliances were effective policy instruments in this sector. Tambach et al. [42] researched the Netherlands' residential sector and stated that although existing policy instruments are appropriate to some extent, additional policy instruments are needed to stimulate and pressure residential renovation. Boza-Kiss et al. [43] evaluated the enhancement of energy efficiency of buildings. They found that although policy instruments such as product standards and labels can have a high impact on energy savings, a clear prioritization of the policy instruments reviewed is not possible in terms of cost-effectiveness. Nair et al. [44] conducted a study in Sweden and stated that reducing household energy consumption was essential for most homeowners. Personal characteristics such as education, income, age, and contextual factors, including home age, past investment, and energy cost, influence homeowners' preferences for a particular energy efficiency measure. In Table 1, a summary of the literature review is given.

Table 1. Summary of literature review.

Authors	Study Area	Policy Instruments	Finding
Sarker et al. [26]	China, India, Indonesia, and Japan.	White certificates and tendering schemes	Market-based instruments (MBIs) have a significant effect in reducing energy intensity.
Trotta [27]	England	Combined data	Households that receive a mortgage tend to invest more in energy efficiency.
Trotta et al. [9]	Hungary, Finland, Italy, the United Kingdom, and Spain	Private initiatives	Interesting initiatives in Hungary, Spain and Italy have been found, particularly in fiscal and financial incentives.
Filippini et al. [22]	European Union (EU)	Financial incentives and energy performance standards	Financial incentives and performance standards play an effective role in promoting energy efficiency.
Noailly [28]	Seven European countries	Regulatory energy standards in buildings codes and energy taxes	An increase of (10%) in insulation standards for walls would likely result in a (3%) increase in filing additional patents.
Lakić et al. [29]	Slovenia	Energy efficiency	When higher investment costs, households tend to pay more attention to energy efficiency.
He and Chen [30]	China	Subsidies paid to developers alone, subsidies paid to consumers alone, subsidies paid to both, and no subsidy	Subsidies can be a positive incentive for the development of green buildings.
Villca-Pozo and Gonzales-Bustos [31]	Spain	Tax incentives and aids adopted in the taxes	Tax incentives have not effectively reduced investment in home energy efficiency improvements, particularly in old construction.
Bonifaci and Copiello [32]	Italy	Tax rebates	Incentive policies alone may not be sufficient to promote minimum energy standards in buildings.
Neveu and Sherlock [33]	The United States	Tax credits	Taxpayers in states with colder weather tend to claim more extensive tax credits, while those with higher electricity costs claim more significant tax credit amounts.
Ameer and Krarti [34]	Kuwait	Stringent energy efficiency codes	Strict energy efficiency codes benefit both households and the government.
Shen et al. [35]	Seven selected countries	Mandatory, incentive, and voluntary implementation tools	Different countries have made good progress in improving buildings' energy efficiency by adopting various policy instruments.
Chen and Hong [36]	China	Subsidy policy	Factors such as policy benefits, construction costs, transfer paid by the end-user, and the developer's preferences will affect the design of the subsidy policy.

Table 1. *Cont.*

Authors	Study Area	Policy Instruments	Finding
Alberini and Bigano [37]	Italy	Monetary and non-monetary incentives	Monetary incentives tend to affect replacing heating systems more than non-monetary incentives significantly.
Charlier [38]	France	Tax credits	Tax incentives for energy efficiency between owners and tenants are inefficient.
Dubois and Allacker [39]	China	Subsidies for renovation, subsidies for demolition, reconstruction projects, and subsidies for building new houses on virgin land	Increasing taxes on virgin land use may be necessary to persuade people to invest in demolishing and rebuilding old homes.
Pasichnyi et al. [40]	Sweden	Energy performance certificates (EPCs)	EPC data quality could be improved by adding or revising EPC features and ensuring the interoperability of EPC datasets.
Murphy et al. [24]	Netherlands	Energy Performance Certificate, covenants, economic, and information tools	Current policy instruments are ineffective in improving existing residential buildings' long-term energy-saving performance.
Linden et al. [41]	Switzerland	Combinations of information, economic measures, administrative measures, and more user-friendly technology	Information campaigns and energy labelling of household appliances are effective policy instruments.
Tambach et al. [42]	Netherlands	Dutch energy transition policy	While existing policy instruments may be sufficient to some extent, additional policy instruments are necessary to stimulate and encourage residential renovation.
Boza-Kiss et al. [43]	European Union (EU)	Product standards and labels	Product standards and labels can have a significant impact on energy conservation.
Nair et al. [44]	Sweden	Investment and energy cost	Education, income, age, and contextual factors, including home age, past investment, and energy cost, influence homeowners' preference for using a particular energy efficiency measure.

Although various studies have been conducted in different countries and regions on the effects of financial incentives, to the best of our knowledge no study has been conducted on the effects of financial incentives on energy efficiency in Lisbon, Portugal. Additionally, in most studies, one or two variables (such as subsidies and tax exemptions) have been considered financial incentives. However, this research's financial incentive includes grants, subsidies, and tax exemptions. On the other hand, in this research, the new MM-QR econometric model and the OLS with fixed effect method are applied to estimate the financial incentives for energy efficiency. Therefore, the next part of this research will deal with the data presentation and the method used in this research.

3. Data and Methods

This section presents the variables and methodological approach used. The first subsection, 3.1, will describe the data and variables, while the second subsection, 3.2, will outline the methodological approach.

3.1. Data

Eighteen municipalities from the Lisbon metropolitan area were selected to carry out this examination, such as **Alcochete**, **Almada**, **Amadora**, **Barreiro**, **Cascais**, **Lisbon**, **Loures**, **Mafra**, **Moita**, **Montijo**, **Odivelas**, **Oeiras**, **Palmela**, **Seixal**, **Sesimbra**, **Setúbal**, **Sintra**, and **Vila Franca de Xira** (see Figure 1 below).

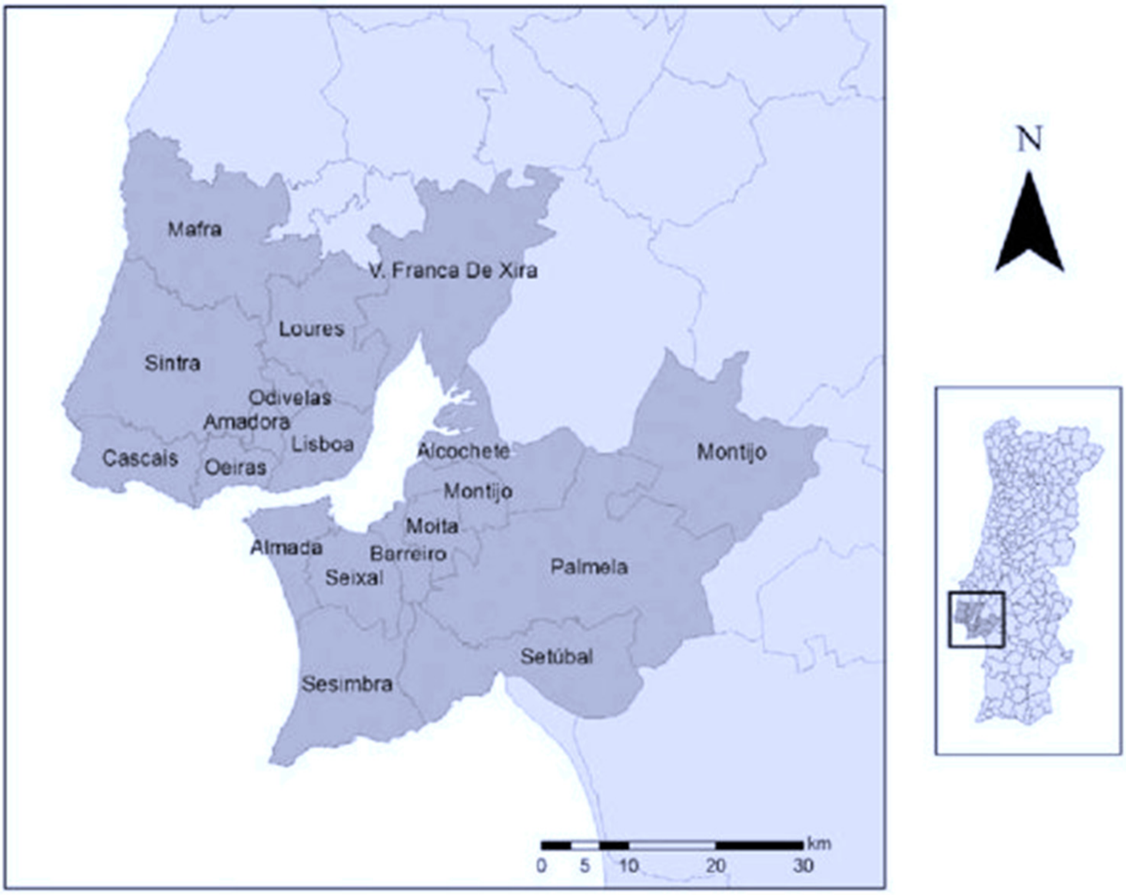

Figure 1. Illustrates the municipalities of the Lisbon metropolitan area. This figure was sourced from Gonçalves and Marreiros [45].

This group of municipalities was selected due to the significant number of eco-friendly houses/dwellings in Portugal concentrated in this region. Moreover, this region receives the most investments in the construction and reconstruction of homes. The period between 2014 and 2020 will be used in this study due to data availability for all municipalities. In other words, this study is limited by the data used. In this empirical investigation, the variables that will be used are presented in Table 2 below.

Table 2. Variable acronyms, descriptions, and sources.

Acronyms	Description	Source	QR Code
	Dependent variable		
GHC	Green or eco-friendly houses certificated. This variable represents the number of dwellings with high energy efficiency certificate ratings, such as A+, A, B, and B−.	SCE [46]	
	Independent variables		
GDP	GDP (base = 2016) for each municipality. This variable was constructed by multiplying the GDP of each region (25 NUTS III) by the ratio of the population of the municipality to the population of the region (25 NUTS III).	Constructed variable with data from PORDATA [47–49]	
HGC	The credit agreement, in Euros (EUR), for the purchase, construction, and renovation of primary or secondary dwellings or rental properties and land purchase for the construction of owner-occupied properties.	PORDATA [50]	
POL	The fiscal and financial incentives for energy efficiency in the residential sector include grants, subsidies, and tax relief. This variable was accumulated over time, where each policy is represented by a numerical value that increases with the addition of new policies throughout their useful life or until their end (e.g., 1, 1, 2, 2, 2, 3, 3).	IEA [51]	
CDT	The number of completed dwellings in new constructions for family housing.	INE [52]	
CRT	The number of completed reconstructions per 100 new constructions.	INE [53]	

Notes: This table was created by the authors.

In this investigation, the dwelling with high energy efficiency certificate ratings (e.g., A+, A, B, and B−) were used as a proxy for "green" or "eco-friendly" dwellings for the following reason. A dwelling or building to be considered "green" or "eco-friendly" needs to have attributes such as ventilation systems designed for efficient heating and cooling, energy-efficient lighting and appliances, adaptive reuse of older buildings, water-saving plumbing fixtures, among others, as mentioned by Ragheb et al. [54]. This same situation occurs in the real estate market, where numerous rating systems assess the environmental impact of dwellings or buildings and classify them as "green" or "eco-friendly" [55]. Energy performance certificates (EPCs) is one of them, as Koengkan et al. [11] and Fuinhas et al. [12] have cited. Furthermore, the EPCs report energy efficiency and recommendations for cost-effective improvements to raise the rating of a dwelling or building [9].

3.2. Method

The following methodology will be employed to carry out this empirical investigation (as illustrated in Figure 2 below).

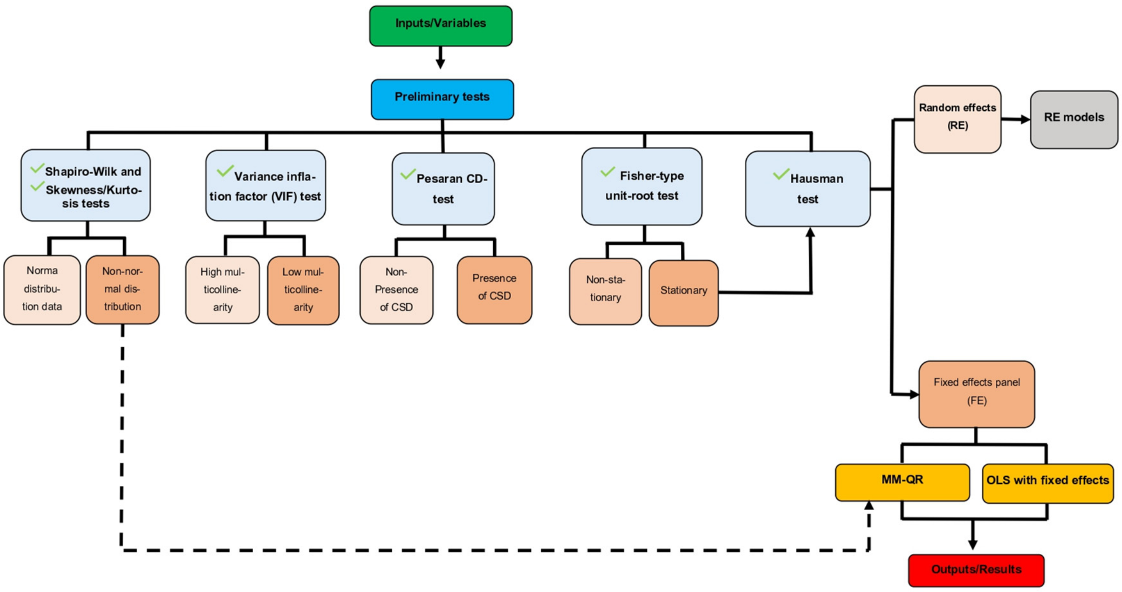

Figure 2. Methodology strategy. (The authors created this figure).

3.2.1. Preliminary Tests

Before conducting the main regressions, it is necessary to perform preliminary tests to verify the characteristics of the variables. For example:

(a) Descriptive statistics of the variables. This test checks the attributes of the variables;
(b) The Shapiro–Francia test [56] checks for normality in the model's variables. The null hypothesis of this test is that the data are normally distributed;
(c) The Shapiro–Wilk test [57] checks for normality in the model's variables. The null hypothesis of this test is similar to the Shapiro–Francia test;
(d) The Variance Inflation Factor (VIF) test [58] checks for multicollinearity between the variables;
(e) The Cross-Sectional Dependence (CSD) test [59] checks for CSD in the panel data;
(f) The Fisher-type unit-root test [60] tests for the presence of a unit root (i.e., nonstationarity) in the all-time series in the panel;
(g) The Hausman test checks for heterogeneity in the panel, i.e., whether it has random effects (RE) or fixed effects (FE).

3.2.2. OLS with Fixed Effects

The ordinary least squares regression (OLS) with fixed effects is used in this investigation. This estimator was chosen for this study because, as Koengkan et al. [11] mention, it allows for estimating the slope and intercepts for a set of observations and further estimates the mean response for the fixed predictors using the conditional mean function. In the literature, this estimation follows the general equation below:

$$l_{it} = a_i + a_1 x_{it} + \varepsilon_{it} \tag{1}$$

where a_i are the intercepts, and a_1 is the value of fixed covariates being fitted to predict the dependent variable GHC_{it}, ε_i is the error term, and each independent variable enters regression for municipality i at year t (e.g., GDP_{it}, HGC_{it}, POL_{it}, CDT_{it}, and CRT_{it}).

3.2.3. MM-QR

This investigation also includes the computation of quantile regressions using the method of moments (MM-QR) to check the previous model's robustness. This estimator was selected for this study because, as mentioned by Koengkan et al. [11], it allows for the estimation of models with endogenous variables in the presence of cross-sectional data. In the literature, the MM-QR estimator follows the general equation shown below:

$$l_{it} = h_i + e'_{it}\beta + \left(y_i + b'_{it}\gamma\right)U_{it}, \tag{2}$$

where $\left\{ \left(l_{it}, e'_{it}\right)' \right\}$ from a panel of n individuals $i = 1, \ldots, n$ over T time-periods with $P\left\{y_i + b'_{it}\gamma > 0\right\} = 1$. Furthermore, the parameters (h_1, δ_i), $i = 1, \ldots, n$, capture the individual i fixed-effects, and b is a k-vector of known differentiable (with probability 1) transformations of the components of e with element l given by $b_l = b(e)$, $l = 1, \ldots, k$. The sequence $\{e_{it}\}$ is *i.i.d.* for any fixed i and independent across t. U_{it} are *i.i.d.* (across i and t), statistically independent of e_{it}, and normalised to satisfy the moment condition $E(U) = 0 \wedge E(|U|) = 1$.

This study conducted all preliminary tests and model estimations using **Stata 17.0**. The Stata commands used are presented in three forms for easy access: through a QR code displayed in Figure 3, in the notes accompanying each results table, and in the Appendix A of this article. The QR code, notes, and appendix provide complete test and regression model instructions.

Figure 3. QR code—All commands of Stata that were used in this investigation.

4. Empirical Results

This section presents the results of the preliminary tests and main models (OLS with fixed effects and MM-QR). First, the descriptive statistics of the variables are presented. Table 3 below shows that GDP and CRT have the most significant and most minor means among the model variables, respectively.

Table 3. Descriptive statistics.

Variables	Obs	Mean	Std. Dev.	Min	Max
GHC	126	711.9841	982.5453	2	5922
GDP	126	1.11×10^{13}	4.62×10^{13}	416,737.8	2.26×10^{14}
HGC	126	1,746,426	3,798,354	0	1.95×10^{7}
POL	126	16.85714	0.9936944	15	18
CDT	126	99.23492	93.25564	1	481.6667
CRT	126	1.487513	4.392428	0	33.3

Notes: The 'sum' command of **Stata 17.0** was used. 'Obs.' denotes the number of observations in the model. 'Std.-Dev.' denotes the standard deviation. 'Min.' and 'Max.' denote the minimum and maximum, respectively.

After displaying the descriptive statistics of the variables, preliminary tests were examined. The first tests were the Shapiro–Francia test and the Shapiro–Wilk test, which were used to check the normality of the data. The results of these tests are illustrated in Table 4 below. The results of the Shapiro–Francia test reject the normal distribution for all variables except for POL. Furthermore, the Shapiro–Wilk test results also support the rejection of the normal distribution for all data. Thus, these findings support the usage of quantile-based estimation methods.

Table 4. Normal distribution tests.

Variables	Shapiro–Francia Test	Shapiro–Wilk Test	Obs
	Statistic	Statistic	
GHC	7.832 ***	8.525 ***	126
GDP	8.882 ***	9.718 ***	126
HGC	8.367 ***	9.198 ***	126
POL	1.068	1.602 *	126
CDT	5.768 ***	6.315 ***	126
CRT	7.880 ***	8.565 ***	126

Notes: The commands *sfrancia* and *swilk* of **Stata 17.0** were used. ***, * denotes statistical significance at (1%) and (10%) levels.

The next test conducted was the variance inflation factor (VIF) test to examine the presence of multicollinearity among the variables. As shown in Table 5, the mean VIF is 1.53, which is less than 6, indicating no severe multicollinearity problem.

Table 5. VIF-test.

Variables	VIF	1/VIF	Mean VIF
GHC	N.A		
GDP	1.01	0.9888	
HGC	2.21	0.4533	
POL	1.11	0.9011	1.53
CDT	1.11	0.8994	
CRT	2.22	0.4511	

Notes: The command *vif* of **Stata 17.0** was used. N.A denotes unavailable.

The next test is the cross-sectional dependence (CSD). The CSD test recognizes the presence of cross-sectional dependence in the panel data. Based on the results of Table 6 below, all the variables have significant *p*-values at the (1%) level, so the null hypothesis is not rejected and there is cross-sectional dependence in all variables. However, the CSD test did not show any results for the variable CRT.

Table 6. CSD-test.

Variables	CD-Test	*p*-Value	Corr	Abs(corr)	Obs
GHC	24.51	***	0.749	0.759	126
GDP	32.71	***	1.000	1.000	126
HGC	29.82	***	0.911	0.911	126
POL	32.73	***	1.000	1.000	126
CDT	18.73	***	0.572	0.594	126
CRT			N.A.		126

Notes: The command *xtcd* of **Stata 17.0** was used; *** denotes statistical significance at (1%); N.A denotes unavailable.

The panel unit root test (Fisher-type) was also conducted. This test detects the presence of unit roots. The results from the Fisher-type unit root test are presented in Table 7. The results show that all variables without and with trends appear to be somewhere boundary between I(0) and I(1).

Table 7. Fisher-type unit-root test.

Variables	Fisher-Type Unit-Root Test (Based on Phillips–Perron Tests)				
	Without Trend			With Trend	
	Lags	Inverse Normal (Z)		Inverse Normal (Z)	
GHC	1	4.2622		2.4883	
GDP	1	9.8403		−2.7589	**
HGC	1	8.5837		−2.2187	**
POL	1	−5.4849	***	11.6394	
CDT	1	2.1062		−3.1858	***
CRT	1	−7.6648		−8.0785	***

Notes: The command *xtunitroot fisher* with the options *pperron lags(1) and pperron lags(1) trend* of **Stata 17.0** were used. ***, ** denotes statistically significant at (1%) and (5%) levels.

After conducting the Fisher-type unit root test it is necessary to perform the final preliminary test. The Hausman test is used to verify heterogeneity, specifically whether the panel has fixed effects (FE) or random effects (RE). Table 8 below shows the results of the Hausman test. The outcomes reject the null hypotheses, indicating that there are fixed effects in the model.

Table 8. Hausman test.

Variables	Coefficients			
	(b) Fixed	(B) Random	(b-B) Difference	sqrt(diag(V_b-V_B)) S.E.
GDP	1.75×10^{-11}	3.00×10^{-12}	1.45×10^{-11}	8.16×10^{-12}
HGC	0.0004	0.0002	0.0001	0.0000
POL	137.7112	138.3249	−0.6136	23.0341
CDT	1.9144	2.3855	−0.4710	0.42729
CRT	−70.8735	−55.2222	−15.6512	5.3865
chi2(3)		20.20 ***		

Notes: The command *hausman* with the option *sigmamore* of **Stata 17.0** was used. *** denotes statistical significance at (1%) level.

After reviewing the preliminary tests, it is time to estimate the primary model's regression. Therefore, the following estimators have been used: fixed effects (FE), FE robust standard errors (FE Robust), and FE Driscoll and Kraay (FE D.-K.). Table 9 below illustrates the findings from the OLS with a fixed effect model.

Table 9. Results from OLS with fixed effect estimators.

Independent Variables	Dependent Variable (GHC)			
	Estimators			
	FE		FE Robust	FE D.-K.
GDP	0.0000	**	***	***
HGC	0.0004	***	***	***
POL	137.7112	***	***	***
CDT	1.9145	***	**	***
CRT	−70.8735	***	**	***
Constant	-2.8×10^3	***	***	***
N	90		90	90

Notes: The command *xtreg* with the options *fe*, *fe robust*, and *fe lag(1)* of **Stata 17.0** were used. ***, ** denotes statistically significant at (1%) and (5%) levels.

The findings of the OLS with a fixed effect model indicate that the impact of the CRT variable (−70.8735) on the dependent variable GHC is negative and significant. However, the variables GDP (0.0000), HGC (0.0004), POL (137.7112), and CDT (1.9145) have a positive and significant effect on GHC. Therefore, the next step after reviewing the principal model regression is checking the robustness of the results. For this purpose, the MM-QR model has been used in this research. This method has been estimated at different quantiles (0.1, 0.25, 0.5, 0.75, and 0.9). The results of the MM-QR model regression are shown in Table 10 and Figure 4 below.

Table 10. Results from MM-QR.

Independent Variables	**MM-QR**									
	Dependent Variable (GHC)									
	Quantiles									
	10th		**25th**		**50th**		**75th**		**90th**	
GDP	2.34×10^{-11}	**	2.09×10^{-11}	***	1.81×10^{-11}	***	1.32×10^{-11}	*	1.15×10^{-11}	***
HGC	0.0001		0.0003		0.0004	**	0.0006	**	0.0007	**
POL	154.63	**	147.4256	***	139.5067	***	125.3343	**	120.372	*
CDT	1.6680	*	1.7730	***	1.8883	***	2.0948	***	2.1670	**
CRT	−92.71758	*	−83.4159	***	−73.1917	**	−54.8935		−48.4866	

Notes: The command *xtqreg* with the option *i(municipality) quantile (0.1 0.25 0.50 0.75 0.90) ls* of **Stata 17.0** was used. ***, **, * denotes statistically significant at (1%), (5%), and (10%) levels, respectively.

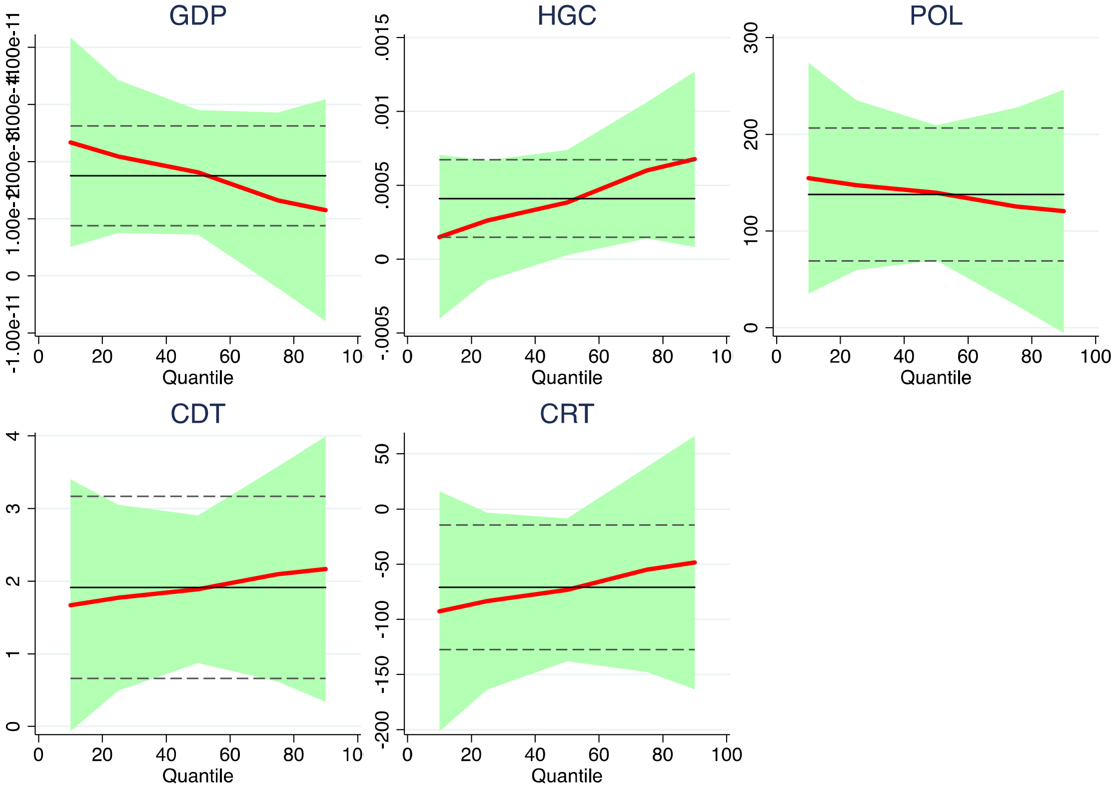

Figure 4. The quantile estimate: Shaded areas are (95%) confidence bands for the quantile regression estimates. The command *qregplot*, with option *ols olsopt(abs(municipality) robust) q(10 25 50 75 90)* of **Stata 17.0,** was used.

The MM-QR results demonstrate that the variable CRT has a negative and significant impact on GHC in the 0.1, 0.25, and 0.5 quantiles. However, the impact of the variables GDP, POL, and CDT on GHC is positive and significant in all quantiles. In addition, HGC positively and significantly impacts the dependent variable GHC in the 0.5, 0.75, and 0.9 quantiles. Therefore, the outcomes of MM-QR confirm that the OLS results are reliable and robust.

In addition, the effect of independent variables on the dependent variable is summarized in Figure 5 below. This figure is based on the findings of Tables 9 and 10 above.

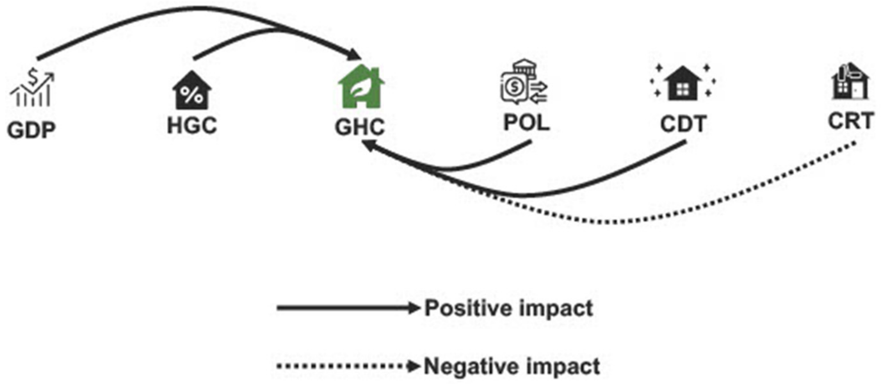

Figure 5. Summary of the variable's effect. The authors created this figure.

In this section, the empirical results of this investigation are presented. Furthermore, in the next section, the discussion will be presented.

5. Discussion

Following the results of the OLS model, corroborated by the MM-QR results, the variable GDP has a positive and significant impact on the dependent variable (i.e., Green House with a certificate/Eco-friendly House with a certificate—GHC). Even though economic growth is usually positively related to energy use, recent data has shown signs of a tendency towards decoupling between economic growth rates and energy demand [61]. One of the factors contributing to this trend is the increasing demand of consumers in developed countries for more energy-efficient utilities (and houses) due to increased environmental consciousness and the cost-reducing effect that energy efficiency can have on household energy costs [61]. Therefore, the signal of the relationship was not surprising. However, its small coefficient raises some questions regarding growth's impact on promoting more eco-friendly houses (in the Portuguese case).

Regarding the impact of HGC on GHC, it was also positive. As in the case of Fuinhas et al. [12], the credit variable demonstrates a positive impact on energy efficiency, contributing to the promotion of more energy-efficient houses. In sum, credit is a tool households can use to materialize their energy-efficient house projects. The variable CDT (number of completed dwellings in new constructions for family housing) also positively impacted GHC, which is unsurprising given the increased demand for energy-efficient utilities and houses. However, the variable CRT (number of completed dwellings in rebuilt houses) negatively impacted GHC, suggesting differences between newly built and rebuilt houses. For example, older buildings often require many steps in the process [62]. As a result, they have high renovation costs [63] that may impede energy-efficient renovations.

Now, regarding the variable POL (fiscal/financial incentive policies for energy efficiency for the residential sector), we can see from the results from both Tables 9 and 10 that the impact of this variable on GHC is positive and statistically significant (in all quantiles). Once again, the results of Fuinhas et al. [12] support this same output. In their estimations, fiscal policies also positively impacted higher-grade certified residential properties (e.g., A+, A, B, and B−). If governments want to promote more energy-efficient households, financial and fiscal incentives can be a powerful tool to achieve this objective. As an example of this fact, we can state the "*Programa de Apoio Edifícios mais Sustentáveis*" (in English, "More Sustainable Buildings Support Program"), which was first launched in 2021 by the Portuguese Government. In this program, the Government called for applications from households interested in financial support to increase their houses' energy efficiency/energy comfort. After the first phase the government had to quickly move to a second one due to the increased interest of households in this program. Indeed, the Ministry of the Environment started this second phase of the "*Programa de Apoio Edifícios mais Sustentáveis*" with an endowment of EUR 30 million, but due to high demand this endowment quickly rose to EUR 60 million. It is expected that this endowment will increase again soon, primarily due to the resources which will be provided by the "*Programa de Recuperação e Resiliência*" (PRR)—"Recovery and Resilience Program" for the "*Fundo Ambiental*" (Environmental Fund) [64,65]. In sum, this means that the financial incentives provided by the Government are showing a high degree of success, being a tool in which the Portuguese Government has placed its trust to promote more eco-friendly residences and buildings.

6. Limitations and Future Recommendations

This research was constrained by data limitations that resulted from the short period under analysis (from 2014 to 2020) and the moderate number of individuals (municipalities) available. Indeed, when working with a micro panel we have limited confidence in the time stability of the relationships found. This restriction also reduces the capacity to analyse temporal effects and can blur the presence of dynamic effects. Thus, these shortcomings can severely constrain the analysis in the presence of viscous variables.

The research also suffers from common trends (cross-sectional dependence), which imposes some econometric drawbacks. Indeed, Lisbon's metropolitan area is particular as it is rich by Portuguese standards and simultaneously one of the most expensive cities in the world context. Hence, comparing the Oporto metropolitan area and other municipalities with the results found in the Lisbon metropolitan area could clarify the general validity of the research findings.

The methodological approach endures the insufficiency of working with proxies for green and eco-friendly dwellings. Indeed, the variable of houses with energy efficiency certificate ratings can only be considered a rough approximation for "green" or "eco-friendly" dwellings. Another methodological variant that can raise new insights and have theoretical consequences is using variables per capita.

Finally, one severe limitation was that the scarce-specific literature imposes constraints in formulating the conceptual framework and restrains the assertiveness of findings. These limitations could compromise the generalisation of results achieved in this research and have put demanding and unanticipated challenges during the realisation of this study.

The housing sector is a critical energy consumer and, consequently, a source of pollution. Hence, there is a need for massive investment to implement the energy transition by the deadlines required to dampen ecological damage and global warming. Therefore, humankind must explore the effect of energy-saving technologies on "green" or "eco-friendly" dwellings.

The significant challenges in the housing sector are the decisions to renovate buildings or build new dwellings. The decision favouring one of these two alternatives has environmental impacts that deserve further research. For example, understanding the implications (i) of renovating buildings to achieve energy efficiency goals, or (ii) what kind of interventions on old buildings can better cope with the harsh winters and summers motivated by climate changes. The former reason is especially worrisome given that it will expose people to the necessity of increasing energy consumption. This issue makes green or eco-friendly houses a priority over a business-as-usual scenario.

Achieving a stage of maturity of energy efficiency technologies will strongly impact the development of the housing sector. Adapting to renewable energy optimises passive energy consumption by improving energy efficiency (better climatisation). Indeed, it will actively contribute to decarbonisation by allowing renewable energy generation. Consequently, investing in fundamental research and patents that support innovation will facilitate the management transition to green and eco-friendly dwellings.

Moreover, linking energy efficiency and housing renewable energy generation with demand management can reduce carbon dioxide emissions. Therefore, further research on policy instruments, like non-financial incentives or penalties for not achieving eco-efficiency certificates, should be pursued to promote these linkages. It can be done, for example, by adding the possibility of creating valences for the generation of renewable energies (e.g., photovoltaic energy and management of energy stored in batteries) in new and renovated dwellings or stimulating the innovation in technological processes that facilitates the adoption of green or eco-friendly dwelling. In short, what needs to be studied are the interactions between energy-saving building technologies, policy incentives, and the financing of dwellings. These issues require a better understanding of: (i) energy poverty and affordability of energy; (ii) the effect of economies of scale on renovating dwellings; (iii) the other kinds of incentives that are also effective in encouraging the adoption of eco-friendly houses in Portugal and elsewhere; and (iv) the availability and ease of obtaining credit to finance, as well as the conditions for obtaining credit (term, grace period, etc.), are contributing to expanding the knowledge of the determinants and accelerating the implementation of eco-friendly houses. Indeed, the mix of incentives is far from clear in the present state of the art.

There are several topics requiring further research. For example: (i) how to achieve a balance between saving and emitting CO_2, as renovated buildings also generate large amounts of CO_2 emissions and other greenhouse gases, or how to make the recycling of construction residues economically attractive; (ii) exploring the finding of this research that new buildings are different from renovated or rebuilt structures; (iii) searching for evidence that identifies specific determinants to design better policies to promote "green" or "eco-friendly" dwellings; (iv) performing similar studies to ensure cross-validation of the findings achieved in this research; (v) pursuing a double verification of this research to confirm (a) if the results are valid in other metropolitan areas, and (b) if the conclusions are generalisable to other contexts that are not metropolitan areas; and (vi) identifying relationships between the several factors that may impact green or eco-friendly dwellings to allow for a comprehensive understanding of how the housing sector can contribute to decarbonising economies.

7. Conclusions and Policy Implications

This article focuses on studying the impact of tax and financial incentives on energy efficiency certificates for houses in 18 municipalities in the Lisbon metropolitan region from 2014 through 2020. The study found that energy efficiency is one of the challenges governments and society face in promoting sustainable economic development and growth, which impacts the population's well-being and quality of life.

In addition, the implementation of economic instruments through the creation of financial and fiscal incentives facilitates the implementation of energy efficiency by reducing energy consumption and public spending on energy, the environment, and health. Furthermore, economic instruments serve as an incentive to motivate people who have not yet adopted actions in favour of energy efficiency.

Europe has implemented energy efficiency measures to promote the rationalization of energy consumption and reduce environmental impact. For example, in Portugal the *National Energy and Climate Plan* has set decarbonization targets by 2030, emphasizing the importance of replacing electricity production from coal with the large-scale use of renewable energy. The government of Portugal has also encouraged increased energy efficiency in houses and the use of renewable energy for self-consumption. By doing so, the country will be able to face the effects of climate change caused by elevated temperatures increasing in frequency and intensity in many regions of Europe.

Based on the results obtained, this article has enormous potential to contribute to formulating and improving public policies in Portugal aimed at energy efficiency and compliance with the carbon neutrality goal by 2050. This contribution includes the reduction in total energy consumption, investments in technologies in the residential sector, increased consumption of renewable energy, and actions to encourage science, technology, and innovation.

The search for energy efficiency in residential properties plays a key role, as climate change has negatively impacted ecosystems, the economy, and human health in Europe. Furthermore, fiscal and financial incentives for technological development in renewable sources of clean energy promote significant advances in renewable energy production chains. Therefore, for the effective implementation of public policies aimed at energy efficiency and to promote improvements in terms of energy and environmental performance of buildings, Portugal created the "More Sustainable Buildings Support Program", which aims to finance measures that boost rehabilitation, decarbonization, energy efficiency, water efficiency, and the circular economy.

In this sense, the work advances to deepen the discussions around energy efficiency in residential properties in Portugal and to investigate the effectiveness of tax incentive policies for energy efficiency seals as an instrument for promoting eco-friendly houses in the municipalities of Lisbon. Likewise, the study highlights the need to focus on the Portuguese capital as it is the most populous city in the country and concentrates a large part of the economic activity.

Finally, it appears that the effective implementation of energy efficiency policies with financial and fiscal incentives and benefits is an important mechanism to promote the energy transition, establishing practices that aim to reduce the economic, social, and environmental impacts of changes caused by long-term weather patterns.

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Appendix A

This appendix provides the Stata commands used in the empirical investigation.
How to do:
* **Table 3**. Descriptive statistics*
sum ghc gdp hcg pol cdt crt
* **Table 4**. Normal distribution tests*
sfrancia ghc gdp hcg pol cdt crt
swilk ghc gdp hcg pol cdt crt
* **Table 5**. VIF-test*
reg ghc gdp hcg pol cdt crt
vif
* **Table 6**. CSD-test*
xtcd ghc gdp hcg pol cdt crt, resid
* **Table 7**. Fisher-type unit-root test*
xtunitroot fisher ghc, pperron lags(1)
xtunitroot fisher ghc, pperron lags(1) trend
* **Table 8**. Hausman test*
qui:xtreg ghc gdp hcg pol cdt crt,fe
estimates store fixed
qui: xtreg ghc gdp hcg pol cdt crt,re
estimates store random
hausman fixed random, sigmaless
* **Table 9**. Results from OLS with fixed effect estimators*

qui: xtreg ghc gdp hcg pol cdt crt,fe
estimates store fe
qui: xtreg ghc gdp hcg pol cdt crt,fe robust
estimates store fer
qui: xtscc ghc gdp hcg pol cdt crt,fe lag(1)
estimates store dk
**estimates table ols fe fer dk, star (0.10 0.05 0.01) stats(N r2 r2_a F) b(%7.4f)*
estimates table fe fer dk, star (0.10 0.05 0.01) stats(N r2 r2_a F) b(%7.4f)
* **Table 10**. Results from MM-QR*
xtqreg ghc gdp hcg pol cdt crt, i(municipality) quantile (0.1 0.25 0.50 0.75 0.90) ls
qregplot, ols olsopt(abs(municipality) robust) q(10 25 50 75 90)

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Article

A Brief History of District Heating and Combined Heat and Power in Denmark: Promoting Energy Efficiency, Fuel Diversification, and Energy Flexibility

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Abstract: The World Energy Council ranks the Danish energy system among best in the world judging by the energy trilemma criteria: energy security, energy equity, and sustainability. District heating (DH) and CHPs are pivotal for this ranking. This brief historical account illustrates how a mix of historical events, collective societal experiences, cultural and political values inform the Danish history of DH and CHPs. After the global energy crisis in the 1970s, public and political sentiment called for energy independence, alternatives to imported fuels, and alternatives to nuclear power. National-scale collective heat infrastructure planning initiatives targeted the energy policy objectives: energy independence, fuel diversification, and energy efficiency, and a political culture of broad coalition agreements made the necessary long-term planning possible. In the following decades, growing environmental awareness and concern called for renewable energy resources as alternatives to fossil fuels. Research considered the role of collective memories and temporal distance (i.e., time) for this sociotechnical journey; it notes the innovative thinking, re-use/re-cycling and energy efficiency focus that still characterize the Danish DH communities today, and it suggests that the intangible, yet reliable nature of heat could lead to the rebound effect in end-user heat-consumption behaviours. The methodological question of how, and to what extent, historical insights and lessons learnt may be translated across contexts is raised and discussed. Although sociotechnical trajectories may have granted the Danish energy system a head-start in the global race towards low-carbon energy transitions, perhaps the route was less direct than popularly portrayed. The Danish DH sector currently faces challenges of growing biomass import dependency, but also the potentials of sector coupling and energy flexibility. Energy efficiency and energy flexibility potential may be harvested via DH and district cooling solutions in future 'smart' energy systems globally. Hopefully, insights and lessons learnt from this brief history of Danish DH and CHPs prove informative elsewhere.

Keywords: energy transition; renewable energy; district heating; combined heat and power; review; energy policy

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1. Introduction

The Danish energy system is ranked among the best in the world by the World Energy Council (WEC) accordingly to the energy trilemma index criteria: energy security, energy equity, and sustainability [1]. The small Scandinavian country of Denmark is well known for its innovative energy sector: for wind power, wind power technologies, and for wind power integration in the grid [2–6]. The lesser-known underground network of district heating pipes throughout rural and urban Danish landscapes are equally important for the top WEC ranking of the Danish energy system, however. In the Danish energy system, district heating and combined heat and power plants (CHPs) ensure energy efficiency, via the harvest of otherwise wasted heat, and the use of low-quality fuels. DH facilitates fuel diversification, the integration of renewable energy resources (e.g., wind and solar) into the grid, sector coupling and increased energy flexibility [7–11]. This all facilitates low-carbon energy transition processes [12] (see Figure 1).

The aboveground wind turbines and wind farms have been subject to intense social and political controversies throughout recent decades [2,13–15]. In comparison, the underground network of heat supply infrastructures have lived rather quiet and anonymous lives [16,17].

From the early days, the Danish district heating sector has been viewed as a frontrunner among the international district heating communities, and the national scale collective heat supply infrastructure planning processes are regarded as unique [18,19]. As a result of these historical heat infrastructure planning processes, district heating networks currently supply approximately two thirds of the domestic households in Denmark with heat. This district heating penetration rate is among the highest in the world [20,21].

Insights and lessons learnt/drawn from the Danish history of DH and CHPs may prove to be beneficial elsewhere, and increasingly so as other countries engage in low-carbon energy transition processes globally [7]. However, the unique history of district heating and large-scale collective heat infrastructure planning in Denmark is overlooked internationally [16]. In outlining the historical role and importance of district heating and the associated technologies for the Danish energy system, this paper provides a start towards filling that long-recognized gap in the literature.

This brief historical account highlights the role and importance of cooperative culture and experiences, bottom-up innovative drive, the growing welfare state, the global energy crisis in the 1970s [22,23], and the subsequent national-scale collective energy planning initiatives [24,25] for this unique socio-technical journey. The research also outlines how Danish energy policy priorities gradually integrated ambitions for low-carbon energy transitions as public and political environmental awareness and concern grew.

The research is guided by the following research questions: (1) *What key historical events informed the emergence and the evolution of the Danish district heating sector?* (2) *What core values and rationales motivated and underpinned the planning and deployment of district heating networks throughout Denmark?* (3) *Reflecting on these historical trajectories: what are some of the future sociotechnical challenges and potentials for the Danish district heating sector?*

In terms of research limitations, the longitudinal historical perspective taken here leads to the compromise of less in-depth historical and political detail.

Heat generation plants for district heating may be fueled a wide range of fuels. For example, fossil fuels (e.g., oil, gas), biomass (e.g., wood chips, straw), wind power via heat pumps, and fuels of relatively poor quality that would otherwise be wasted, for example, household waste. District heating can utilize surplus or waste heat from other industries. In other words, district heating technologies are flexible in terms of fuel use. In Combined Heat and Power plants (CHPs) waste heat from the production of power is used for district heating purposes. Fuel efficiency in CHPs is approximately 90%, sometimes even more. District heating systems enable short term, longer term and seasonal thermal storage. This facilitates energy sector coupling. In brief, district heating and CHPs facilitate energy efficiency, fuel diversification, energy flexibility and the integration of renewable energy resources into the energy systems.

District Energy Scheme. Source, Danfoss, 2021 . Printed with Permission.

Figure 1. District energy/the integrated energy system. Sources [7,10,12,26].

2. Methodology

This research is conducted in the style of an integrative literature review [27]. For this purpose, the data that were collected from sector reports, legal documents, news, and sector websites supplement the academic literature on the subject matter. Importantly, integrative reviews welcome "experts as valid sources of evidence and as providers of continuous data collection and synthesis" [27]. For this research, more than 20 semi-structured interviews were conducted in 2019–2020 among district heating interest groups, sector consultants, legal experts, government experts, and district heating researchers. Informal interviews [28–30] were carried out while participating in district heating-related seminars, workshops, etc. Mixed methods research insights and data from the interdisciplinary research project InterHUB (see interhub.aau.dk) also provide important background information for the current study (These data include, for example, 1161 open-ended survey responses from a total of 175 respondents)

The longitudinal research perspective allows for rigorous critical assessment of the historical claims or beliefs held by stakeholders involved, and for exploring the long-term effects of decisions, plans, and rationales from the past [31,32]. Overall, this research draws upon and contributes to the interdisciplinary research domain that is Science and Technology Studies (STS) (see Table 1).

Table 1. Timeline: the first century of district heating in Denmark. This timeline shows key events that proved important for the Danish history of district heating. It notes key heat supply policy decisions, and important international reports and agreements.

1903	First waste incineration and DH plant in Denmark built in Frederiksberg; Provided heat and electricity for municipal institutions;
1914	1914–1918: WWI;
1920s	1920s–1930s: District heating systems infrastructures are developed;
1939	1939–1945: WWII;
1957	The Danish Association for District Heating is established;
1958	Nuclear power is considered as a future energy resource in Denmark;
1963	The book "Silent Spring"by Rachel Carson;
1962	Maersk awarded the right to investigate and exploit oil and natural gas resources in the Danish part of the North Sea; Danish Underground Consortium (DUC) established;
1968	Ministry report on the potential use of natural gas in Denmark;
1970	Swedish authorities permit construction of the nuclear power plant, Barsebäck, which is sited on the Swedish coast within proximity of Copenhagen;
1972	92% of the total national energy consumption is based on imported oil;
1973	1st International Energy Crisis;
1974	Ministry workgroup identifies 9 locations that are suitable for nuclear power plants in the western part of Denmark;
1976	The Danish Energy Agency (DEA) is established; The Danish Energy Plan 1976 prepares for long-term energy policy;
1979	2nd International Energy Crisis;
1979	Public protests against nuclear power;
1979	Danish Energy Policy;
1979	1st Heat Supply Act: Introduced domestic natural gas into the heat supply infrastructures via the planning concept of 'zoning' and ensured the use of waste heat from industry and from power generation via CHPs;
1980	54% of the heating is based on oil;
1981	1981–1982: National scale heat planning throughout the country. District heating and natural gas heat supply areas or zones are determined via the concept of zoning;
1984	Extraction of natural gas from the Danish part of the North Sea begins;
1985	Parliamentary decision: They voted no to nuclear power in the Danish energy system; Coal excluded from national heat planning;
1985	The price of oil drops; Energy taxes are increased to ensure the continued focus on energy efficiency;

Table 1. *Cont.*

1985	94% of the power generation in Denmark is based on coal imports;
1986	Nuclear disaster at Tjernobyl;
1986	The political co-generation agreement; Emphasis on small-scale CHPs;
1987	The Brundtland Report: Our Common Future;
1897	The biogas action plan. Aim: to develop competitive biogas plants
1990	Energy 2000: The first plan for low-carbon energy transitions in the world;
1990	2nd Heat Supply Act: New heat infrastructure planning system introduced, and it plans directives and guidelines for fuel choice and CHPs introduced for municipalities and local authorities;
1990	Specific prerequisites regarding fuel choice and co-generation sent to various municipalities;
1992	Subsidies introduced to support energy efficiency measures, CHPs, and renewable energy;
1992	United Nations Framework Convention on Climate Change, UNFCCC;
1993	Political agreement made on the use of biomass in power generation; Criteria set for the future use of biomass;
1997	The Koyoto Protocol implements objectives of the UNFCCC;
2000	3rd Heat Supply Act: Parliamentary decision to improve conditions for small- and medium-sized decentralized CHPs and bare field plants.

3. The Early Days

3.1. The 1900s—WWII: The First District Heating Plant in Denmark

The first district heating plant in Denmark was a primitive Waste-to-Energy (WtE) plant. It was inaugurated in Frederiksberg in 1903. Located outside of Copenhagen at the time, the municipality of Frederiksberg attracted workers from afar to the growing industrial sector, and the population grew rapidly. The land that was used for landfills was in short supply, and it was expensive. Without no landfills for waste disposal, growing mounds of household waste accumulate on the streets.

Inspired by a recent innovation in Hamburg, the authorities solved this problem with a primitive waste incineration plant that produced heat and electricity. The waste was collected in horse-drawn carriages, loaded into storage silos, and from there, it was sent to the incinerators. In the form of steam, the heat was then transported to a nearby municipal hospital, an orphanage, and a house for the poor via underground tunnels. Thus, the first district heating system in Denmark was born [22,33,34] (see Figure 2).

This first district heating system proved to be inspirational throughout Denmark. Most of the existing power plants at the time were built in the 1900s, and they were obliged to deliver both power and heating. In the 1920s, these power plants needed to be restored and modernized. In this process, many municipalities chose to construct primitive combined heat and power plants (CHPs), and they used excess heat from the production of power for heating, e.g., dwellings or institutions close by. These first systems were mostly small and located close to the end-users/consumers [22,34,35]. The fuel import dependency at the time also motivated the energy efficiency advantages of the CHPs [19]. From early on, the values and management practices of the Danish cooperative movement [36,37] found new footing within the growing energy sector [4,22]. Particularly in smaller provincial towns and villages, local cooperative initiative groups invested in and managed the district heating plants [4,22,36] (see Figure 2).

Figure 2. Top left: landfill and waste management challenges. Top right: sectional drawing of Aarhus incineration plant. Bottom: horse-drawn garbage wagon. Source: [38].

3.2. Post-WWII: The Emergent Welfare State, Cooperative Values, and Favorable Financing

Decreased fossil fuel imports during WWII led to an energy crisis in Denmark, and the German occupation of the country from the year 1940 effectively stopped further expansion of the district heating networks [4,34,39,40]. Fuel was in short supply, it was rationed, and heat-only boilers were established as backups at some CHP plants. After the war, it seemed rational to expand the existing heat supply infrastructures with this excess heat production capacity [4,33,34]. At the time, electricity production was mostly centralized. Coal was still the prioritized fuel, and therefore many of the newly established power plants were located by the coast, as this facilitated the transport of coal. The Danish Government commenced the import of hydropower from the neighboring country of Norway [23].

The human atrocities of the World Wars emphasized that technological Innovations could also unleash powers of mass destruction such as those of the atomic bombs, and the East–West divide scarred the post-war political landscape.

Fuel rationing lasted until 1953 [41–44]. In the 1950s and 1960s, the public sector grew. The Social Democrat, Viggo Kampmann (prime minister 1960–1962), formalized the notion of the Danish welfare state, and the government adopted legislation based on the social rights of citizens. Social welfare was equal for all, and this social welfare included all of the sectors of society [41]. In the rural and urban landscapes throughout Denmark, public schools, nursing homes, and other public institutions were established, and new residential areas emerged. The energy sector grew rapidly in the 1950s and 1960s, and the underground network of district heating infrastructures took in new territories [18,22,34].

Two main ownership models for district heating were predominant. (1) Cooperative ownership of district heating plants was the most common ownership model in the more rural areas, when local initiative groups jointly invested in local district heating plants (see Figure 3). (2) In the more densely populated urban areas, municipal ownership was the most common model. Municipalities typically invested in larger-scale centralized CHPs, and sometimes they did so in cross-municipal partnerships [42,43]. Some municipal power plants were CHPs, and others released the waste/excess heat from production of power into the ocean [22,34]. Favorable long-term loans (e.g., 20–50 years) for these large-scale expensive heat infrastructure projects were available via the Municipal Credit Bank [33,43] (see Figure 3).

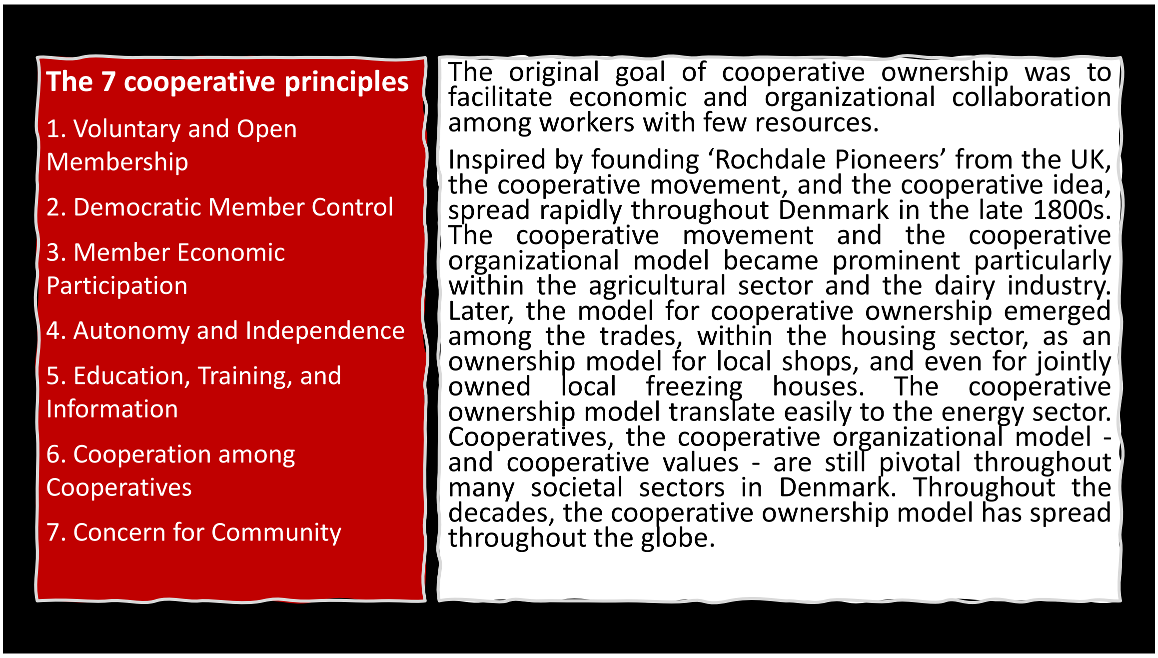

Figure 3. The 7 cooperative principles. Source: [36].

3.3. The 1960s: Economic Upswing, Technological Advances, and International Instability

The 1960s saw the Vietnam War and the Cuba Crisis, the assassination of President Kennedy, the Civil Rights Movement, and the Hippie Movement, the first man on the moon, the Beatles, Woodstock and Jimmie Hendrix, and the Anti-Nuclear Power Movements. In 1962, the book 'Silent Spring' by Rachel Carson documented the detrimental impact of the pesticide DDT on the ecosystem. Her meticulous research and poetic descriptions alarmed the world [40]. In the 1960s, A.P. Møller Mærsk (Maersk) was awarded the right to exploit any of the oil and natural gas reserves in the Danish part of the North Sea [23,39].

Economic upswing characterized the 1960s. In Denmark, the Danish welfare state continued to grow. Living standards improved, and consumption grew accordingly [22,23,39]. Oil was abundant and inexpensive. Oil was easy to transport and to handle. Oil was the prioritized fuel in this almost totally import-dependent country. The industry transitioned to the use of oil. The carpool grew. Oil burners were installed in residential housing, and the demand for oil grew. In 1967, the Six-Day War served as a brief reminder of the political unrest in the Middle East [6,22,39].

The future energy roadmap for the Danish energy system was not yet final in the 1960s. Nuclear power was still considered an option, and in 1966, the Nuclear Power Committee presented their report on potential nuclear power plant sites in Denmark [39]. Public opinion was largely against nuclear power, however [4,22]. In 1970, the Swedish authorities voted for the construction of the nuclear power plant, Barsebäck. Barsebäck was in operation by the mid-1970s, and it was visible from the Danish capital, Copenhagen, on a clear day.

In the early 1970s, approximately three quarters of the 500 Danish district heating plants were heat-only generation plants, and the rest of them were either CHPs or WtEs. Most of these were fueled by heavy oil [18,34]. The district heating technologies improved. Pipes and insulation technologies became more efficient, and low supply temperature district heating was introduced in some towns [34]. With these improvements, the popularity of district heating grew [45,46], (see Figure 4).

Figure 4. Deployment of 300 mm main pipes across the water in Aarhus, 1955. Source: Affaldvarme Aarhus; this was printed with permission.

As the populations grew, and as urbanization processes took off, the Danish suburbs also grew. The newly built suburbs were strategically planned, and were typically designed with district heating [39,46,47]. By the early 1970s, approximately one third of the Danish dwellings were supplied with district heating. This district heating penetration rate was among the highest in Europe [18].

In brief, the early days of district heating in Denmark were characterized by the cooperative culture, a bottom-up pragmatic approach to solving local heat-supply challenges, and the growing welfare state.

4. The International Energy Crisis

4.1. From Free Market to Energy Policies and Long-Term Energy Planning

In 1972, almost two thirds of the oil that was consumed globally was produced outside of Europe, the USA, and the USSR. The price of oil was low, and oil was readily available. At the time, Denmark was almost 100% dependent on energy imports. Ninety-two percent of the total energy consumption (TEC) in the country was based on the use of oil, and approximately ninety percent of this oil was imported from the Middle East [6,23,48–51]. The Government practised what has been described as a “lasseiz-faire policy and reliance of market forces” for ensuring the future stability of the fuel and energy supplies [38,39]. Thus, the international oil and energy crisis was a wake-up call for the Danish authorities: The price of oil quadrupled, and the household budgets for heating increased accordingly. The economy suffered, and unemployment soared [6,39,52–54]. The energy crisis had global ramifications, and the experts predicted a future shortage of energy and raw materials [40]. The Danish Government now set out to ensure that the national energy supplies would not be left to the dynamics of the free market in the future [4,39].

In 1972, the oil platform Dan field in the Danish North Sea produced the first oil. That same year, the commercial transmission company for natural gas (D.O.N.G. A/S, the company is now known as Ørsted/Orsted) was established. At the time, the Danish State was the only shareholder [23,40].

As a response to the global energy crisis, the Danish Government introduced short-term and long-term remedial measures to mitigate fuel shortage. Short-term remedial measures comprised lowering the speed limit in towns, no driving on Sundays (i.e., the so-called Sundays without cars, see Figure 5), encouraging the use of public transport, and incentives for reduce oil consumption within the transport sectors and in industry [23,39]. Colder indoor temperatures and cold showers became the norm. Throughout the Danish population, people felt the consequences of the energy crisis [23], and the Danish population was ready for change [23,46,49].

The Danish Government also commenced long-term strategic energy planning [56]. The Danish Energy Agency (DEA) and the Ministry of Energy were established to perform the job. Within public, academic, and political realms, energy-related questions, and future energy scenarios, were intensely discussed, and within the Danish Energy Agency itself, experts and energy professionals were split by their differing and ideologically weighted views of the future energy roadmap for Denmark.

By the late 1970s, anti-nuclear protests were common, and anti-nuclear sentiments were widespread among the Danish public. The anti-nuclear movements promoted the use of renewable energy resources (e.g., wind and solar) as alternatives to nuclear power (see Figure 6) [18,49,50]. In 1976, the energy planning priorities and policy principles for the Danish energy system going forward were finally published in the Danish Energy Plan 1976, see [56]. The main ambition of this plan was to reduce the energy import dependency of Denmark, thereby also reducing the associated economic vulnerability of the country [35,57–59].

Figure 5. The energy crisis. Sundays without cars. Source: [55].

Figure 6. Left: public protest nuclear power. Right: the iconic "Nuclear Power? No Thanks" icon from the Danish anti-nuclear movement. Source: [55].

4.2. Danish Energy Policy: Energy Efficiency, Energy Independence, and Fuel Diversification

The 1976 Danish Energy Plan [56] focused on ensuring reliable energy supplies for Denmark going forward. To this end, the goals were: (I) reducing energy import dependency, (II) more diversification of fuels used, and (III) promoting energy efficiency and reducing the total amount of energy consumed nationally. This plan comprised plans for large-scale collectively heat infrastructures, the use of otherwise wasted heat from industry, integration of CHPs in the energy system, and the harvest of locally available renewable energy resources. To this end, the plan also boosted renewable energy technology research and development [56–59].

The 1979 first Heat supply Act (HSA) [see [57]] supplied the legal framework for the heat planning initiatives ahead. The HSA supported the energy policy ambitions of (I) energy independence, (II) fuel diversification, and (III) energy efficiency. The HSA also called for (IV) integration of the newly discovered natural gas from the Danish North Sea into the Danish energy system. Tax revenues from the natural gas project supported the rapidly growing costs of the Danish welfare state [60–62]. The HSA also (V) prepared for the principal decision about nuclear power in the Danish energy system [39,57,59].

The heat infrastructure planning initiatives ahead targeted: A 53% market share of district heating by the year 2000 compared to the 1981 base of approximately 43%, a market share of Danish North Sea natural gas of 16% by the year 2000 compared to the 1981 base of 2%, and a reduction in domestic oil burners to 18% by the year 2000 compared to the 1981 base of 51% [9,39,63,64]. The Danish Government introduced 20% subsidies for renewable energy technologies [39,59], and deliberately worked towards broad political coalition agreements to ensure that the necessary long-term energy planning could be carried out. This political tradition (or culture) of broad political coalition agreements is still predominant today [59,61,62].

In 1985, the public and political debate about the integration of nuclear power in the Danish energy system was finally over. The Danish Government voted against nuclear power. Plans were also made to phase out the use of coal [39,59]. In April 1986, the nuclear disaster in Chernobyl, Ukraine, shocked the world [39,40].

4.3. National Scale Heat Supply Infrastructure Planning

The large-scale heat planning initiatives set out by the HSA involved a process referred to as 'zoning' (see Figure 7). The purpose of zoning was to (a) define the geographical zones or boundaries for the natural gas networks and the district heating networks, and by doing so also ensuring (b) the most efficient heat supplies in the cities and other urban areas. This process involved assessing and comparing the costs of the natural gas networks, the district heating networks, and the individual household oil boilers. The zoning process also ensured that (c) heat from the larger CHPs and waste incinerators supplied the local district heating systems via transmission systems [25,64,65].

The heat infrastructure planning activities took place throughout Denmark in April 1981. Municipalities who had not yet completed the task by the given deadline were instructed to do so promptly [39]. Experts involved in the heat planning initiatives at the time recall the process as being characterized by vibrant enthusiasm, and by the belief that these heat planning initiatives would bring about widespread social and environmental benefits.

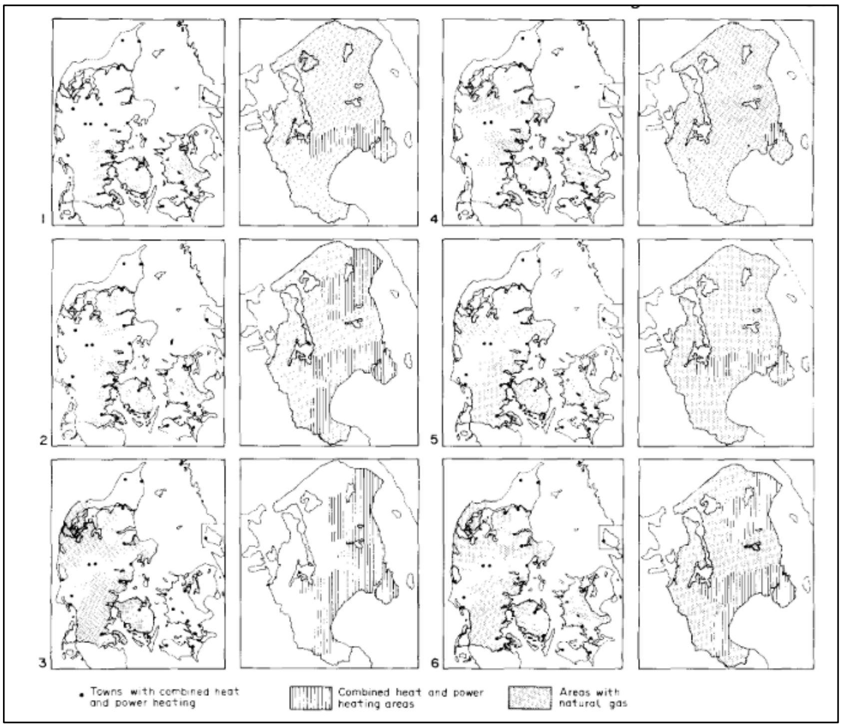

Figure 7. Proposals for regionalization/zoning of heat supply by type of heat supply system. Source: [25]. Notes: The process of zoning comprised three independent stages: (1) Individual municipalities mapped their heat demands, heat supply sources, fuel usage, and assessed future changes in heat demand/heat supplies. The municipalities then sent this information to the regional authorities. The regional authorities were responsible for producing a regional-scale overview of the heat supplies. Based on this regional overview, (2) the municipalities created preliminary plans for their future heat supplies. The counties summarized these plans at the regional level. (3) The counties then developed regional-scale plans for their future heat supply infrastructures [25,59,64].

The purpose of the zoning processes was to prevent over-investment in the expensive underground heat infrastructures, and to prevent internal competition between the collectively planned heat supply infrastructures for DH and natural gas [25,59,64].

4.4. The 1980s: Danish North Sea Oil, Natural Gas, and the Question of Nuclear Power

The 1980s saw the first mobile phones, the emergence of the World Wide Web, more relaxed East–West relations, and the fall of the Berlin Wall. The 1980s also saw explosive population growth, the Ethiopian famine, spread of the AIDs epidemic, and the Bhopal disaster in India [40]. Scientists began discussing phenomena such as global warming, the greenhouse effect, the 6th mass extinction, and the age of the Anthropocene [66]. In 1987, the Brundtland Report introduced the concept of 'sustainable development' for the first time [67]. That year, only 17% of the Danish population even considered the importance of reducing energy consumption according to the Danish opinion polls [39].

In 1980, American experts estimated that the oil and gas reserves in the Danish part of the North Sea could lead to energy independence in Denmark, and perhaps for as long as 20 years. That same year, activist groups argued that the rights to these natural resources should belong to the Danish State, and not to the Danish Underground Consortium (DUC) and the private entrepreneur, A.P. Møller Mærsk [38,39]. The Danish Government initiated negotiations with the DUC about the return of these resources to the Danish State, but after

294 days, the parties were no closer to an agreement [39]. The subsequent negotiations *did* result in stricter concession terms, however. The State demanded the more rapid production of oil and gas, and it secured rights to 40% of these. The Danish North Sea oil and gas organization generated revenue for the first time in 1988 [23,39,68].

The Danish economy was not performing well by the mid-1980s, and the Government introduced restrictive fiscal policies. The economy of the natural gas project was also poor, and a 1984 political coalition agreement ensured political support for the use of—and the further integration of—natural gas in the national heat supply infrastructures [9,39]. The 1986 political co-generation agreement prioritized the co-generation of heat and electricity (CHPs), and the state-owned electricity companies were told to establish a total of 450 MW smaller scale decentralized CHPs that were fueled by natural gas. Test- and demonstration projects for experimenting with the use of, e.g., waste, biomass, and biogas, were also included in this political agreement [39,59,69]. To ensure sufficient natural gas supplies, in 1989, the State and D.O.N.G. A/S signed a natural gas contract with the Danish Underground Consortium (DUC) which lasted from 1989 to 2012 [39,69,70].

Danish engineers improved the district heating pipe technologies substantially between the 1970s and 1980s. These products became important international exports, and a Danish thermal engineering knowledge hub of the district heating providers, equipment manufacturers, and consulting engineers was established [68]. In the late 1980s, electric heating was banned nationally in newly established housing in the natural gas or district heating zones [9,35,39]. Despite minimizing the competition from alternative heat supply sources, the economy of the collectively planned natural gas heat supply infrastructures was still poor. The experts suggested introducing a so-called ‘mandatory connection’ to the collectively planned heat supply infrastructures. The experts also suggested that some of the selected power plants should use surplus natural gas instead of coal [9,39,59] (see Tables 1 and 2). For an overview of the relevant legislation and historical commentary, see [71–75].

5. Growing Environmental Awareness and Concern

5.1. The 1990s: Low-Carbon Energy Transitions

By the 1990s, environmental awareness and concern were growing in Denmark and globally. The United Nations Framework Convention on Climate Change (UNFCCC) was adopted in 1992. The UNFCCC was based on the common understanding that the climate change was real, and that it was predominantly caused by humankind. The UNFCCC committed signatories to the reduction of greenhouse gas emissions. The 1997 Kyoto Protocol extended the objectives of the UNFCCC [9,39,66].

In Denmark, the heat-supply infrastructure planning and zoning processes that had been initiated in the 1980s were almost complete in 1990. Danish energy politics and environmental politics became intimately intertwined in the 1990s. ‘Green growth’ and sustainable development was the order of the day. In 1990, the Danish Government published the first plan for greenhouse gas reductions in the world: the Energy 2000 Action Plan. The Energy 2000 Action Plan targeted reduced energy consumption and reduced CO_2 emissions. To this end, it proposed a range of subsidies for energy efficiency measures, and for the integration of more renewable energy technologies (RETs) into the energy system. It recommended environmental taxes, updating of the building regulations, and more control of the heat-related infrastructures [39]. The Energy 2000 Action Plan also aimed to secure the economy of the national natural gas project [35,39,59].

To implement the objectives of the Energy 2000 Action plan from 1990, the Heat Supply Act (HSA) was revised that same year. The 1990 revision of the HSA [70] mandated the integration of more CHPs in the national heat supply infrastructures. It also called for increased integration of natural gas, biomass, and wind power in the energy system [39,59,76].

In the 1990 revision of the HSA, the heat supply infrastructure planning was decentralized, and heat supply infrastructure planning would be conducted on a project-to-project basis going forward. The purpose was to increase the local ownership of the municipal heat supply projects, and to facilitate the integration of local ideas and initiatives in municipal heat planning practices [59,70]. Local municipalities/municipal councils were now responsible for ensuring that the future heat supply infrastructure projects were carried out in accordance with the Ministerial criteria [24,70]. To minimize the investment-risks associated with the large-scale collective heat supply infrastructure projects, the Executive Order for 'the mandatory connection' to collective heat infrastructure was adopted [59,70] (see Table 2, Figures 8 and 9).

5.2. Specific Executive Orders for Co-Generation

In September 1990, the energy minister sent targeted Specific Executive Orders (see Table 2) to the local councils in the Danish municipalities. Some of these ordered for the reconstruction of named/specific local district heating plants to become decentralized CHPs fueled by natural gas, and others into biomass plants, by the year 1998 [39,75,77]. This ensured that the natural gas networks and district heating networks did not compete internally, but that they fed into separate heat supply areas. The Minister at the time, Poul Nielson, relaxed the language of these Specific Executive Orders, re-labeling them as 'writings of precondition' (In Danish: Forudsætningsskrivelser) [75]. Regardless of word choice, however, the named municipalities were obliged to follow the Ministerial instructions (see Table 2).

In the decentralized CHPs fueled by natural gas, the natural gas companies avoided the risks of a distribution network for natural gas. In the following years, 87 of these decentralized CHPs were dubbed 'bare field plants', a label suggestive of the relatively low housing density in the heat supply areas they served. Bare field plants typically served smaller towns or villages [59,75]. The label 'bare field plants' is not mentioned in the Heat Supply Act, but it is mentioned in the drafts and in the preparatory works [75].

At the time, the price of electricity was high, and the price of the natural gas was low. So, despite the acknowledged heat loss in the heat distribution networks throughout the low-density housing heat supply areas the bare field plants served, their economy was sensible from the outset. The price of gas increased unexpectedly, however, and the economy of many bare field plants suffered [17,59,75].

In 2000, a political majority voted for the economic support of these decentralized bare field DH plants and CHPs [39,75,77]. In order to do so, the Heat Supply Act was revised yet again [77]. More economic support was granted the bare field plants in the following years, and the natural gas companies supported the bare field plants economically too [17,59,75].

Table 2. The three key legal principles from the Danish Heat Supply Act. Source: [59].

The Non-Profit Principle	In Denmark, district heating is subject to the *nonprofit principle*, sometimes also referred to as the *principle of necessary* costs. According to the non-profit principle, the final price of heating for the end-user reflects no more or no less than the total price of heat generation and heat distribution. In other words, the final prices of heating for the end-user comprises and reflects the cumulated and necessary costs of heat-production transmission and distribution, investments and operating depreciations, maintenance, management, legal advice, consulting, service, and so on. Revenues and expenses must balance throughout the years. Utilities cannot generate profit or debt from heat-sales, as this indirectly subsidizes or taxes the end-users. Heat prices for all Danish utilities are publicly available via the Danish Utility Regulator (DUR) homepage.
The Mandatory Connection	The 'mandatory connection' empowered municipalities to enforce subscription/connection to the collectively planned heat infrastructures in the municipality. For municipalities, the mandatory connection guaranteed a minimum of end-users/consumers to the heat distribution net, thus minimizing the economic risks involved with the long-term investments necessary to finance the expensive underground heat infrastructures. Thus, the mandatory connection ensured a healthy economy for heat infrastructure projects. Municipalities could choose to enforce the mandatory connection fully, partially, or not at all. Citizens subject to the mandatory connection were free to supplement their heating with other heat sources, but obliged to pay the annual subscription fees for collective heat infrastructures.
General & Specific Executive Orders	The Heat Supply Act (HSA) empowers the relevant Minister to regulate municipal heat planning via Executive Orders. These may be nation-wide (General Executive Orders), or they can apply for specific named geographical areas (Specific Executive Orders). General Executive Orders ensure that the local councils responsible meet the objectives of the HAS. They also ensure that the municipal administrative practices reflect those criteria. General Executive Orders determine the general criteria for fuel choices, heat planning/reconstruction deadlines/timeframes, co-production and stability of supplies. They also take into account socioeconomic and environmental issues, technical advances etc. Specific Executive Orders for heat planning determine criteria for local fuel choices, limitations to or boundaries between different types of heat supply, etc.

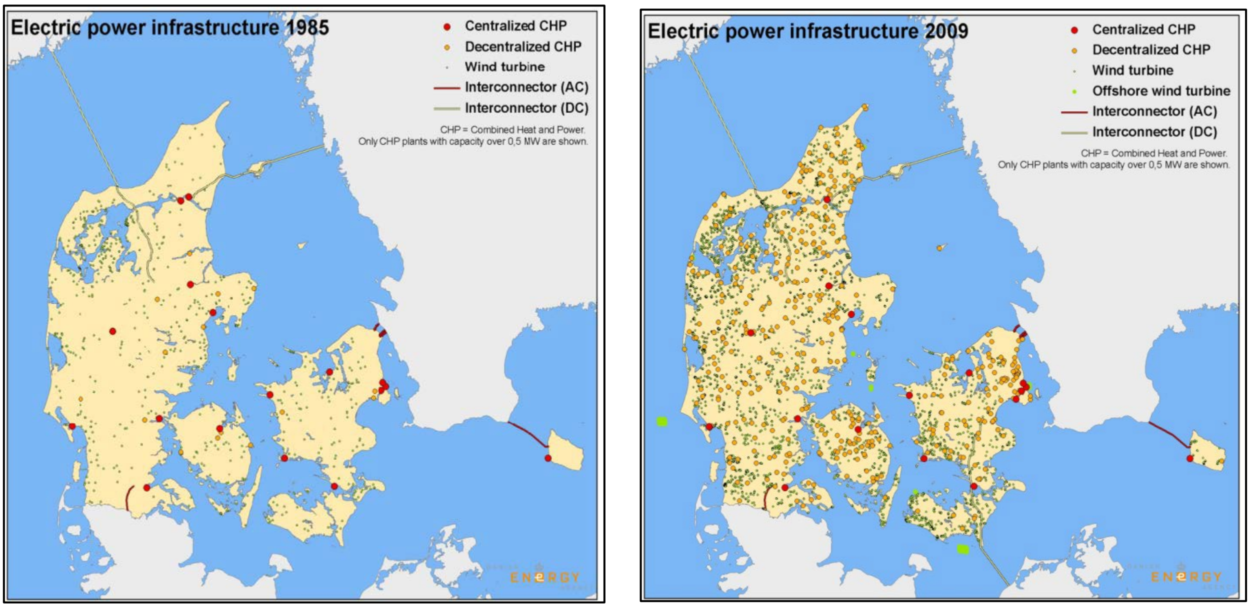

Figure 8. Centralized and decentralized CHPs in Denmark. Left: year 1985. Right: year 2009. Source: [69].

In 1997, the Danish Government adopted the first complete ban on landfills in the world [78]. In 1998, the previously energy import-dependent country of Denmark was finally energy self-sufficient due to the profitable Danish North Sea oil and gas [6,39].

6. Turn of the Century: New Challenges and Potentials for District Heating

The turn of the century was shadowed by 9/11 and the War on Terror. Environmental concerns grew, and climate change was increasingly accepted as a fact. The 2000s also saw the explosive growth of internet use, internet trade, and social media [40].

In 2001, Danish politics took a less environmental turn as a new right-wing government came into power. The responsibility for the energy sector was then moved from the Ministry of the Environment and Energy (1994–2001) to the Ministry of Economy and Industry (2001–2005) [69,79]. Remarkably, the ambitious policy goals set out in the 1976 Energy Policy and the 1979 Heat Supply Act were more than achieved by the year 2000 [80] (see Figures 8 and 9).

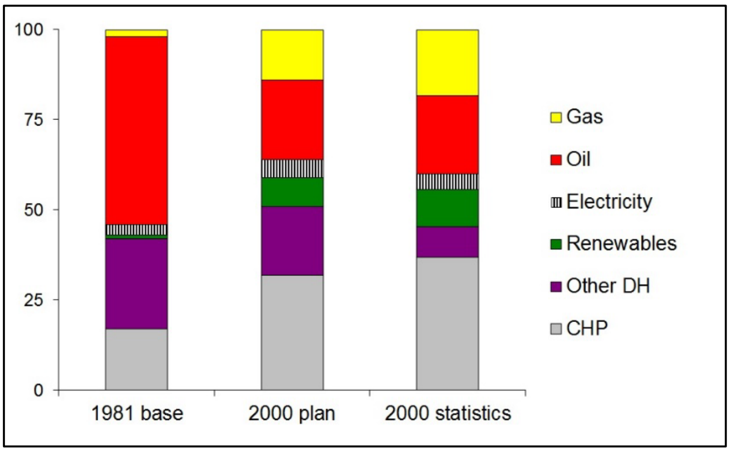

Figure 9. Heat sources in Danish households: Columns from left to right: 1. Year 1981 base. 2. Year 2000 model results made in the 1980s. 3. Year 2000 statistics. Source: [80].

Moving into the 21st century, the ratios of intermittent renewables in the energy systems increased. As energy systems became more increasingly integrated nationally and internationally, energy flexibility and energy sector coupling processes became the new order of the day. The Danish district heating sector now faced a new set of challenges and potentials. A key challenge for the sector was increasing biomass import dependency.

DH suppliers throughout Denmark had successfully integrated large ratios of renewable energy resources, most notably biomass, into the district heating systems over a relatively short time [6,39,62] (see Figures 9 and 10). This transitional process emphasized the technical diversity, flexibility, and adaptability of the Danish district heating sector. However, the growing biomass demands also led to increasing volumes of biomass imports from various European countries, as well as from the USA, Russia, North America, and South America [81]. Various stakeholders increasingly (and rightly so) questioned just how sustainable these large-scale biomass imports were [62,82]. Ironically, then, in the face of the global climate crisis, and just decades after the collective experiences of oil-import dependency during the global energy crisis of the 1970s, the rapid transitional process of the Danish district heating sector had resulted in fuel import dependency yet again.

Novel potentials of the Danish underground heat supply infrastructures were also revealed, however. The district heating infrastructures facilitated energy flexibility, and thereby also energy sector coupling [7,8,11,12]. Notably, research suggests that, internationally, district heating technologies may provide heating and cooling solutions in future 'smart' energy systems at markedly lower costs than alternative solutions [83,84].

The Energy Roadmap 2050, a report from the European Commission, proposes six strategies for reaching the EU annual greenhouse gas reduction target of 80% in 2050 compared to the year 1990 [85]. Interestingly, these scenarios do not involve large-scale district heating, but instead focus on electrification of the heat sector (e.g., via heat pumps) and electricity savings.

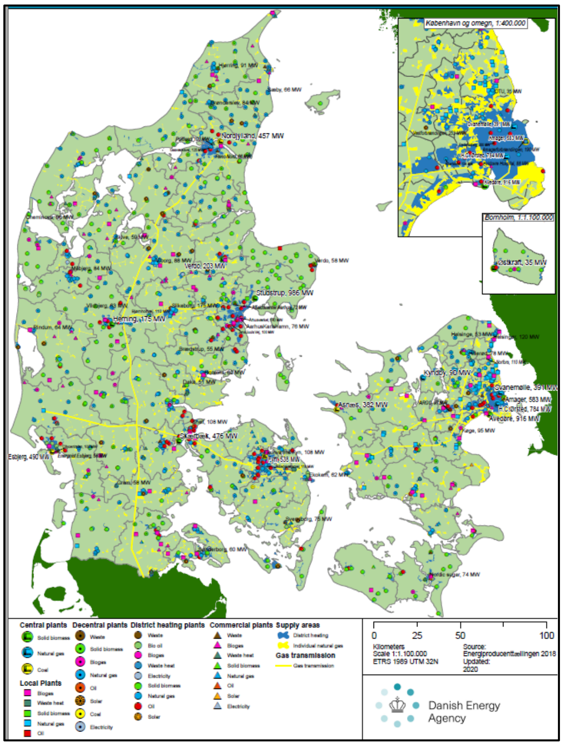

Figure 10. Danish heat supply infrastructures in 2020. Source: [86].

7. Discussion

This section discusses insights and lessons that may be drawn from this brief socio-technical account. It also highlights paradoxes and questions raised by way of this socio-technical journey. It discusses: (1) the role and importance of collective societal memories and time, (2) the possible sustainability flipsides of current norms and standards for heat supply service provision, and (3) raises key methodological questions via-a-vis the translation of contextual lessons across time(s) culture(s), and place(s). Finally, (4) the noted and striking similarities between the global energy crisis of the 1970s and the 2020s raise (perhaps slightly uncomfortable) sociopsychological questions.

The discussion is not to provide answers, but rather zooms in on tacit, and perhaps overlooked, frictions, dilemmas, and their consequent policy challenges. Hopefully, this will inspire enriching debate and future research enquiry.

7.1. Reliable and Affordable Heat Supply Provision as Policy Priorities

Global historical events, and their national repercussions, informed the Danish history of district heating and CHPs. This section considers the role and importance of national scale collective memories and temporal distance (i.e., distance in time) for this historical journey.

Collective memories of energy resource scarcity during the World Wars and the global energy crisis in the 1970s motivated support for CHPS and DH among the Danish public and among the political leadership. Throughout later decades, the lingering Cold War tensions provided a constant reminder of this national history of *energy import dependency*. In this light, the *energy independence potential* of the Danish North Sea oil and gas, and the strategic integration of this natural gas into the Danish energy system, was highly attractive. Ownership issues and the economy were the topics of public protests and contestation at the time (see Section 4.4).

Interestingly, popular historical accounts of the Danish energy system often downplay (if not downright ignore) the economic role and importance of the Danish North Sea oil and gas for not only the Danish energy system, but also for the Danish welfare state. Questions of why linger.

As collective memories of the global energy crisis faded through time, and as the Danish energy system evolved and improved, energy supply questions were no longer topics of public debate. According to sector professionals, local engagement and interest in energy supply questions dwindled. Consumers, or end-users, had increasingly come to expect the reliable and affordable heat service provision that had now become the norm. Meanwhile, the norms for what constituted 'normal' inside temperatures gradually crawled up the scale on the thermometer [23,46]. So, as the collective memories of energy resource scarcity faded, environmental awareness and concern grew among the Danish public. Meanwhile, the norms for minimum or 'normal' inside temperatures called for warmer and warmer temperatures inside. This paradox, too, remains strangely overlooked in public and political debates.

7.2. Reliable, Affordable, and Invisible Heat Supply Provision: The Flipsides?

The DH sector norms of affordable, reliable, and invisible heat supply service provision may not be conducive of more sustainable end-user/costumer heat consumption behavior. Indeed, perhaps quite to the contrary. This reasoning is underpinned by various observations. The underground nation-wide network of heat supply infrastructures throughout the rural and urban Danish landscapes have lived rather quiet lives. In part, this may be because these underground energy infrastructures are less visible in the landscape than, for example, the aboveground wind farms are. Additionally, the district heating community norms for good heat service provision are reliable, stable, affordable, and invisible heat service provision that 'just works' [87]. As a result, the heat (and energy) consumed for maintaining certain inside temperatures is easily accessible and intangible for the ordinary end-user/consumer.

However, the intangible nature of heat for heating combined with the easy use of this energy resource for end-users may lead to less conscious energy usage among the end-users, perhaps ultimately leading to excessive energy usage. Within related research domains, variants of this phenomenon are known as the "rebound effect", see [88,89]. So, judging by research on the 'rebound effect, a flipside of the DH sector norms and standards for good heat supply service provision may be increasing or growing heat demands among the end-users.

As we discuss below, the energy crisis of the 2020s may have changed this, however.

7.3. The Importance of Context: What Can We Learn from History?

This brief historical account raises the key methodological question: To what degree—and how—may contextual lessons learnt be translated across time(s) culture(s), and place(s), if at all?

Certain contextual factors and phenomena were fundamental for, and underpinned, the historical sociotechnical trajectories of DH and CHPs in Denmark. For example, (I) the collective societal memories of energy resource scarcity, and (II) the bottom-up tinkering, pragmatic problem solving, and innovative drive from the early days of Danish district heating gradually translated into almost a *culture* of re-use, recycling, and energy efficiency. This culture underpins the Danish district heating communities today [87]. (III) From the top down, a political culture of broad political coalition agreements allowed for the long-term strategic energy planning that spanned decades. Finally, (IV) high levels of general societal trust and low levels of corruption facilitated the broad public support for these large-scale energy planning initiatives [90,91].

Interestingly, district heating and collective heat infrastructure planning are most common in the former USSR, in China, and in Scandinavia [20]. In comparing these political systems or regimes, the Scandinavian social democracies stand out with mixed economies, high levels of general social trust, and very little corruption [90,91]. Much has changed in the Denmark since the 1980s and the 1990s, when the national-scale heat infrastructure planning initiatives were first carried out. Experts involved in the energy planning initiatives at the time held that similar initiatives would *not* be publicly supported, or even possible, today. These expert interviews were carried out immediately before the global energy crisis of the 2020s, however. No-one could have predicted these future global events, nor the scale of their global impact, at the time. In view of these global and national sociotechnical dynamics and change-processes, perhaps the experts would have answered differently now.

So, can contextually bound historical insights and lessons learnt be translated across contexts? And if so, to what degree? The answer to this highly relevant question could be some variant of: "it depends!" Perhaps followed by: "what is the alternative?" After all, while we cannot learn from the future, we can do our very best to learn from the past. In seeking to learn from these invaluable lessons of history, we should account for the role and importance of *context*, at various levels, and at various domains. This implies considering the interchanging sociotechnical dynamics associated with, for example, historical time(s), specific national, local, or organizational culture(s), and relevant geographical sites or place(s). In this way, via careful cross-cultural analysis, the insights and lessons that can be drawn from historical successes and failures may inform similar socio-technical journeys elsewhere.

7.4. Back to Square One? Energy Security Versus the Climate Change Challenge

There are striking similarities in public and political reactions towards the global energy crisis of the 1970s and the 2020s.

For example, (i) it seems that the energy crisis of the 2020s has resurrected the rhetoric of energy independence, energy security and energy affordability (see Section 4) from the embers of the Cold War. Climate change, and climate change-related issues, now seem of secondary concern in public debates. (ii) What were previously referred to as almost sacrosanct norms for comfort (i.e., the norms for 'appropriate' inside temperatures) are once again debated, and the Danish public has miraculously found ways to save energy (see reports on this at ens.dk.). From the top down, (iii) the Danish Government has initiated remedial energy sufficiency measures, for example, the relaxation of sustainability criteria for certain fuels.

So, what do these reactions/responses to the 2020 energy crisis imply for low-carbon energy transition processes?

Positively, and in terms of change readiness among the public, this global energy crisis has showed that we can change our energy-related behaviors quickly. Less positively, however, these reactions also emphasize that we prioritize the comfort and the challenges of the here and now. After all, the *short-term* societal challenges of energy insecurity and growing energy costs are now the key foci of public debates, with sustainability-related issues and environmental concerns all but removed from the agenda. Thus, the *longer-term,* more abstract, and more psychologically distanced [92,93] public and political concerns (e.g., climate change and climate change-related challenges) are overshadowed by the more psychologically proximate energy crisis that is a crisis of here and now.

Indeed, judging by popular and political debates, the more psychologically distanced climate change challenges have aptly faded into the corners of our individual and collective attentive spheres, superseded by the day-to-day challenges afforded by the current energy crisis. These observations call for systematic mapping of - and research enquiry into—our associated fundamental social psychological consumption-related rationalization processes.

Positively, recent years have also seen rapidly growing climate consciousness and proactive engagement among particularly the younger generations. This suggests that they perceive climate change-related issues as pressing and as more psychologically proximate.

8. Conclusions

The WEC has ranked the Danish energy system among the top countries in the world according to the energy trilemma criteria: energy security, energy equity, and sustainability. Although DH, CHPs and their associated technologies are pivotal for this top WEC ranking of the Danish energy system, their importance is largely overlooked internationally. Energy planners and district heating professionals have long called for more international focus on the unique history of DH, CHPs, and large-scale energy planning in the Danish energy system. Setting out to fill this gap in the literature, this brief history of DH and combined heat and power in Denmark explored how historical events, societal dynamics, and changing political and social rationales have all informed the emergence and the evolution of the underground heat supply infrastructures throughout rural and urban Danish landscapes.

After the global energy crisis in the 1970s, the public and political sentiment called for energy independence, alternatives to imported fuels, and for alternatives to nuclear power. The overarching energy policy priorities: energy independence, fuel diversification, energy efficiency, and later sustainability, were operationalized in the Heat Supply Act, which provided the legal framework for the national-scale collective heat infrastructure planning initiatives ahead. Broad political coalition agreements allowed for the necessary long-term strategic heat supply infrastructure planning initiatives. The Heat Supply Act granted wiggle room for bottom-up initiatives and experimentation. High levels of general societal trust, low levels of corruption, and collective memories of the energy crisis, may all have contributed to the broad societal support for these large-scale collective energy infrastructures. In the following decades, growing environmental awareness and concern called for renewable energy resources as alternatives to fossil fuels.

The paper suggested that a mindset (or even culture) of innovative thinking, heat re-use/re-cycling, and energy efficiency focus still characterizes the Danish district heating communities today. It noted the DH sector norms for good heat supply service provision as being affordable, reliable, and rather quiet heat supplies, and discussed how consumption of such highly intangible energy (here energy in the form of heat) may lead to less conscious energy usage, and ultimately perhaps to excessive energy usage, among the end-users.

Interestingly, the energy crisis of the 2020s demonstrated how quickly end-users could, once again, refocus on - and reduce - their use of energy, including heat. In facing these contemporary energy security-related grievances, the public and political debates have aptly swept climate change issues and sustainability concerns aside. Echoing public and political rationales from the global energy crisis almost half a century ago, energy security and energy price-related issues have, once again, taken center stage.

Perhaps history, and historical sociotechnical trajectories, did grant the Danish energy system a head start in the global race towards low-carbon energy transitions. Yet, as this paper revealed, that route may not have been quite as direct as popularly portrayed. The Danish district heating sector currently faces the challenges of growing biomass import dependency, but also the potentials of sector coupling and energy flexibility. Research suggests that energy efficiency and energy flexibility potential may be harvested via district heating and district cooling solutions in future 'smart' energy systems all over the world. To this end, and for other countries embarking upon the low-carbon energy transitions journey, hopefully the insights and lessons drawn from this condensed account of district heating history in Denmark may prove both valuable and inspirational.

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Article

The Balance and Optimization Model of Coal Supply in the Flow Representation of Domestic Production and Imports: The Ukrainian Case Study

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Abstract: The successful supply of an economy with coal fuel, for a country that carries out its large-scale extraction and import, is a complex production and logistics problem. Violations of the usual supply scheme in conditions of crises in the energy markets, international conflicts, etc., lead to the problem of simultaneous restructuring of the entire supply scheme. This requires changes in the directions and capacities of domestic production and imports. In this article, the above problem is solved by the economic and mathematical model of production type. The developed model includes subsystems of domestic production and import supply. The results of modeling economy supply with thermal coal for different values of demand are given. The model was used to determine the amounts of coal production for Ukraine with the structure of the coal industry of 2021 and under the condition of anthracite consumers' transformation to the high volatile coal. Simulations have shown that eliminating the use of anthracite requires the modernization of existing coal mines. Under those conditions, the import of high volatile coal will amount to 3.751 million tons in 2030 and 11.8 million tons in 2035. The amounts of coking coal imports will be 5.46 million tons, 5.151 million tons, and 7.377 million tons in 2025, 2030, and 2035, respectively.

Keywords: coal supply; model of production type; flow representation; domestic production and imports

1. Introduction

Energy balances in Ukraine are currently undergoing significant and large-scale changes, caused by a number of extraordinary influencing factors [1]. Namely, first of all, a military-political crisis is ongoing in the state, which is marked by the occupation of the country's territories, the violation of the usual traditional supply schemes, the general economic recession [2], and the related reduction in demand for fuel products, both in the energy sector and in industry, rural economy, transport, and the social sphere [3–8].

Another factor of changes in the supply of energy resources is the global tendency to reduce the consumption of carbon-containing types of fuel, which has gained significant strength in recent decades against the background of the rapid development of technologies of renewable energy sources (RES) [9–13], and systems of their accumulation and storage [14]. Technological progress in these energy sectors has led to a significant increase in the practical application of RES and their relatively safe integration into existing power systems, with minimal disruptions to their operation modes [15,16].

Under these circumstances, almost all types of coal fuel have become one of the most important groups of energy carriers for Ukraine, which has been successfully displaced from economic circulation. Chronologically, the state was the first to experience a significant shortage of coal of anthracite grades [17–19], which arose due to the occupation of certain areas of the Donetsk and Luhansk regions, and the country was forced to transfer almost all power units of thermal power plants to the consumption of coal of the gas group [20–27].

Recently, studies have appeared that directly point to Russia's geopolitical claims as a direct and already existing threat to Europe's energy security. For example, in [21,22] it is shown that many countries in the European Union imported a significant amount of energy resources from Russia. At the same time, the share of imports from Russia for individual countries reached 50%. The article [23] indicates that one of the motives for starting a military conflict on the territory of Ukraine may have been due to mineral deposits, including coal, oil, and gas. Article [23] also shows that the geopolitics of Russia in recent years has been aimed at controlling energy facilities in the republics of the former USSR, in particular in Moldova and Transnistria. In support of this, it is important to note that, since 2014, part of the coal mines have been located in territories that the Ukrainian state authorities do not control, but which have been supported by Russia. With the start of the military invasion in February 2022, the number of such mines has increased. It is estimated [24] that the share of mines located in the territory controlled by Russia has reached 63%.

As a result of the development of the military confrontation and the expansion of the territories of hostilities, energy-intensive enterprises, in particular metallurgical enterprises, were damaged or destroyed, which caused a decrease in demand for the coking group of coal brands. Correspondingly, the amount of imports of coking coal of grades and quality indicators necessary for metallurgy, which are not mined in Ukraine, also decreased [28–30].

In addition, ensuring the currently available consumption volumes no longer requires the intensive work of all the country's mines at the level of their established production productivity. Moreover, the urgent need to support the global trends of low-carbon development, as well as the extremely high cost of production of coal-mining enterprises with practically exhausted reserves and a high depth of occurrence, gives rise to the problems of the simultaneous assessment of the structure of domestic mining enterprises, and the appropriate directions for the development of the coal fuel base in the country, as well as all possible directions of external supply of coal products. An important aspect to take into account is the import requirements and opportunities of the Ukrainian economy for coal products [31,32] in particular the differentiated need for them in the energy sector and industry, taking into account physicochemical characteristics, brands, quality indicators [33–37], etc., as well as the structure and volume properties of logistic supply schemes [38,39].

The authors previously developed various scenarios for the development of the coal industry in Ukraine [40], which included not only an assessment of the prospective volumes of coal production for various purposes but also the cost of its production. After the start of the military conflict, as mentioned above, the share of mines controlled by the Ukrainian authorities decreased. In this regard, it becomes impossible to estimate the possible volumes of coal production in the future due to insufficient data on the state of such mines and the possibility of their further functioning. In such a situation, in order to meet the needs of thermal power plants, most of the power units in Ukraine operate on coal fuel, so it is necessary to import missing volumes. At the same time, considering the coal balance as a whole, especially in the context of the tasks of general energy supply by all types of fuel and energy resources, forecasting the volume of supply of energy carriers under conditions of economic growth, their economically expedient or forced mutual substitution, as well as taking into account energy security criteria, it is necessary to be able to review the composition of the mining capacities of the coal industry, its expansion through the construction of new mines, as well as the restoration of the previously closed unprofitable mining enterprises [41–44]. The usual logistics schemes will also be subject to revision in connection with political and security (military) restrictions on import supply routes.

Thus, in the study of the circulation of coal products in the country's economy as a closed technological process, efforts to increase the efficiency and safety of the production and use of all types of energy and raw coal, taking into account the balances of other energy carriers, especially in the energy sector, leads to the need for simultaneous interconnected consideration of all links of this process, which are usually described by specialized balance and optimization mathematical models of various levels of detail [45–56], which allow determining the most appropriate operating conditions of a coal complex based on certain criteria. Among such criteria is the total volume of domestic coal production, its individual grades, and technological purpose, the volume of production of a separate coal-mining enterprise, and the volumes and directions of supply of coal products that satisfy the requirements for standard fuel [57,58], electricity, and heat generating enterprises of thermal energy, costs for such fuel supply, volumes of environmental pollutant emissions by thermal power plants [59–62] due to coal burning, volumes of forced coal imports and corresponding indicators of energy security [63], etc.

In this way, determining the appropriate volumes and directions of coal supply to the economy appears as a multi-product production and network-transport problem with safety restrictions that bind the volumes of these subsystems. The need for a formal presentation of such a supply system in this work is provided by an economic model, which provides for the representation of production facilities and the supply network in a single way in the form of production activities: vector-matrix structures of the production type model [64,65]. Building such a model for the coal supply system of the economy is an important task, given the need to combine such aspects of coal supply as multi-product production technologies, and the structure of the transport subsystem and is the main goal of this work.

The optimal volumes of domestic production and importation of all types of coal products needed in the economy, obtained from its solutions, satisfy the requirements both for volumes and for the necessary levels of security of supply. At the same time, the results of the calculations can serve not only to determine the amount of necessary income but also to develop a system of measures for the transformation of the energy sector and other industries that consume coal, in the direction of a gradual transition to a stable and guaranteed coal balance.

In particular, recent changes in the structure of the mining sector of the fuel and energy complex of Ukraine, caused by reasons of a political and economic nature, have led to a significant, and for some brands of coal, complete reduction in production [3,4]. Territorial separation of mining enterprises producing anthracite groups of coal currently make it impossible to reliably and uninterruptedly supply this type of fuel to consumers from sources of own production. In this state of the industry, meeting the needs of consumers in anthracite coal is possible only through imports.

From the point of view of energy security requirements [66,67], such a state of the coal supply system is acceptable, in which supply from the country's own sources prevails over import volumes. Such a state can be achieved by carrying out measures to modernize or reconstruct existing mining enterprises that have the potential to increase production capacity in order to increase the level of domestic production [68,69].

Summarizing all of the above, the novelty of this paper is its new approach to the entire coal supply–transformation–consumption system representation. First, a certain network scheme of its production and transportation links is created, which in the most uniform way describes all technologically different aspects of coal circulation in the economy. Next, this associated network is used to create a matrix representation of the system in the form of sequential production activities, composed of the technological matrix introduced by L.V. Kantorovich.

Despite the fact that this article presents the system of coal supply to the Ukrainian economy, the application of the proposed model may be highly valuable for other countries, the share of coal in the balance of which is significant. In particular, the presented model may be important for European Union countries in the view of the uncertainty and instability of supply of other energy carriers, for example, natural gas and its significant price volatility in the world oil and gas markets, threats of disruption of traditional schemes, and directions of supply.

The next part of this document is organized as follows. Section 2 is devoted to the presentation of the network-matrix formalism of production type model used. The structure of the coal supply model for Ukraine in terms of abstract network of production or import sources and product flow links is described in Section 3. The results of coal flow calculations are also placed here. They demonstrate, in particular, the refutation of the hypothesis of a mandatory decrease in the level of energy security, caused by the forced reduction of the coal mining base. Section 4 covers conclusions on modeling and testing results and a discussion of future model development.

2. Materials and Methods

To obtain the mutually agreed presentation of coal production (mining) objects, as well as a network system of its receipt by import and supply from domestic coal mining enterprises, the authors proposed, in a certain sense, a dual approach to the presentation of such objects. It consists of the application of the economic model of production activities and products proposed by L.V. Kantorovich [70–73] using the concept of "production activity" for a model representation of both technology (a production facility) and product transport links between sources of production, importation, transformation, and consumers of coal products. At the same time, the classical "production activity" [71] is considered here as a connection between the input products of the technology—raw materials and materials, and the output main product of such technology. As a result, a complete coal supply system can be represented by the graph structure of a certain associated supply network and the corresponding equivalent technological matrix of the classical model of production type, according to L.V. Kantorovich. The development of this approach can be found in the works of the authors. A production type model, for example, according to [64,74], can be written in the form of a balance flow model.

In order to express the structure of the flow supply of the fuel supply system into the structure of the data set of the production type model, we have offered to identify its elementary components: the nodes and lines (edges) in the graph of the flow model and the mapping of these elements into the production activities (or their groups) of the production type model. The proposed structural elements of the model of production type are intended to form a general unified system of product balance equations of interconnected networked and non-networked systems of fuel supply. The basic elements of the flow model of the system, intended for the construction of structural elements, which are comprised of the Kantorovich production activities, are the line and the node of the abstract supply system, shown, respectively, in Figures 1 and 2.

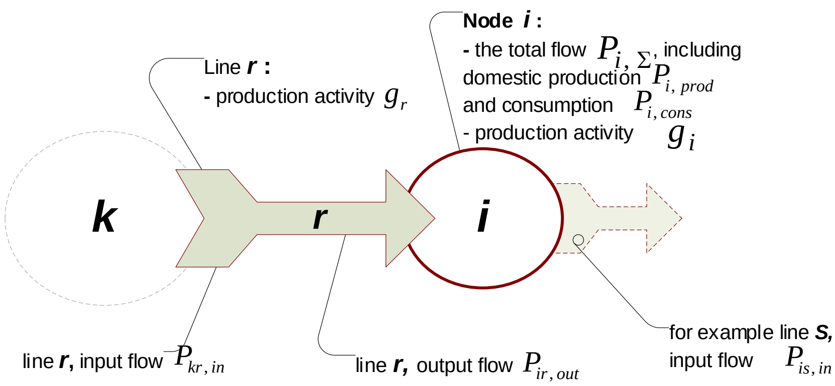

Figure 1. The products of network line [64], (p. 209).

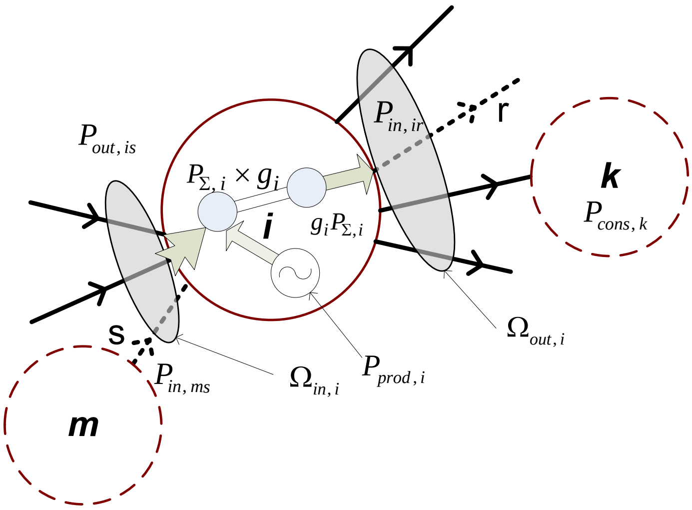

Figure 2. The products of network node [64], (p. 210).

The line ***r***, which receives physical flow from node ***k*** and outputs it to node i, is associated with the production activity of the line, in which the model product, the output flow of node k $P_{k,\,out}$ is consumed, the model product of the output flow of the line $P_{ir,\,out}$ is produced, and the ratio of their values is determined by the technological coefficient of input and output of the line g_r. The structural element of the line in the model of the production type is comprised of a single production activity, the model product of which is the output flow of the line.

The structural element of node i with sets of input and output flows $\Omega_{i,\,in}$ and $\Omega_{i,\,out}$, respectively, is formed by an ordered group of production activities, that, in series, (1) produce a variable amount of domestic production of fuel in the node $P_{i,\,prod}$ without consumption of other model products with the appropriate technological coefficient of domestic production $g_{i\;prod}$, (2) produce the input flows of the node $P^{node}_{ir,\,in}$ while consuming the output flows of the lines $P^{line}_{ir,\,out}$ with the proper technological coefficient $g_{ir} = 1$, (3) sum up the amounts of domestic production $P_{i,\,prod}$ and input flows of the node $P^{node}_{ir,\,in}$ and the consumption of this total amount for the production of the total output flow of the node $P_{i\,\Sigma}$ with the technological coefficient of the node g_i.

Equations (1)–(3) represent a generalized material balance.

$$g_{i\;prod} \cdot P_{i,\,prod} + \sum_{r \in \Omega_{i,\,in}} P^{node}_{ir,\,in} - P_{i,\,\Sigma} = 0, \quad i = 1,\, N_{node}\,, \tag{1}$$

$$g_i \cdot P_{i,\,\Sigma} - \sum_{r \in \Omega_{i,\,out}} P^{line}_{kr,\,in} = P_{i,\,cons},\; i = 1,\, N_{node}\,, \tag{2}$$

$$-\,P^{line}_{ir,\,out}\Big|_{r \in \Omega_{i,\,in}} + g_r\, P^{line}_{kr,\,in}\Big|_{r \in \Omega_{i,\,out}} = 0,\; r = 1,\, N_{line}\,. \tag{3}$$

The system of the balance equations of the node and line products determined in this way represents interconnected networked and non-networked subsystems of fuel product supply in the integrated system of fuel supply. For non-networked systems, the amounts of specific consumption and production of fuel products in the technological links of their production, conversion, and consumption are set by the technological coefficients of nodes $g_{i\;prod}$, g_i and lines g_r, and the balance of amounts is provided by the node material balance condition for the introduced set of products—by the Equations (1) and (2), as well as the abovementioned structure of the system (1)–(3) according to Kantorovich's production activity approach.

The specific definition of the structure of the constructive element of the node with the production activity of production of its total flow and the corresponding technological coefficient allowed us to take into account the interaction of networked and non-networked systems at the level of the conversion amounts of fuel products.

According to the above flow representation of the production system structure, the coal balance equations for different schemes of supply, including the sources of domestic production, technological modernization of mining enterprises, and imports, were formulated.

3. Results and Discussion

3.1. Results

The formal representation of the economic model of the coal supply system in the form of balance equations for the amounts of coal products is determined by the structure of the technological interrelationships of this system, as well as the main goals and tasks of its functioning. The goal of the country's coal supply system is to meet the needs of consumers of various types of coal products through coal mining, its refinement and preparation at the country's enterprises, as well as its import from abroad by sea and railways. The coal demand, in turn, is divided according to its technological destination and is determined by the consumption amount of coking and thermal coal [31,32,75].

From this point of view, the country's coal supply system is a set of technological and economic links for the supply of all types of coal products to the country's economy, both from domestic mining enterprises and imports. The technological processes used to satisfy the demand include mining, refinement, preparation, and transportation of coal from the coal mining enterprise to the final consumer. Import supply consists of the combination of the purchase of the necessary amounts of coal in exporting countries, which are considered as sources of imports, transportation on international trade routes, as well as transportation within a country to enterprises of its final use or transformation [76].

Taking into account these technological processes in the sequence described above for solving the problem of determining the optimal amounts and directions of coal supply is the basis for creating the structure of the balance and optimization model of the country's coal supply, which accounts for the differentiation of coal products by brands and technological destination, as well as the possibility of increasing the competitiveness of the coal industry through the modernization and reconstruction of its enterprises [77,78].

The optimization criterion of the economic model proposed below is the cost of supplying all brands of coal and any technological destination from sources of domestic production and import. Moreover, the country's coal mining enterprises are provided with the possibility to work in one of two operating states: normal production, with the current state of mining equipment, as well as with improved mining technologies and/or total reconstruction (modernization) of the enterprise [77].

The important conditions determining the system of constraints of the proposed model are requirements for:

- The guaranteed demand provision for each of all coal brands;
- Sufficient capacity of import routes, in particular, sea trade ports of the country and its railways;
- Amounts of own production at the enterprise, determined by the variant of its functioning;
- Meeting the energy security requirements according to the quantitative criteria "The share of own sources in the balance of fuel and energy resources of the country" and "The share of fuel imported from one country (company) in its total imported amount" [66].

The model is formulated as follows. It is required to minimize the total costs of coal supply for all brands and any technological destination from sources of domestic production and importation in the possible current and/or technologically improved (modernized) operating state of coal-mining enterprises (1)

$$L = \sum_{k=1}^{N} \sum_{i \in I} \sum_{s \in \{0,\,1\}} \theta_{i,K,s} \cdot C_{i,\,k,s}^{prod} \cdot x_{i,\,k,s}^{prod} + \sum_{i \in I} \sum_{d=1}^{M} C_{i,d}^{imp} \cdot x_{i,d}^{imp} \to min \quad (4)$$

subjected to the following conditions:

- The consumers' demand is totally provided for each coal brand *i*

$$\sum_{k=1}^{N} \sum_{s\in\{0,\ 1\}} g_{i,k,s}^{prod} \cdot x_{i,k,s}^{prod} \cdot \theta_{i,k,s} + \sum_{d=1}^{M} x_{i,d}^{imp} \geq \ X_{i,\ max} \Bigg|_{i\in I} \tag{5}$$

- The total amount of imports does not exceed the total throughput capacity of sea trade ports and railways

$$\sum_{i\in I} x_{i,d}^{imp} - X_{tpc,\ max} \leq \ 0 \tag{6}$$

- If coal-mining enterprise $\boldsymbol{k}$ operates in the state of installed technological equipment with (I) or without (II) reconstruction or modernization (s = 1 and $\boldsymbol{s}$ = 0, respectively), the total amount of domestic production of coal brand *i* is determined as follows

$$\sum_{k=1}^{N} \sum_{s\in\{0,1\}} x_{i,\ k,s}^{prod} \cdot \theta_{i,\ k,s} - x_{i}^{prod} \Big|_{i\in I} = 0 \tag{7}$$

- The total amount of imported coal of the brand *i* is determined as a sum of the amounts received from the import source *d*

$$\sum_{d=1}^{M} x_{i,\ d}^{imp} - x_{i}^{imp} \Big|_{i\in I} = 0 \tag{8}$$

- Imbalance between the total amount of domestic production and the threshold amount of total coal supply of the brand *i*, by the criteria of energy security, is the positive value

$$e_i \geq 0|_{i\in I}, \tag{9}$$

If this imbalance is determined by the legislation regulated ratio γ of domestic production and the total coal supply of the brand *i* [39]

$$x_{i}^{prod} - \gamma \cdot X_{supply,i}^{\Sigma} \ = e_i \Big|_{i\in I}, \tag{10}$$

and the total coal supply of the brand *i* is defined as

$$x_{i}^{prod} + x_{i}^{imp} = X_{supply,i}^{\Sigma}, \tag{11}$$

- Imbalance between the amount of imported coal of brand *I* from each source of import and the threshold amount of this brand's import by the criteria of energy security, is the positive value

$$\Delta_i \geq 0|_{i\in I}, \tag{12}$$

if this imbalance is determined by the legislation regulated ratio Δ_i for the threshold amount of import from each source *d* [39]

$$x_{i}^{imp} = \lambda \cdot \sum_{d=1}^{M} x_{i,\ d}^{imp} + \Delta_i \Bigg|_{i\in I} \tag{13}$$

In the model (1)–(13), the coefficients of the target function represent specific values of the cost of coal supplies to the country:

$$C_{i,\ k,s}^{prod} = C_{i,\ k,s\ mining} \cdot \theta_{i,\ k,s} + C_{i,k,\ preparation} \tag{14}$$

$$C_{i,\,d}^{imp} = C_{i,d\ imp} + C_{i,d\ transp\ ,\ ext}, \tag{15}$$

where L is the total cost of coal supply for all brands of coal and sources of domestic production and imports; $C_{i,k,s}^{prod}$ is the coal domestic production specific costs for the brand i at the enterprise k in the variant of operation s within the calculation period; $x_{i,k,s}^{prod}$ is the technologically available maximum amount of domestic production of coal of the brand i from source k in the variant of operation s; $\theta_{I,k,s}$ is the binary variable, determining the variant of operation of enterprise k, which produces coal of the brand i;

$$\theta_{i,k,s} = \begin{cases} 0, \ without\ modernization; \\ 1, \ with\ modernization. \end{cases}$$

$C_{i,d}^{imp}$ is the coal supply specific costs for brand i and source of import d; $x_{i,d}^{imp}$ is the amount of imported coal of the brand i from the source of import d; I is the set of all brands of coal—both thermal and coking coal; $g_{i,k,s}^{prod}$ is technology coefficient of preparation of coal brand i, produced at the enterprise k in the variant of operation s within the calculation period; $X_{i,max}$ is the total demand of consumers for coal of the brand i; N is the number of coal domestic production sources; M is the number of import's sources; $X_{tpc,max}$ is the throughput capacity of the sea import route (total throughput capacity of seaports); x_i^{prod} is the total amount of domestic production of coal of the brand i at all coal mining enterprises; x_i^{imp} is the total amount of coal imports for brand i; e_i is the equalizing variable, determining the value of imbalance caused by the supply of coal of the brand i in case of violation of the conditions of energy safety "Domestic sources share in the total fuel supply to the system"; γ is the value of the indicator of energy security, which determines the share of domestic sources in the balance of fuel and energy resources of the country; $X_{\mathrm{sup}ply,i}^{\Sigma}$ is the total supply of coal brand i into the country; $\gamma_{\min}$, $\gamma_{\max}$ are the minimum and maximum admissible share of domestic production sources in the total fuel consumption of the system, allowed according to the requirements of energy security, respectively; Δ_i is the equalizing variable, determining the amount of imbalance caused by the supply of coal of brand i in case of violation of the energy security requirement on "Part of fuel imports from one country (company) in the total volume of its imports"; λ is the value of the indicator of energy security, determining the share of fuel imports from one country (company) in the total amount of imports; $\lambda_{\min}$, $\lambda_{\max}$ are the minimum and maximum admissible share of the volume of imports from one source, allowed according to the requirements of energy security, respectively; $C_{i,\,k,\,s\ mining}$ is the specific cost of coal production for brand i at enterprise k in variant of operation s;

$$C_{i,\,k,s\ mining}^{\theta} \ = \begin{cases} C_{i,k}^{0}, \ without\ modernization; \\ C_{i,k}^{1}, \ with\ modernization. \end{cases}$$

$C_{i,k\ preparation}$ is the specific cost of coal preparation of the brand i, produced at the enterprise k;

$C_{transp,\ ext}$ is the specific cost of internal coal transportation;

$C_{i,d\ imp}$ is the specific purchase price of coal of the brand i at the source of imports d;

$C_{i,d\ transp,\ ext}$ is the specific cost of external coal transportation of the brand i from the source of import d.

Each Equation of the system (1)–(13) is presented in the model in more detail in terms of a specific network scheme of coal products supply in the form of a set of Equations (1)–(3), which, in turn, are the conditions of the balance of production and transmission amounts, transmission and conversion, transmission, and final consumption. In other words, as balances between node and branch elements of some imaginary network. Such a scheme was developed in this work [76] for the system of supply of thermal coal to the economy of the country, which includes separate subsystems of coal fuel supply by groups: high volatile (D, DG, G brands of coal) and anthracite (A and P brands of coal). These alphabetical designations of coal brands (A, D, DG, G, K, P, PS, Zh) correspond to the Ukrainian coal classification [33].

In each of these subsystems the coal supply is presented by domestic production and import nodes, thus ensuring the competition of supply sources and the influence of the world market on the distribution of coal flows in the system. The sources of supply for each brand of coal have been chosen under the assumption of matching the thermal coal supplied from the exporting countries to the world market [79], and the coal of the domestic production. Considering the differences in the classification of coal [33,34], the comparison of types of imported coal and brands of domestic coal products was carried out according to the indicator of volatiles output.

When modeling the supply of each brand of energy coal there is the possibility of simultaneous inputs by different transportation methods, e.g., by sea, from the countries far afield. Besides the sea route, anthracite and high volatile coal may be transported by railway from the countries nearby, e.g., from Russia and Kazakhstan. These brands may be mined within the territory of Ukraine, which is currently not controlled by the state government, so the scheme of coal supply by brands includes the possibility of input from these territories with their own prices and amount variables.

The structural scheme of supply of the anthracite group, which includes coal of A and P brands, is presented in Figure 3. The supply of the high volatile coal (D, DG, and G brands) is shown in Figure 4.

The sources of anthracite imports from far afield are Vietnam and South Africa (nodes 35, 36, respectively), in view of their significant share in the total volume of trade on the world market [80]. The sources of anthracite supply from nearby areas, except for Russia (node 37), also include the territory of Ukraine, which is currently not controlled by the state government (node 38), because possible schemes of coal supply may include inputs from these territories to the government-controlled part of Ukraine. Russia is the main source of brand P supply to the economy of the country by import (node 39). Other sources of this brand imports were not considered, and the import of this brand from far afield is denoted with dots, as a possible direction of supply. This is caused by the international coal classification features according to which physical and chemical properties, related to brand P, are included in the class of anthracites, without separation to groups in the available statistical data.

The supply of coal of brand D by import is carried out only from the countries nearby—Russia, Kazakhstan, and the territory of Ukraine, which is currently not controlled by the state government (nodes 42, 43, and 51, respectively). The DG brand may be imported from the far afield countries—Australia, Indonesia, the USA (nodes 44, 45, 46, 47, respectively), and nearby countries—Russia, and also from the territory of Ukraine, which is currently not controlled by the state government (nodes 48, 53). The possible sources of brand G imports are Australia, Russia, and the territory of Ukraine, which is currently not controlled by the state government (nodes 40, 41, 52). This structure of imports is proposed as a result of the mentioned coal brands' availability in the markets of these countries.

Coal products received from certain sources of import are accumulated in the nodes, forming the total amount of imports from the countries of far abroad and nearby abroad (nodes 1, 2, 5, 8, 10, 11, and 14 respectively). Coal imported by sea comes to the hub-node, which represents the total throughput capacity of the sea trade ports of the country (node 16). Its amount is further divided to two parts in the next node (node 17). This supply structure was created due to the assumption that some part of the imported coal may be stored at the port for certain period of time. In this part node, two subsystems, namely supplying anthracite and high volatile coal groups, are merged. At the same time, the possibility of mutual substitution of brands is not provided.

The amount of domestic production of brands of anthracite group (nodes 3 and 6, respectively), as well as brands of high volatile group (nodes 9, 12, 15) are subjected to refinement and preparation processes in nodes 19, 22, 25, 28, and 31 to increase their consumer characteristics, finally forming the amount of ready for consumption coal products.

Technology coefficient of preparation [69] for all brands of coal is taken equal to 0,5 [69]. Imported coal is not subjected to refinement and preparation.

Ready-for-consumption coal of domestic production is added to the total import amounts, and the total amounts of coal products (nodes 20, 23, 26, 29, 32) are directed to consumption nodes of anthracite (A+P) (node 33) and high volatile (D+DG+G) (node 34) coal groups, the demand for which was specified as model input data [3,81].

Amounts of imported coal products must meet the requirements of energy security of the state. To check this requirement in the model the amounts of coal supplied from different sources of import and the amount of domestic production must be obtained.

Total imports from the countries of far abroad and nearby abroad for each brand separately are formed in the appropriate nodes (18, 21, 26, 27, 32). These amounts are subjected to the restriction of energy security "The share of domestic sources in the total supply of fuel to the system".

In order to allow for the restriction of energy security "The share of import from one source" for the anthracite coal group, the model includes the total import node (node 49), which represents the summation and distribution structure for brands A and P. The input and output flows of this node are equated to each other by brands. The total import amount formed in this node is further used in proportion with coal flows coming from separate sources of imports separately for A and P brands.

The total amount of import for the high volatile group (D, DG, G) of coal (node 50) is included in the model to allow for the permissible share of each brand of this group in the total imports of this group.

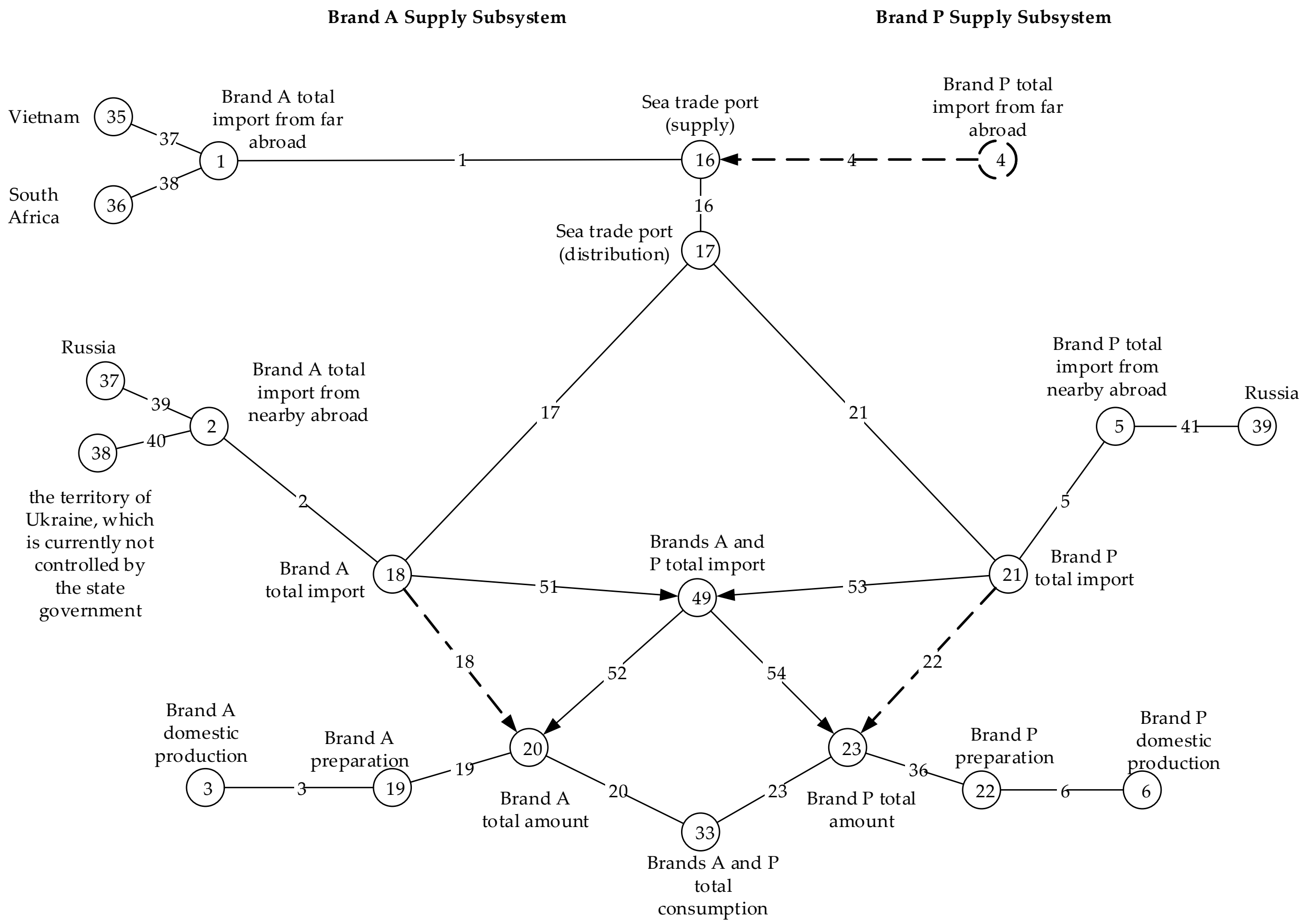

Figure 3. Anthracite supply subsystem [82], (p. 99).

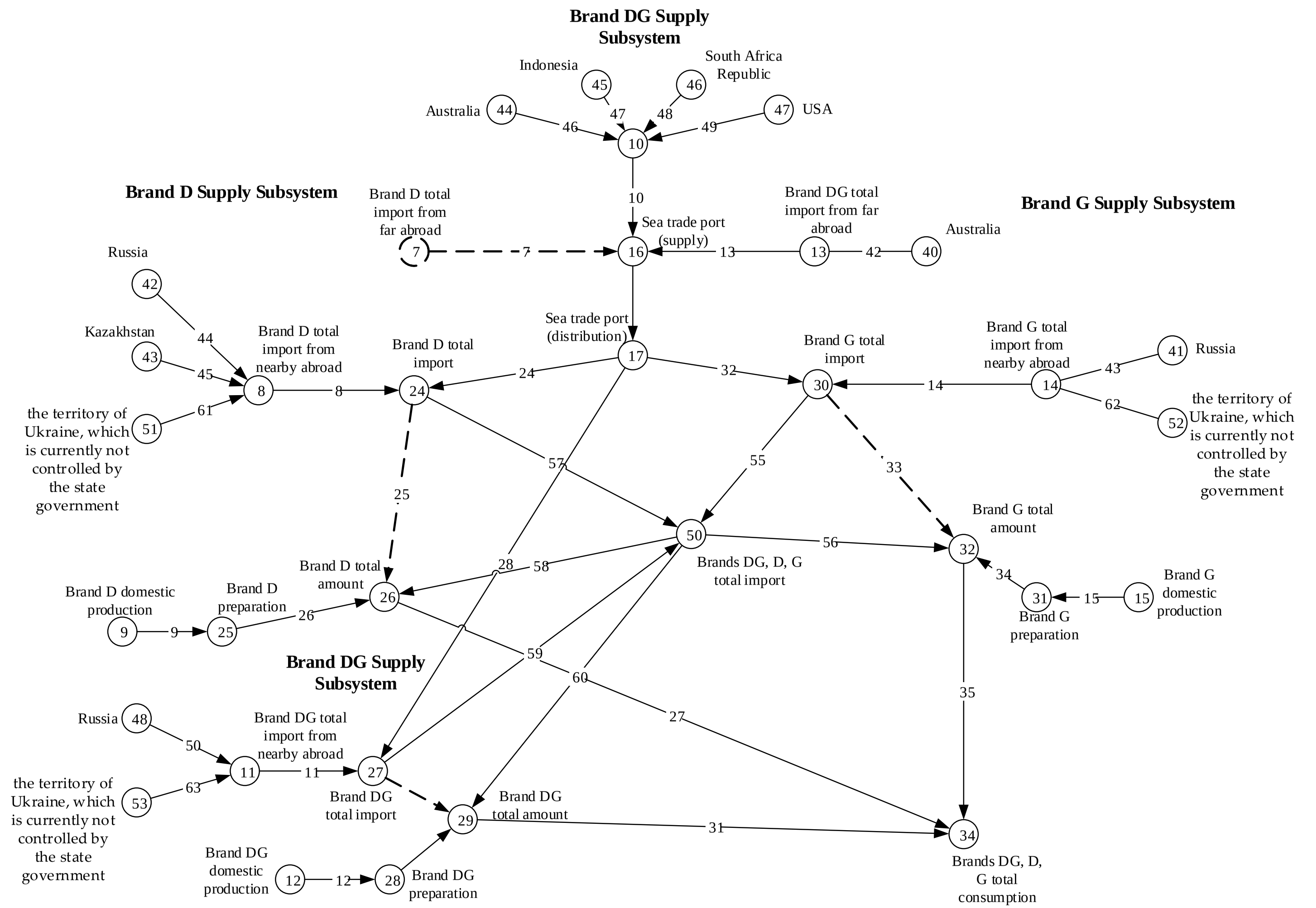

Figure 4. High volatile coal supply subsystem [82] (p. 100). The application of this model to the Ukrainian coal sector implies that only some part of mines can be reconstructed or modernized at the coal mining enterprises located on the controlled territory of the country [83–85]. Other enterprises have practically exhausted reserves, and the implementation of high-cost modernization measures is considered unreasonable for them. Reconstruction of enterprises that are privately owned is beyond the scope of this work considering that the state does not have a significant influence on the owners for investing in their development.

In calculations of coal balances of the country by means of the developed model, the volumes of consumption of different types of coal products were changed according to the possible variants of development of the economic and political state of the state. In particular, the assumption of complete cessation of consumption of anthracite coal group and the transfer of all consumers to the gas group after 2025 were investigated. Among the general economic conditions of modeling, which influenced the limitation of the changed model, the level of its detailing, and data sources for calculations, the following should be named:

- The lack of well-grounded state-level strategies and plans for the development of industrial sectors, which makes it impossible to clearly define the structure and volumes of coal fuel consumption;
- Limited access to long-term plans for reconstruction and development of enterprises that are part of the end use sector;
- The government cannot guarantee the renewal of production of deficit brands of coal, which currently remain on the territory of Ukraine, which is currently not controlled by the state government;
- Reducing the resource capacity of power units of thermal power plants that consume coal fuel, as well as the need for the construction of new or additional reconstruction of existing generating capacities, which will meet the environmental standards of the European legislation and will operate after the end of the life of existing power units;
- Construction of new generating capacities requires the possibility of using project fuel, but the availability of certain brands of coal for the medium and long term remains uncertain.

At the same time, economic efficiency of technological renewal of mines means both energy saving, improvement of ecological conditions [83], and an increase of basic technical and economic indicators: an increase in amounts of coal production, reduction of inputs of material and human resources due to concentration of production, and improvement of quality of coal products, in particular, reduction of their ash content [86]. All these effects of reconstruction and modernization were allowed for in the model by specific cost values.

In particular, in [40,87,88] the authors obtained the estimates for ready-to-use coal product prices for the period up to 2035. These prices were evaluated in the state of implementation of reconstruction and modernization of mining enterprises, and alternatively, in the state without such reconstruction or modernization. Each of the examined enterprises was highly effective in 2015.

The prices used by the model are shown in Table 1.

Table 1. The estimates for ready-to-use coal product prices for the period up to 2035, USD.

Enterprise	Calculated Value					
	2025		2030		2035	
	I	II	I	II	I	II
State enterprise “Pivdennodonbaske №3 by M.S. Surhai“	42.84	50.77	38.49	50.77	37.31	50.77
State enterprise “Krasnoarmiiskvuhillia(G)”	38.49	60.78	35.26	60.78	33.52	60.78
State enterprise “Selydivvuhillia (G)“	35.26	35.26	34.82	35.26	34.82	35.26
State enterprise “Pervomaiskvuhillia (G)“	39.85	103.90	35.26	103.90	35.26	103.90
State enterprise “Lvivvuhillia“	39.43	42.05	38.17	42.05	40.83	47.98
New construction mines	27.59		19.78		14.54	
State enterprise “Mine administration “Pivdennodonbaske №1“	46.75	46.75	44.66	46.75	44.56	46.75
State enterprise “Selydivvuhillia (DG)“	43.67	64.18	41.30	64.18	39.93	64.18
State enterprise “Pervomaiskvuhillia (DG)“	68.79	158.16	59.75	158.16	59.75	158.16

Table 1. *Cont.*

Enterprise	Calculated Value					
	2025		2030		2035	
	I	II	I	II	I	II
Open joint stock company "Lysychanskvuhillia"	40.29	43.02	38.95	43,02	38,95	43,02
State enterpise "Volynvuhillia"	90.50	116.03	90.50	116,03	90,50	116,03
New construction mines	30.71	38.81	27.59	38,81	27,59	38,81
State enterpise "Krasnoarmiiskvuhillia (Zh)"	37.31	46.75	36.24	62,21	35,26	62,21
State enterpise "Toretskvuhillia"	52.04	62.21	52.04	46,75	52,04	46,75
New construction mines	38.49		27.59		27.59	
New construction mines	27.59		21.19		21.19	

The estimated values of coal production cost at private enterprises are shown in Table 2.

Table 2. The estimated values of coal production cost at private enterprises for the period up to 2035, USD.

Enterprise	Calculated Value		
	2025	2030	2035
DTEK Dobropilliavuhillia Limited	21.28	19.94	18.51
Open joint stock company "Pavlohradvuhillia"	25.98	30.12	38.49
Company with additional responsibility "Mine Bilozirska"	38.49	35.26	33.52
New construction mines	27.59	19.78	14.54
Open joint stock company "Pavlohradvuhillia"	12.66	14.85	17.03
New construction mines	30.71	27.59	27.59
Open joint stock company "Krasnolymanske"	50.47	50.47	50.47
Open joint stock company "Ukrvuhlebud"	65.54	65.54	65.54
New construction mines	38.49	27.59	27.59
Private joint stock company "Mining Management Group «Pokrovske»"	17.69	17.69	19.78
New construction mines	27.59	21.19	21.19

Table 3 shows the results of calculations of coal balances carried out on the basis of the developed balance and optimization model of the coal supply of the country with differentiation by brands and technological purposes. The presented above solutions of models (1)–(10) for the amounts of coal supply by brands show that changes in the consumption structure significantly affect the possibility of ensuring the coal balance, in particular, through reconstruction and modernization or increase of imports.

Additionally, the modeling results indicate that the complete termination of anthracite consumption requires the reconstruction and modernization of mines producing high volatile coal groups by 2025, and up to 2035 almost all of the mines currently located in the government-controlled territories will have to be reconstructed to meet the maximum values of their productive capacity.

Under these conditions, imports of high volatile coal will be approximately 3.751 million tons in 2030 and 11.8 million tons in 2035. The amounts of coke coal imports will increase up to approximately 5.46 million tons, 5.151 million tons and 7.377 million tons in 2025, 2030 and 2035, respectively.

Table 3. The results of calculations of coal balances for the period up to 2035.

Indicator	2020	2025	2030	2035
1. Consumption, million tons (input)				
z	2.067	0.0	0.0	0.0
G+DG+D	23.917	32.801	41.6	52.401
Coke coal, total	19.225	18.946	20.726	21.452
2. Supply, million tons (calculated values)				
2.1 Import				
A				
Vietnam	0.62	0.0	0.0	0.0
South Africa Republic	0.62	0.0	0.0	0.0
Russia	0.62	0.0	0.0	0.0
The territory of Ukraine, which is currently not controlled by the state government	0.207	0.0	0.0	0.0
D				
Russia	0.0	0.0	0.0	2.403
Kazakhstan	0.0	0.0	0.0	2,403
The territory of Ukraine, which is currently not controlled by the state government	0.0	0.0	0.0	2.06
G				
Australia	0.0	0.0	1.313	1.727
Russia	0.0	0.0	1.313	1.727
The territory of Ukraine, which is currently not controlled by the state government	0.0	0.0	1.125	1.48
DG				
G (for coking)				
Australia	0.447	0.0	0.0	0.0
The territory of Ukraine, which is currently not controlled by the state government	0.0	0.0	0.0	0.0
PS				
Australia	3.22	1.911	1.803	2.582
Russia	3.22	1.911	1.803	2.582
The territory of Ukraine, which is currently not controlled by the state government	2.76	1.638	1.545	2.213
2.2 Domestic production, million tons				
DG				
State enterpise “Mine administration “Pivdennodonbaske №1”	0.95	0.95	**1.045 ***	0.95
State enterpise “Selidivvuhillia”	0.491	0.491	**1.230**	**1.320**
State enterpise “Pervomaiskvuhillia”	0.075	0.075	**0.535**	**0.570**
State enterpise “Lysychachnskvuhillia”	1.13	1.13	**1.390**	1.13
Open joint stock company “Pavlohradvuhillia”	**14.55**	**14.44**	**10.355**	**7.79**
State enterpise “Volynvuhillia”	0.143	0.143	**0.24**	**0.24**
New construction mines	**0.8**	0.172	**2.85**	**2.85**
G				
State enterpise “Pivdennodonbaske №3 by M.S. Surhai”	0.8	0.8	**1.425**	**1.520**
State enterpise “Selidivvuhillia”	1.71	1.71	1.71	1.71
State enterpise “Pervomaisvuhillia”	0.18	0.18	**0.91**	**1.140**
Open joint stock company “Pavlohradvuhillia”	**1.053**	**3.23**	**2.375**	**1.425**

Table 3. *Cont.*

Indicator	2020	2025	2030	2035
State enterpise "Lvivvuhillia"	1.185	1.185	**1.450**	1.185
State enterpise "Krasnoarmiiskvuhillia"	0.85	**0.915**	**1.4**	**1.9**
New construction mines	0.0	**2.85**	**5.7**	**10.83**
DTEK Dobropilliavuhillia Limited	1.196	**4.895**	**5.605**	**6.55**
Company with additional responsibility "Mine Bilozirska"	0.0	**1.425**	**1.71**	**1.9**
K				
New construction mines	0.0	**2.85**	**4.94**	**4.94**
Private joint stock company "Mining Management Group «Pokrovske»"	**7.2**	**7.2**	**7.2**	**5.7**
Zh				
State enterpise "Krasnoarmiiskvuhillia"	1.4	1.4	1.4	1.4
State enterpise "Toretskvuhillia"	**0.625**	**0.755**	**0.755**	**0.755**
Open joint stock company "Krasnolymanske"	**0.8**	**0.81**	**0.81**	**0.81**
Open joint stock company "Ukrvuhlebud"	0.0	**0.47**	**0.47**	**0.47**
New construction mines	0.0	0.0	0.0	0.0
Total amount of High volatile group preparation	1.196	1.790	2.080	2.620

* here and further in the table the variant of operation of the mine enterprise, which requires reconstruction or modernization, is denoted in bold.

3.2. Discussion

In modeling, the authors used the structure and potential volumes of consumption that existed or were projected to change at the time of the beginning of the military conflict. The current situation in Ukraine creates uncertainty on both the structure of the coal mining industry and the structure of consumption. The advantage of the proposed model is the possibility to take into account different volumes of coal supply and consumption in the sectors of the economy, also taking into account changes in the transport infrastructure.

Obviously, the criterion of efficiency of the functioning of the coal industry used in the article can serve as an indicator of its productivity and efficiency only for specific areas of technical and economic analysis. However, this criterion includes the main costs of the industry in mutually linked technologies of coal production and supply. Some aspects of the coal industry operation are not covered by this criterion. For example, the decision on the termination of operation of low-profitable mines is made on the models of prospective basis. Furthermore, conclusions on the re-equipment of the mine with innovative technologies are usually made on the basis of research in the framework of technological development models. The results of these studies were used in the article mainly to estimate prices for ready-to-use coal products at highly profitable enterprises equipped at the new technology level and mines, which have at this time outdated extraction technologies. In addition, the proposed method of determination of the amounts of production and supply of coal in this paper presents subjection to restrictions of energy security, thus giving a higher level of ensuring the reliability of supply in comparison with the models of technological development, transportation problems, and pure optimization models on the graphs of networks.

As can be seen, the network representation of the supply model allows us to take explicit account of the interrelationships between different technologies and industries, especially highlighting the links between industries in terms of their products. This will make it possible in the future to extend this model to secondary fuels, such as electricity and thermal energy, which will allow the construction of more complete energy balances and constraints on the supply of other fuels and energy.

4. Conclusions

The study of optimal sources and flows of coal products is one of the most important problems of economic and energy security for a country with a developed coal-fuel base, a significant sector of coal-fired thermal energy, that is in a state of military-political conflict and has occupied territories. To solve this problem, the article proposes the structure of the model of coal supply, which takes into account differentiated consumption of almost all brands of coal, restricted supply possibilities from the national resource base and imports, and technological re-equipment of mining enterprises, criteria of energy security.

In our work, we considered coal supplies as a multistream system, differentiated, among other things, by coal brands. Our research shows that already, in 2035, the needs of the economy, including the fuel and energy complex, will exceed the supply of high volatile coal brands from domestic production. In this regard, by 2035, it will be necessary to develop an effective concept of changing the structure of consumption and production of coal fuel, taking into account projects for the development of transport infrastructure.

In this sense, the inherent advantage of the model is the interconnectedness and simultaneous consideration of the volumes of domestic production and transport, as well as technological limitations on these volumes and the limitations caused by military conflict.

Taking into account the occupation while modeling the coal supply is carried out by creating a special structure of the energy coal supply system for the territories under government control, in which the temporarily occupied territories are considered as sources of import with their own amounts and cost indicators of supply and elements of transport infrastructure, as well as including the consumption of enterprises in these territories. The possibility of such modification of the model is ensured by the proposed authors' network representation of the production and supply scheme.

Modeling results demonstrate that imports of high volatile coal will be approximately 3.751 million tons in 2030 and 11.8 million tons in 2035. The amounts of coke coal imports will increase up to approximately 5.46 million tons, 5.151 million tons, and 7.377 million tons in 2025, 2030, and 2035, respectively.

Highly specific conditions of supply of certain groups of energy coal, anthracite and high volatile groups, both from the sources of domestic production and import, are taken into account in the model by individual subsystems of supply, which interact with each other to distribute the number of imports among exporting countries from nearby and far afield while satisfying the throughput capacity of the national transport infrastructure.

Modeling results of the balance of coal products by means of the proposed economic model demonstrate the increase in the level of energy security together with the forced reduction of the coal mining base as a result of the simultaneous decrease in total consumption of all brands of coal, and the availability of high volatile group coal for substitution anthracite before 2025.

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Modelling the Nexus between Financial Development, FDI, and CO_2 Emission: Does Institutional Quality Matter?

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Abstract: The present study draws motivation from the United Nations Sustainable Development Goals, with a special focus on SDGs 7 and 13, which highlight the need for access to clean and affordable energy in an environment devoid of emissions; it addresses climate change mitigation in the context of Sub-Saharan Africa. To this end, a carbon-income function setting for Sub-Saharan Africa (SSA) is constructed. The dynamic relationship between financial development and climate change is evaluated using three indicators and foreign direct investment and carbon dioxide emissions (CO_2), while accounting for regulatory institutional quality using a "generalized method of a moment" estimation technique that addresses both heterogeneous cross-sectional issues. Empirical results obtained showed a positive statistical relationship between economic growth and CO_2 emissions in SSA at the <0.01 significance level. This suggests that, in SSA, the economic growth path is pollutant emissions driven. This indicates that SSA is still at the scale phase of her growth trajectory. However, an important finding from the present study is that regulatory institutional indicators, such as political stability, government effectiveness, control of corruption, and voice and accountability, all exert a negative effect on CO_2 emissions. This implies that regulatory measures militate against emissions in SSA. Based on the empirical findings of this study, it can be concluded that clean FDI inflows assist in ameliorating emissions. Thus, the need for a paradigm shift to cleaner technologies, such as renewables, that are more eco-friendly, is encouraged in Sub-Saharan Africa, as the current study demonstrates the mitigating role of renewable energy consumption on CO_2 emissions. Further policy prescriptions are presented in the concluding section.

Keywords: clean technologies; financial development; pollutant emission; renewable energy consumption; Sub-Saharan Africa (SSA)

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1. Introduction

Climate change mitigation has become an issue of great concern for policymakers and researchers around the world in the last few decades. This is because the last century has seen an increase of nearly one degree in global temperatures, which has potentially dire consequences for human livelihoods and the environment, as manifested in sea level rise, floods, drop in crop yields, and the extinction of species, among others. It is not surprising, therefore, that the [1] has described greenhouse gas targets, climate change, and universal access to energy as crucial issues for the century. This supports the argument of [2] that, in striving for global sustainability of economic development, reduction in CO_2 emissions in energy production must be at the forefront of policy. Africa's share of global emissions is only 20% of the global average, but it is the worst affected by climate change impacts [3]. The negative effects of traditional sources of energy have led to calls for alternative sources of clean fossil and renewable energy to deal with the problem [4–6]. This is consistent with the recent World Nuclear Association report (2019), which claimed that the need for reliable, predictable, and clean electricity generated by nuclear has never been greater.

Generally, clean, and renewable energy systems produce little or no carbon dioxide emissions and, therefore, have the twin benefits of mitigating global warming and promoting energy security [7,8]. The Africa Progress Panel [9] suggested that renewable energy could enable the transformation of the African continent because of its flexibility and adaptability. The [10,11] noted that lack of access to energy critically limits the growth of African countries. Ref. [12] suggested that universal access to sustainable energy is critical in supporting overall economic development through the protection of ecosystems and enhancing income distribution. Ref. [13] reported that increasing the production of renewable energy (RE) can contribute to achieving many of the SDGs, which seek to enhance the overall welfare of citizens. SDG 7 has the objective of facilitating access to clean energy, encouraging energy efficiency and promoting the use of cleaner fossil-fuel technology by 2030. Any serious effort to achieve the sustainable development goals will require an invigorated agenda to promote clean energy development. This is pertinent when it is considered that 50% of the population in developing nations reside in homes without clean cooking facilities, which corresponds to 38% of the global population who must pursue their lives without clean cooking facilities, most of those affected living in developing Asia (41%) and SSA (55%) [14]. Moreover, the abundance of renewable sources of energy (solar and wind), especially in many parts of Africa, makes it imperative for countries to consider their development.

According to the [11,15,16], in 2014, renewables represented almost 50% of the world's new power generation capacity and over 60% in 2016. The [17] also indicated that, in the last 15 years, the world has invested nearly USD 3.0 trillion in clean energy, and noted that global investments in renewables exceeded USD 200 billion annually. With an investment worth USD 126.6 billion, China was leading the rest of the world with respect to investment in renewables, and that investment was further increased by 31 per cent in 2016. Ref. [17] reported that 2017 recorded the highest growth in clean energy production. This was possible due to a substantial increase in renewable power capacity, accompanied by advances in enabling technologies, as well as increases in investment in renewables. Of interest is the observation that Africa's relative share is only about 2–3%, which suggests considerable potential for renewable energy deployment. This is buttressed by the fact that, although the installed solar energy capacity increased by over 27,000 times over the period 2000–2015, from 0.88 GW to 222 GW, the African continent contribution increased from 500 MW to 2100 MW for the period 2013–2015, with the largest capacity being installed in South Africa [18]. Ref. [19] asserted that Africa has great potential for renewable energy development and suggested that 70% of African countries are suitable for investment in renewables. More importantly, in most of SSA, the potential for clean renewable energy can match its current domestic energy consumption. Accordingly, the onus is on us to discover and understand the key drivers of clean energy to provide the policy space for its accelerated development and use. This responsibility motivates this study.

Motivated by global energy demand and usage, this study examines the key determinants of pollutant emission and their environmental implications for energy development and consumption. In the recent past, scholarly attention in the energy-induced growth literature has focused increasingly on examination of the dynamic relationship between foreign direct investment (FDI), energy consumption, economic growth, the price of crude oil, and financial development. Of particular interest are capital flows of foreign direct investment and the nature of the financial sector in clean renewable development. Many studies have looked at the independent or individual effects of FDI and financial development (FD) on clean energy, with some looking at their combined effect, among other control variables, on clean energy development. The results of these studies have been inconsistent [7,20–22]. We argue that many of the studies suffer from omitted variable bias as many of the studies ignore the influence of political factors in clean energy development. The [23], for example, suggests that government policy is critical to reducing the negative effects of climate change because over 70% of global energy investments are government-driven. Additionally, the authors report that economic or technical problems are not fundamentally responsible for transition problems, but such challenges are politically and institutionally based reflected in the calamitous scale of cross-country differences in source and impact vulnerability. Simply put, clean energy consumption cannot be discussed without taking into consideration both the economic and political institutions through which clean energy policy decisions are made [7,24,25].

However, these issues have not been addressed in the empirical literature as determinants of conventional energy development. Accordingly, in achieving the research objective, we contribute to the literature in three main ways. First, this is one of the first studies, of which the authors are aware, that takes into consideration the economic and political institutions in the development and consumption of conventional energy, as well as the use of broader measures for financial development, represented by three different proxy measures of financial development indices, namely, domestic credit to the private sector (% of GDP), domestic credit provided by the financial sector (% of GDP), and domestic credit to the private sector by banks (% of GDP) to provide a holistic picture. The motivation of the SSA bloc arises from the fact that SSA ranks high on energy deficit, i.e., energy poverty, with approximately 600 million people lacking access to the electric power supply. The limited access to electricity has led to increased pollution and death [26]. However, the bloc has contributed the least to global CO_2 emissions, contrary to the dominant argument in the extant literature. The region's emissions contributions are the least, but it suffers the greatest effects of climate change due to the channels of emissions through trade, financial development, and industrialization/globalization. Figure A1 (see Appendix A section) highlights global CO_2 emissions for different regions, illustrating that advanced or developed economies emit more CO_2 relative to the less developed blocs, such as SSA. International bodies, such as African Progress has promoted (2016) the need for a paradigm shift to clean energy sources to mitigate the adverse effects of fossil-fuel energy [21]. This study seeks to bridge the gap in the related literature in the context of the SSA bloc which has received little attention. Second, unlike many other studies, this study investigates whether there are differential determinants for non-renewable and renewable consumption. Third, the current study contrasts with previous studies in terms of method by utilizing the recent and robust panel econometrics tool, two-step system GMM, to contribute to an evidence-based conventional energy policy.

The remainder of the paper is organized as follows: Section 2 focuses on a review of related literature. Section 3 describes the methodological procedure, while Section 4 presents interpretations of the empirical results. Finally, Section 5 provides the conclusions and suggestions for future policy direction.

2. Review of the Literature

In the FDI literature, the consensus is that the host nations' benefit is pronounced as a result of the enhancement of the nation's productivity, as well as the promotion of economic growth. In other words, while FDI is guaranteed to bring about direct capital financing (DCF), its contributions transcend DCF to include the creation of positive externalities using new technologies and technological know-how. The augmentation and efficiency properties of FDI are, thus, expected to exert a positive effect on both economic growth and environmental quality. With respect to energy, however, it could be argued that competition and direct knowledge transfer are the key channels through which FDI impacts energy consumption [27]. These views are consistent with ecological modernization theory which suggests that new technologies provide enormous opportunities and have the potential to solve the ecological problems caused by industrialization. From a practical point of view, ecological modernization theory is applied in the development and implementation of renewable energy solutions.

From the perspective of new trade theory, Ref. [28] argues that, upon entry into new markets, foreign firms, especially in developing countries, usually raise the threshold for efficiency in service delivery for all firms. Ref. [29], for example, noted that FDI discourages the use of unclean energy, and that, therefore, the influx of FDI acts as a catalyst for improving the energy efficiency of domestic firms. A similar argument was made by [30], who suggested that FDI promotes competition and spurs the development and use of clean energy by domestic firms as most foreign firms maintain high standards from their home country. The authors note that only weak evidence supports the view that some foreign investments occur in sectors characterized by a high level of pollution. Furthermore, because of the successful adoption of FDI, the energy intensity of the host nations is reduced, and new technological innovations are developed. As [31] have claimed, the introduction of technological innovations into the nexus of FDI, CO_2 emissions and financial development injects a unique dynamic into scholarly debate For instance, with technological innovation, switching from non-renewable to renewable energy sources becomes relatively easily attainable [32].

The empirical findings from the study of [33] in which data from 1980 to 2011 was used to investigate the role of the energy-saving potential of FDI in thirteen East African nations, suggest that the bidirectional reinforcement that existed between FDI and industrialization was the fundamental foundation required to enhance energy productivity. Additionally, the authors reported that income and globalization reinforced the FDI-energy productivity relationship. Ref. [34] studied the effect of domestic and foreign investment on clean energy development for EU, G20, and OECD countries, spanning the period 1993–2012. The authors demonstrated that both domestic and FDI had a positive effect on clean energy use. Furthermore, in a comparative study of the three blocs of countries, Ref. [32] found that factors such as FDI, political globalization, and stock market development, played a significant role in determining the long-run promotion of clean energy use. Specifically, political globalization and clean energy consumption exerted negative effects on CO_2 emissions; however, a positive linkage was established between clean energy consumption and economic growth for the OECD, G20 and EU economies.

In a related study of the same group of countries using the FMOLS, [35] reported that both stock market development and FDI had a significant impact on clean energy and a negative effect on carbon dioxide emissions. In an earlier study of 20 emerging economies, spanning the period 1991–2012, Ref. [22] demonstrated that, after controlling for cross-sectional dependence, FDI and stock markets positively impacted clean energy consumption. In a recent study of frontier economies in Africa, Ref. [36] found that trade integration, economic integration, and financial integration were key determinants of energy demand. More specifically, the results showed that a positive and direct relationship between FDI and trade led to an increase in clean energy consumption, while energy consumption, in turn, determined the reactions in terms of stock market indicators and industrialization. The authors, therefore, recommended that environmental planning in the countries studied should boost economic growth and energy demand using trade and financial development as tools. Ref. [37] employed a spatial econometric approach to test the merging of energy intensity and reported that FDI could stimulate the convergence of energy intensity. The authors noted that this could be attributed to the spillover effect of FDI. Ref. [38] examined the case for the BRICS region from the period 1985–2017, using the Fourier ARDL technique, to show that, while FDI had a positive effect on clean energy in Russia, it had no effect in South Africa and China; trade, however, had a negative effect in Russia, China, and South Africa.

On the other hand, Ref. [39] examined the case for G20 economies over the period 1971–2009 and demonstrated that FDI did not have a significant impact on clean energy use. Ref. [40] examined the case of South Asia based on FE, RE, and LSDV techniques for the period 1990–2013. The results suggested that FDI had no significant effect on energy intensity. Similarly, Ref. [41] used OLS and panel analysis to examine micro-level panel data for 60 developing countries for the period 1975–2004. The results showed no support for the view that FDI inflows reduced the energy intensity of developing countries. Of interest is the finding that foreign development aid appeared to be related to energy efficiency gains. Ref. [42] contributed to the literature by comparing domestic and foreign investment and demonstrated that the Chinese favor indigenous innovations as a prerequisite for energy intensity more than foreign innovations. Using 13 years of data starting from 2000, Ref. [42] found, for 30 provinces in China, that the impact of foreign innovation was dependent on the technological absorptive capacity of the host country. Ref. [43] examined the causal factors affecting European Union energy intensity over the period 1995–2015 and found that FDI did not influence energy intensity, while the price of coal had a negative effect on energy intensity. Thus, the energy-saving role of FDI was not supported.

Ref. [27] investigated the energy-saving role of FDI for 100 countries over the period 1980–2015 and found that the results were determined by the level of development. The authors reported a differential effect for low, middle, and high-income countries. More importantly, the authors showed that there was an inverted U –shaped relationship between FDI and energy consumption. A similar result was reported for imports when income level was controlled for. Ref. [44] studied the case of Bangladesh using time-series data spanning 1980–2015 and found no causal relationship between FDI and renewable energy in the short run.

Similar results were also reported for the financial development and clean energy consumption relationship. Ref. [45] argued that financial development offers more opportunities to develop the renewable energy sector by providing more funds to innovative firms. Thus, financial development leads to improvements in financial activities, such as the stock market and banking sector activities, and possibly bond market activities [41,46]. In addition, countries can increase renewable energy supply and consumption through efficient policy direction and sound financial systems. In the case of FATF countries, policy direction encouraged the use of key financial instruments, such as dynamic fundraising schemes, vibrant venture capital industry, green bonds, and loan schemes for energy-efficient technology, in their campaign for increased clean energy consumption.

Using panel data techniques to examine the determinants of clean energy, [47] found that economic growth enhanced clean energy, but financial development reduced it. Using OECD data from 1990 to 2014, Ref. [48] established a crucial link between renewable energy and financial development. The study further confirmed variance in the impact of financial development on the innovation growth rate and carbon intensity. It was noted that non-biomass and biomass renewable energy technologies affected the interactions between energy and financial development. The authors concluded that, for technological development to thrive, the financial markets must function well. In a related study of OECD countries during the period 1980–2016, based on the Driscoll–Kray standard errors panel regression technique, Ref. [49] found an inverted U-shape relationship between financial development and energy consumption, as well as between economic growth and energy consumption. Ref. [50] reported similar findings in a study of 28 EU countries in the European Union (EU) over the period 1990–2015. However, they observed that capital market development did not influence renewable energy in new EU Member states.

In a study of 28 Chinese provinces over the period 1999–2014, based on the GMM estimation technique, Ref. [12] showed that a poorly functioning financial system has a negative effect on energy intensity. The authors argued that inadequate access to finance reduces the incentive for investment in the energy sector. Ref. [51] investigated the financial development—energy consumption nexus in China for the period 1980–2016 and demonstrated that financial development increased energy demand, while globalization had a negative and significant impact on energy demand. In contrast, Ref. [52], using 141 listed Chinese firms, investigated the relationship between clean energy and financial development. Their findings suggest that while green financial development should be coveted, its long-term and short-term impacts differed sharply in the case of the investigated Chinese firms. As reported, generally, bank loan issuance decreased with increasing development of green financing and tended to slow the pace of development in renewable energy investment efficiency. However, for short- and intermediate-term impacts, investment efficiency resulting from the issuing of bank loans was minimal in the short-term, with no traceable effects observed in the long run.

Ref. [53] examined 150 listed Chinese firms, finding a curvilinear relationship between green economy development and renewable energy investment. Their results indicated a dual-threshold effect of green credit on renewable energy and green economy development. However, Ref. [54], in a study of 32 high-income countries, found negligible effects of financial development on energy consumption, though an increase in the stock market index was associated with a slight decline in energy consumption. Using panel data techniques to examine the determinants of clean energy, [20]) found that economic growth enhanced clean energy use but financial development reduced it. On the other hand, FDI was not found to have a significant impact on clean energy for countries in the BRICS bloc. Ref. [55] using data from 22 emerging economies and application of the GMM technique, evaluated how energy consumption in the countries considered was impacted by investments in financial development from 1990 to 2005. Their results confirmed the existence of a relationship between energy consumption and financial development, especially when financial development was measured using stock mark criteria.

Ref. [56] examined the energy savings role of banking sector performance for 43 SSA countries from 1998 to 2012 and reported that improved banking performance fostered energy efficiency, both in the short and long run. Interestingly, this study found that democracy had the opposite effect. The authors argued that achieving energy efficiency would require special initiatives to achieve necessary developments in the banking sector and to safeguard the sector from policy directions of democratic governments in the sub-region. Ref. [7] investigated the determinants of renewable energy in China and found that the financial sector was critically important for China's renewable energy development. More importantly, the results revealed that the capital market had the most significant effect, followed by foreign investment. Additionally, the authors reported that effective policies were needed to upgrade the energy structure to cope with climate change. This supports [24] assertion that the smooth development of renewable energy is inseparable from a supportive legal framework. Ref. [57] also showed that the transition to green innovation and energy efficiency was driven by a country's institutional quality. In an examination of the energy efficiency performance of a cross-section of 71 developing and developed countries, the authors reported that strong government support and reliable government institutions were critical in promoting energy innovations.

While acknowledging the relationships and interdependencies among FDI, and clean energy use, it is important to point out that the degree of dependency or influence may be altered by the policy direction or strategies implemented in the study context. For instance, Ref. [58] posited that policies such as low-carbon city construction, when used with a preferential policy such as financial subsidy, had the potential to not only increase and improve the productivity of energy-intensive industries, but also to mitigate against the associated risk of operating such energy-intensive industries by encouraging a complete shift to low-carbon development. In other words, while FDI has been empirically demonstrated to improve host clean energy use, the application of such policies, as discussed above, can foster greater impact of FDI on CO_2 emissions, or even renewable energy use.

Furthermore, in economies that encourage the implementation of green finance policy, that is, where there is intentional commitment by government and the global financial system to prioritize channeling investment into green projects [59], it is expected that climate change mitigation will be attained faster in comparison to nations without such policies. In the context of SSA, where such policy is either non-existent or in a fledging state, it is important to note that reliance on FDI inflow in ameliorating emissions is critical to the mitigation goals of the bloc. Given that policy directions or developmental strategies may be influential in determining the outcome of investments in clean energy and the associated pollutant-related emissions, SSA's adoption of institutional regulatory policies, alongside FDI inflow, is essential to the attainment of climate change mitigation goals.

3. Data, Model and Methods

The present study contributes to the politics of the CO_2 emissions debate focusing on SSA countries. According to [60], panel data models can be either static or dynamic. The former accommodates individual fixed effects, studying behavior in a repetitive framework. However, GMM estimation techniques incorporate various instrumental variables to circumvent endogeneity issues. This implies that the GMM approach provides consistent, reliable, and robust coefficient estimates even in the face of heterogeneity (see [61]). For robustness analysis, post-estimation tests are outlined in a later section to illustrate the superiority of the GMM estimation in comparison to conventional panel ordinary least squares, random effect and fixed effect models. The GMM model is robust to other static models and corrects for fixed or country-specific correlations, such as cross-sectional issues. Thus, to achieve the study objective, the following functional form was structured [8,62] as follows:

$$\begin{aligned} LCO2_{it} = {} & \beta_0 + \beta_1 LRGDP_{it} + \beta_2 LFD_{it} + \beta_3 LREN_{it} + \beta_4 LFDI_{it} + \beta_5 ROL_{it} + \beta_6 GOV_{it} + \beta_7 COC_{it} + \beta_8 RQI_{it} \\ & + \beta_9 VOA_{it} + \beta_{10} POL_{it} + \varepsilon_{it} \end{aligned} \tag{1}$$

where Ln denotes the natural logarithm transformation of all series to make elasticity interpretations and inferences; CO_2 = carbon emission; FDI = foreign direct investment net inflow (Bop); REN = renewable energy consumption; RGDP = economic growth; FD = financial development, proxied by three indicators, namely, (i) domestic credit provided to the private sector by banks (% of GDP) (DCPB), (ii) domestic credit provided by the financial sector (% of GDP), and (iii) domestic credit to the private sector as % of GDP (DCFS), to check for the robustness of the study objectives; the other variables ROL, GOV, COC, RQI, VOA and POL represent rule of law, government effectiveness, control of corruption, regulatory quality, voice and accountability, and political stability, respectively.

The data employed to achieve the study objective cover the period 2002 to 2014 for 31 countries in sub-Saharan Africa, including Angola, Burkina Faso, Cameroon, Cape Verde, Central African Republic, Democratic Republic of the Congo, Equatorial Guinea, Gabon, Ghana, Guinea, Ivory Coast, Kenya, Lesotho, Madagascar, Malawi, Mali, Mauritius, Mozambique, Namibia, Nigeria, Republic of the Congo, Rwanda, Sao Tome and Principe, Senegal, Sierra Leone, South Africa, Sudan, Tanzania, Togo, Uganda and Zambia. The exclusion of other countries was due to data availability; other SSA countries without data for all study variables under consideration limited extension of the study data significantly. The variables and sources for the current study are presented in Table 1. The institutional variables range between −2.5 and 2.5 following the world bank's standard measurement of these factors.

Table 1. Variable Description.

Variable	Abbreviation	Source
CO_2 emissions (metric tons per capita)	CO_2	WDI
GDP per capita (constant 2010 US$)	RGDPPC	WDI
Domestic credit to the private sector (% of GDP)	FD1	WDI
Domestic credit provided by the financial sector (% of GDP)	FD2	WDI
Domestic credit to the private sector by banks (% of GDP)	FD3	WDI
Renewable energy consumption (% of total final energy consumption)	REN	WDI
Foreign direct investment, net inflows (BoP, current US$)	FDI	WDI
Rule of law index (−2.5 weak; 2.5 strong)	ROL	WDI
Government effectiveness index (−2.5 weak; 2.5 strong)	GOV	WDI
Control of corruption (−2.5 weak; 2.5 strong)	COC	WDI

Table 1. *Cont.*

Variable	Abbreviation	Source
Regulatory quality index (−2.5 weak; 2.5 strong)	RQI	WDI
Voice and accountability index (−2.5 weak; 2.5 strong)	VOA	WDI
Political stability index (−2.5 weak; 2.5 strong)	POL	WDI

4. Results and Discussion

4.1. Pre-Estimation Diagnostics

First, basic summary statistics for the underlined variables were generated. Table 1 presents measures central tendency, such as averages, maximum-minimum and standard deviation. FDI showed the highest mean over the sampled period as well as the highest maximum and minimum, with economic growth measured by GDP. Renewable energy consumption showed the lowest average over the period investigated. All indicators of financial development were around the same value, with significant deviation from their means, as represented by the standard deviation measure. Table 2 presents pairwise correlation analysis of the study variables. A positive and statistically significant relationship between economic growth and pollutant emission (CO_2) in the case of SSA was observed. This outcome implies that the growth of SSA is pollutant driven. It suggests that SSA is still on her growth trajectory—a phase where the focus is on economic growth rather than the quality of the environment. A positive statistical relationship was observed between all measures of financial development and economic growth. FDI-led growth was supported by the observed positive relationship between FDI and economic growth. All the positive relationships observed were represented using binned scatterplots, as presented in Figure 1. The binned scatterplots correspond to the outcomes of the correlation analysis outlined in Table 2. The binned scatterplots highlight the nature of the relationship between CO_2 emissions and the macro-economic variables under consideration, i.e., the positive relationships observed in this study. However, the correlation analysis results which are presented in Table 3 to demonstrate the strength of relationships amongst variables, are not sufficient on their own to determine causality; hence, further econometric tests were conducted.

Table 2. Summary Statistics.

Variable	Obs.	Mean	Std. Dev.	Min	Max
		Variables at level			
CO_2	403	0.999	1.924	0.019	9.979
RGDPPC	403	2388.495	3455.403	276.056	20,512.940
FD1	403	21.394	27.560	0.491	160.125
FD2	403	22.900	24.140	−23.199	120.349
FD3	403	18.849	18.945	0.449	106.260
REN	403	0.572	0.713	0.000	2.540
FDI (million)	403	841	1620	−7120	9890
ROL	403	−0.635	0.629	−1.79	1.08
GOV	403	−0.699	0.587	−1.85	1.04
COC	403	−0.612	0.598	−1.77	0.94
RQI	403	−0.574	0.538	−1.68	1.13
VOA	403	−0.483	0.723	−1.98	0.97
POL	403	−0.466	0.905	−2.70	1.20

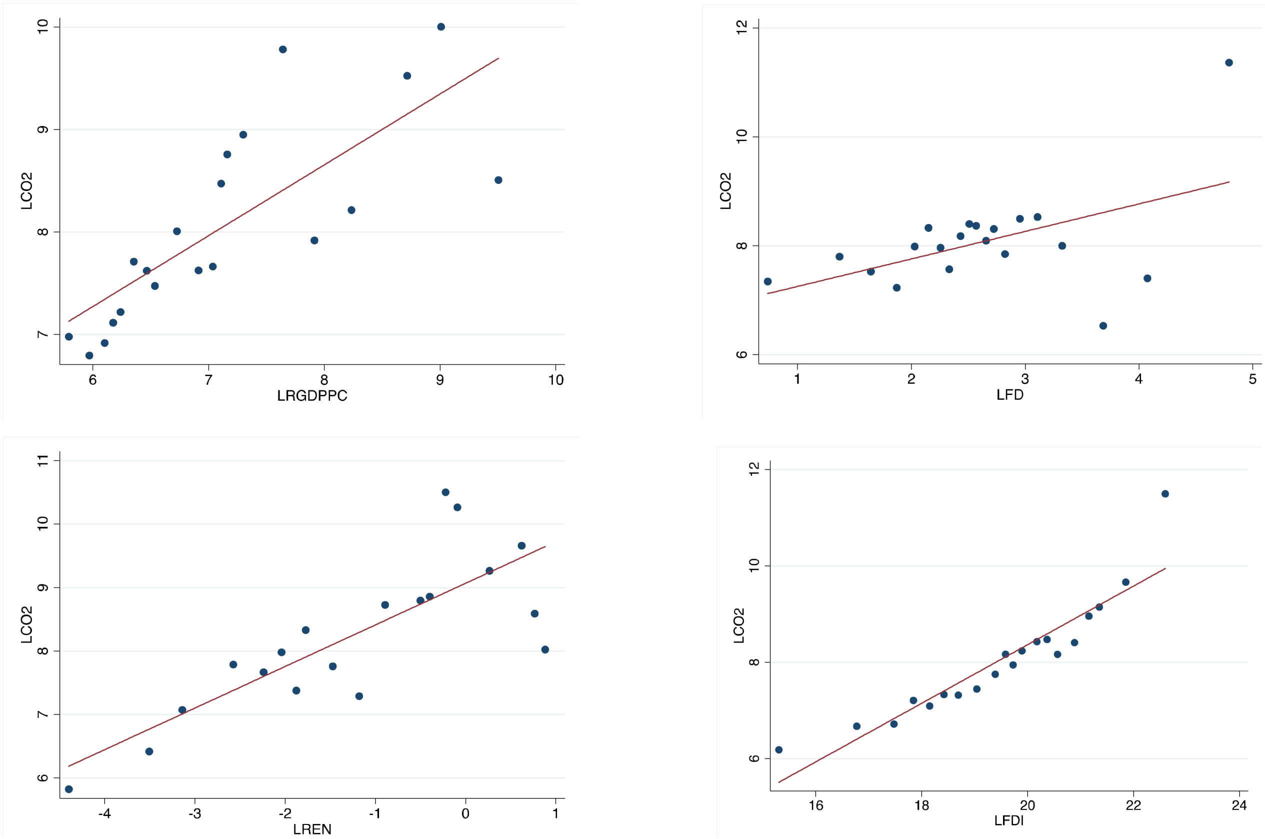

Figure 1. Binned scatterplots of the variables.

Table 3. Pairwise Correlation.

	LCO_2	**LRGDPPC**	**LFD1**	**LFD2**	**LFD3**	**LREN**	**LFDI**
LCO_2	1						
	–						
LRGDPPC	0.4405 *	1					
	0.0000	–					
LFD1	0.2844 *	0.3831 *	1				
	0.0000	0.0000	–				
LFD2	0.1486 *	0.3134 *	0.7421 *	1			
	0.0038	0.0000	0.0000	–			
LFD3	0.2252 *	0.3684 *	0.9894 *	0.7402 *	1		
	0.0000	0.0000	0.0000	0.0000	–		
LREN	0.6134 *	0.0153	−0.0056	−0.0367	−0.0362	1	
	0.0000	0.7673	0.9143	0.4902	0.4835	–	
LFDI	0.6630 *	0.3156 *	0.0841	0.0019	0.0554	0.6048 *	1
	0.0000	0.0000	0.0981	0.9714	0.2763	0.0000	–

* represents 5% level of significance.

4.2. Dynamic Panel-Data Estimation, Two-Step System GMM

The study regression model is presented in Table 4 with the aid of a two-step GMM. To establish robustness of the coefficients and estimates, a sensitivity test was conducted by exploring the theme with different measures of financial development, as presented in

Tables 5 and 6, respectively. The partial impacts of institutional indicators, such as the political stability index, the rule of law, government effectiveness index, control of corruption, regulatory quality, and voice and accountability with respect to carbon emissions for the case of SSA were also evaluated. Table 4 shows a positive, statistically significant (<0.01) relationship between economic growth (GDPPC) and carbon dioxide emissions (CO_2).

Table 4. Results of dynamic panel-data estimation, two-step system GMM-financial development, proxied by (i) domestic credit to the private sector (% of GDP) (DCPS).

Dependent Variable: LCO_2								
$L.LCO_2$	0.299 **	0.283 **	0.216 **	0.292 **	0.298 **	0.278 **	−0.0284	−0.125
	(0.127)	(0.124)	(0.101)	(0.123)	(0.129)	(0.127)	(0.127)	(0.155)
LRGDPPC	1.045 ***	1.168 ***	1.195 ***	1.142 ***	1.008 ***	1.199 ***	1.563 ***	1.292
	(0.329)	(0.354)	(0.280)	(0.369)	(0.353)	(0.343)	(0.406)	(0.818)
LFD1	0.155 ***	0.154 ***	0.170 **	0.170 ***	0.148 ***	0.150 ***	0.230 *	0.213
	(0.0545)	(0.0562)	(0.0863)	(0.0542)	(0.0531)	(0.0568)	(0.125)	(0.139)
LREN	−0.0358	−0.0282	0.0112	−0.0263	−0.0344	−0.0376	−0.0346	−0.0225
	(0.0397)	(0.0493)	(0.0600)	(0.0486)	(0.0386)	(0.0411)	(0.0390)	(0.0667)
LFDI	−0.00983	−0.0111	−0.00499	−0.00827	−0.00969	−0.0116	−0.00521	−0.000831
	(0.0122)	(0.0125)	(0.0154)	(0.0112)	(0.0127)	(0.0124)	(0.0149)	(0.0194)
ROL		−0.256						−0.124
		(0.348)						(1.511)
GOV			−1.525 ***					0.183
			(0.520)					(1.355)
COC				−0.337				−0.0298
				(0.327)				(1.810)
RQI					0.120			0.856
					(0.246)			(0.939)
VOA						−0.368 *		0.577
						(0.214)		(0.735)
POL							−1.105 **	−1.503 **
							(0.536)	(0.629)
Observations	298	298	298	298	298	298	298	298
No. of Instruments	15	15	15	15	15	15	15	15

Robust standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

This implies that economic expansion for SSA was pollutant-driven over the investigated period. This outcome is consistent with the study of [63] for selected EU-16 countries. This suggests that SSA is still at the growth trajectory stage, where the emphasis is on economic growth rather than the quality of the environment [64]. This means that government administrators in SSA should be encouraged to move from conventional energy from fossil fuel energy sources to cleaner energy sources, such as renewable photovoltaic (solar) energy, wind energy, or hydroenergy sources [65]. Financial development, proxied by (i) domestic credit to the private sector, exhibited a positive, statistically significant (<0.01) relationship with economic growth. The finding validates the interpretation that financial development is associated with growth for SSA. This result is consistent with that of the study by [66].

Table 5. Financial development by (ii) domestic credit provided by the financial sector (% of GDP) (DCFS).

Dependent Variable: LCO_2								
L.LCO$_2$	0.178	0.175	0.151	0.174	0.176	0.176	−0.0332	−0.134
	(0.113)	(0.116)	(0.0946)	(0.111)	(0.110)	(0.113)	(0.114)	(0.138)
LRGDPPC	0.994 ***	1.021 **	1.193 ***	1.097 ***	1.071 ***	0.949 ***	1.510 ***	1.255 *
	(0.333)	(0.396)	(0.286)	(0.364)	(0.352)	(0.342)	(0.402)	(0.725)
LFD2	0.223 ***	0.220 ***	0.173 **	0.219 ***	0.235 ***	0.233 ***	0.174	0.214
	(0.0671)	(0.0630)	(0.0758)	(0.0663)	(0.0668)	(0.0678)	(0.125)	(0.135)
LREN	0.0891 **	0.0925 *	0.133 *	0.107 **	0.0915 **	0.0901 **	−0.0131	−0.0369
	(0.0397)	(0.0544)	(0.0686)	(0.0454)	(0.0386)	(0.0399)	(0.0651)	(0.112)
LFDI	−0.00295	−0.00345	−0.00124	−0.00130	−0.00264	−0.00202	−0.00184	0.00405
	(0.0120)	(0.0113)	(0.0132)	(0.0106)	(0.0112)	(0.0117)	(0.0147)	(0.0162)
ROL		−0.0498						−0.273
		(0.455)						(1.419)
GOV			−1.179 ***					0.352
			(0.438)					(1.003)
COC				−0.296				−0.140
				(0.298)				(1.235)
RQI					−0.223			0.550
					(0.257)			(0.739)
VOA						0.0848		0.782
						(0.189)		(0.666)
POL							−0.861 ***	−1.215 ***
							(0.300)	(0.407)
Observations	278	278	278	278	278	278	278	278
No. of Instruments	15	15	15	15	15	15	15	15

Robust standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

The results indicate that financial development is a key driver for economic growth in SSA, while FDI and renewable energy exert a negative impact on pollutant emissions (CO_2) for the study area. This outcome was not statistically significant for the SSA area over the investigated period. This represents a clarion call for pragmatic policy action on the part of government officials to operate a cleaner environment or eco-system without compromising on economic growth. Our study demonstrates that institutional indicators, such as political stability, government effectiveness, control of corruption, voice and accountability, all exert a negative effect on pollutant emissions. That is, regulatory indicators help to militate against pollutant emissions in SSA. Government effectiveness, voice and accountability, and political stability showed relationships with pollutant emissions at the 1%, 5% and 10% significance levels, respectively.

Thus, the importance of the need to reinforce institutions to achieve a cleaner environment is highlighted by the present study. Tables 5 and 6 present a sensitivity analysis, with domestic credit provided by the financial sector (% of GDP) (DCFS), and domestic credit provided to the private sector by banks (% of GDP) (DCPB), respectively, to check robustness. Both tests corroborated the outcomes of Table 4 as financial development dampened the quality of the environment, while FDI improved environmental quality. The results support the pollution halo hypothesis, rather than the pollution haven hypothesis

(PHH). This outcome suggests that institutions in SSA are on an environmentally conscious trajectory. The obtained coefficients are reported in Table 7; the post-diagnostic results indicate that the AR (1), AR (2), and Sargen and Hansen tests were satisfactory at all statistical threshold levels.

Table 6. Financial development proxied by (iii) domestic credit provided to the private sector by banks (% of GDP) (DCPSB).

Dependent Variable: LCO_2								
L.LCO$_2$	0.293 **	0.277 **	0.212 **	0.284 **	0.292 **	0.273 **	−0.0295	−0.126
	(0.126)	(0.123)	(0.100)	(0.121)	(0.127)	(0.126)	(0.124)	(0.156)
LRGDPPC	1.030 ***	1.151 ***	1.181 ***	1.134 ***	1.001 ***	1.180 ***	1.545 ***	1.292
	(0.326)	(0.354)	(0.280)	(0.367)	(0.349)	(0.341)	(0.400)	(0.824)
LFD3	0.164 ***	0.163 ***	0.175 **	0.183 ***	0.158 ***	0.158 ***	0.233 *	0.218
	(0.0560)	(0.0580)	(0.0888)	(0.0561)	(0.0540)	(0.0583)	(0.126)	(0.143)
LREN	−0.0364	−0.0289	0.0103	−0.0260	−0.0353	−0.0381	−0.0352	−0.0221
	(0.0387)	(0.0483)	(0.0591)	(0.0483)	(0.0381)	(0.0403)	(0.0385)	(0.0664)
LFDI	−0.0102	−0.0115	−0.00541	−0.00854	−0.0101	−0.0119	−0.00572	−0.00101
	(0.0123)	(0.0125)	(0.0153)	(0.0112)	(0.0126)	(0.0124)	(0.0147)	(0.0197)
ROL		−0.255						−0.148
		(0.352)						(1.513)
GOV			−1.510 ***					0.239
			(0.515)					(1.360)
COC				−0.372				−0.0913
				(0.335)				(1.844)
RQI					0.0934			0.849
					(0.243)			(0.943)
VOA						−0.357 *		0.622
						(0.213)		(0.746)
POL							−1.094**	−1.509 **
							(0.526)	(0.632)
Observations	298	298	298	298	298	298	298	298
No. of Instruments	15	15	15	15	15	15	15	15

Robust standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 7. Post-estimation Diagnostics.

A model with financial development proxied by (i) domestic credit to the private sector (% of GDP) (DCPS)		
Tests	**Statistic**	***p* Value**
Hansen Test	chi2(10) = 17.51	0.064
Sargan Test	chi2(10) = 101.12	0.000
AR (1) Test	z = −2.10	0.035
AR (2) Test	z = −0.27	0.784

Table 7. *Cont.*

The model with financial development by (ii) domestic credit provided by the financial sector (% of GDP) (DCFS)		
Tests	**Statistic**	***p* Value**
Hansen Test	chi2(10) = 19.24	0.037
Sargan Test	chi2(10) = 64.85	0.000
AR (1) Test	z = −1.86	0.063
AR (2) Test	z = −1.43	0.153
The model with financial development by (iii) domestic credit provided to the private sector by banks (% of GDP) (DCPSB)		
Tests	**Statistic**	***p* Value**
Hansen Test	chi2(10) = 17.22	0.000
Sargan Test	chi2(10) = 100.48	0.070
AR (1) Test	z = −2.03	0.042
AR (2) Test	z = −0.39	0.698

5. Conclusions and Policy Recommendations

Developed countries reduced their share of fossil energy consumption by 43% from slightly over 70% in 1970 to about 40% in 2014, whereas the developing world's fossil energy consumption share increased by 28% from 40% to 55.7% over the same period [67]. The authors believe that the findings could provide the necessary impetus and commitment required to promote cleaner energy and reduce dependence on fossil fuels, especially in an era of declining cost of renewable energy production [68]. To achieve this, the present study focused on the determinants of pollutant emissions in Sub-Saharan Africa (SSA), which has been little reported in the literature. There is no current consensus on the issue in the literature. Thus, the current study extends the frontier of knowledge by considering the carbon-income relationship, using regulatory institutional indicators, such as political stability, government effectiveness, control of corruption, voice and accountability, in a panel framework, using a generalized method of moments (GMM) methodology, for a selected panel of SSA countries based on data availability.

Empirical findings from the study support the hypothesis that financial development induces pollutant emissions in SSA. This suggests that the current financial system promotes carbon dioxide emissions. The need for a cleaner and more eco-system-friendly financial system is encouraged in an area plagued with huge financial liberalization after the global financial crises. Interestingly, regulatory institutional qualities showed a capacity for reducing pollutant emissions in the region over the sampled period. The current study failed to find support for the pollution haven hypothesis according to which FDI inflow increases pollutant emissions. Additionally, the economic growth path of SSA is still at a point where the emphasis is on increasing income level relative to the quality of the environment. This explains the positive statistical relationship between economic growth and CO_2 emission levels.

Our study illustrates that renewable energy can mitigate against environmental degradation. This suggests that the consumption of renewable energy is of positive value to the environment in the selected SSA countries. The present study also showed that FDI and regulatory indicators, such as government effectiveness, and the regulatory index, mitigate CO_2 emissions. This supports the suggestion of [69] of the need to strengthen institutions for the better benefit of humankind, encompassing the quality of the ecosystem, through the adoption of clean technologies. This emphasizes the need to transition the SSA energy mix to clean energy options to enable sustainable economic growth without compromising the quality of the environment.

Several policy recommendations are presented below:

(a) There is an urgent need on the part of the government to embark on more action to decouple economic expansion from pollutant emissions. This path can be attained by focusing more on renewables and cleaner energy technologies to drive economic growth.

(b) The role of regulatory institutional indicators is important for reducing pollutant emissions. There is a need for government administrators of the sampled countries to reinforce and strengthen their institutional arms to achieve goals 3, 7 and 13 of the SDG. This may be achieved through commitment to environmental treaties, such as the Kyoto protocol, and to national/regional environmental regulations.
(c) Policies such as green financing and low-carbon city construction have been demonstrated in contexts such as China to foster a nation's drive towards clean energy use and ultimately climate change mitigation. SSA nations should consider incorporating such strategies as part of their strategic development plans to facilitate the expected impact of FDI flows and other regulatory institutional indicators that are being implemented to achieve the SDG goals of access to clean and affordable energy in an environment devoid of emissions.

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

Appendix A

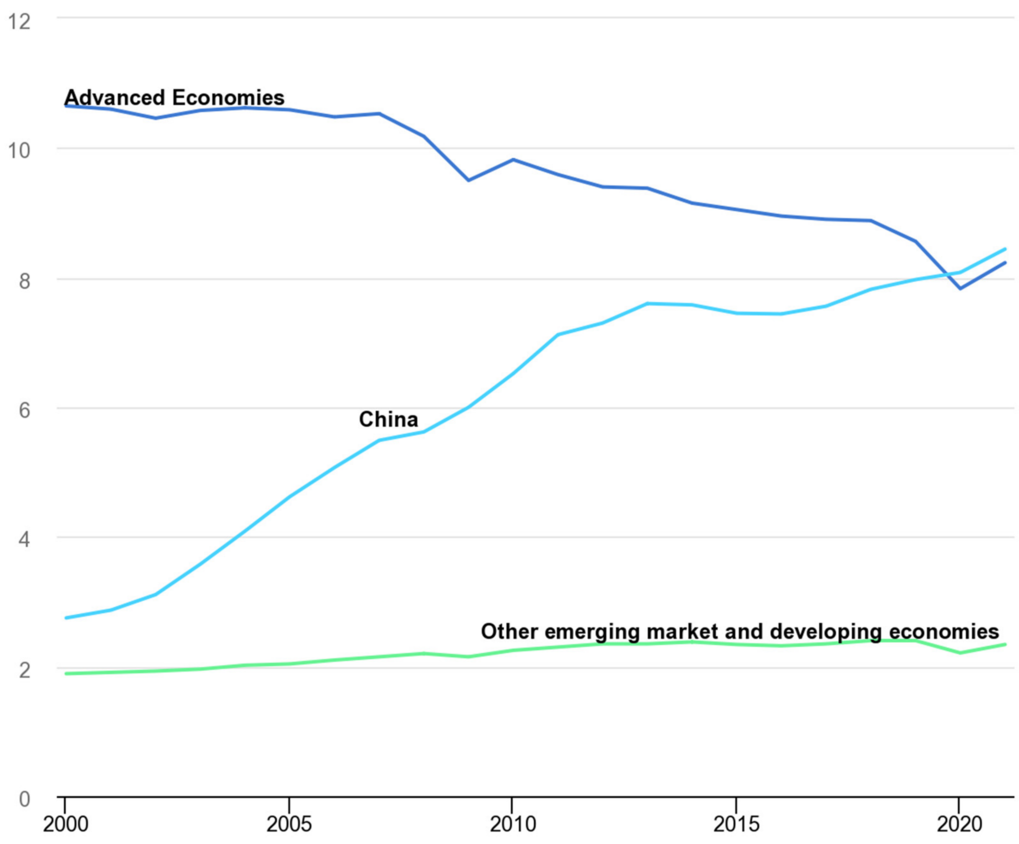

Figure A1. Graphical scheme for CO_2 emissions by region. Sources from IEA available at CO_2 emissions per capita by region, 2000-2021—Charts—Data & Statistics—IEA.

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Article

Fossil Fuel and Biofuel Boilers in Ukraine: Trends of Changes in Levelized Cost of Heat

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Abstract: An increase in the share of renewables in heat supply systems is a promising direction to reach sustainable development goals and decarbonization. Decision makers should consider various factors, including energy market prices, the availability of biofuels, boiler and auxiliary equipment costs, logistic costs, and the taxation system. In the European Union, the energy crisis causes a rapid increase in fossil fuel prices. Moreover, the use of fossil fuels results in greenhouse gas emissions, which threatens the achievement of sustainable development goals. We studied the influence of the delivery cost and the value of environmental tax rates on the levelized cost of heat. Low-capacity boilers (up to 1 MW) and different fossil and renewable fuels were analyzed. An analysis was carried out on the example of Ukraine. The European trends were factored in. The obtained results showed that biofuel boilers had lower levelized costs of heat than fossil fuel boilers. Delivery costs and environmental taxes have a significant impact on heat energy costs.

Keywords: biofuel; levelized cost of heat; heat supply; thermal energy; delivery costs; environmental tax rates; solid fuel boiler

1. Introduction

In 2019, the European Commission put forward the concept of the European Green Deal [1], the goal of which is to create a modern climate-neutral, resource-saving, and competitive economy. The key areas of this course are the transition to the use of clean energy, the fight against climate change, reducing environmental pollution, etc. The EU aims to become climate neutral by 2050, and to this end, most EU countries need to phase out coal, the largest global source of emissions, by 2030. Even the global energy crisis, which began in 2021, did not seem to be able to stand in the way of achieving these goals. However, the rapid increase in energy resource prices and their shortage in Europe during the last months of 2022 has created new challenges for achieving environmental goals in the EU and Ukraine.

In early 2020, Ukraine's 2050 Green Energy Transition Concept [2] project was presented, which, in general, sets goals close to the goals of the European Green Deal. According to this plan, energy efficiency and renewable energy sources are becoming the priority areas of Ukraine's green energy transition. Carbon dioxide, which is released when fossil fuels are burned, is the most common greenhouse gas in the world. A decrease in carbon dioxide emissions results in a gradual abandonment of fossil fuels in favor of renewable energy sources [2].

The climatic conditions of Ukraine are similar to those in some European countries. In these countries, the heating season lasts around six months. Their heat supply systems use primarily organic-fuel-based boilers.

Most EU countries, including Ukraine, use natural gas, coal, electricity, and biofuels for heat generation. The problems of their energy security and the diversification of energy imports, especially natural gas, are becoming more acute. The relevance of the replacement of fossil fuels with biomass has significantly increased.

In many countries, including Ukraine, there are areas, especially in the countryside, where the existing power grids do not allow consumers to use electric boilers with a capacity of more than 500 kW. This makes them use fuel-based boilers, which is why these boilers were the subject of our study.

Biomass-based fuels, such as wood chips, wood pellets, sunflower husk pellets, straw briquettes, straw peat, wood, and peat briquettes, are manufactured and used for heat generation in Ukraine. Ukrainian companies manufacture biomass boilers taking into account the characteristics of burning these types of fuels for both domestic and industrial consumers. In 2020, the total primary energy supply was 3617.39 TJ, including biofuels, and the generated waste was 177.52 TJ (according to Energy balance of Ukraine 2020). The domestic supply of solid biofuel was 137,539 TJ.

Among the reasons that stand in the way of investments for their implementation in Ukraine, we can single out the imperfection of environmental taxation, constant increase in environmental tax rates, frequent price changes for various types of fuels, significant exchange rate fluctuations, etc.

The importance of research is also confirmed by a significant number of relevant publications in the direction of this study. Articles [3–25] were devoted to various aspects of burning biofuels. Celebi et al. [3] examined combined heat supply systems that use lignocellulosic biomass. Cheney and Deo [4] studied wood-based biofuels for heat supply systems. They revealed that wood chips could substitute up to 80% of fossil fuel. Jasinskas et al. [5] analyzed the possibilities of using reeds for energy purposes and provided the results of experimental studies on their use for the production of heat energy; in particular, they determined the elemental composition of reed pellets, ash content, and calorific value, and the impact on the environment during their burning. Kim et al. [6] suggested the novel concept of a decentralized biorefinery to substitute hard coal. The objective of another study [7] was to determine the optimal combination of biochar and bio-oil production and its end use to achieve environmental and economic benefits using a life cycle assessment and costing approach. Musule et al. [8] analyzed conventional and wood-based residential heat supply systems. Rover et al. [9] developed a novel biomass-based fuel that can be used for co-firing in coal power plants. This novel biofuel reduces the emissions of sulfur and nitrogen compounds. Sawai et al. [10] examined alternative torrefied solid biofuel to be used by coal-fired boilers and power plants. Bermúdez et al. [11] used an Eulerian fixed-bed biomass combustion model coupled with the commercial CFD code ANSYS-Fluent to simulate a large-scale moving grate biomass furnace. Karim et al. [12] developed a 3D CFD model for biomass combustion in a moving grate furnace. Shi et al. [13] constructed a supercritical oxyfuel combustion system based on a CFB boiler burning coal, lignite, and sawdust to evaluate the performance of the system. Another study [14] presented the results of the experimental studies of the ignition processes of a large set of wood-coal composite fuel particles under the conditions of high-temperature radiative–convective heating. Verma et al. [15] conducted studies in which one multi-fuel domestic pellet boiler (40 kW) was tested under standard laboratory conditions when burning eight different biomass pellets, and two boilers (35 kW) were tested under real conditions when burning DIN plus certified wood pellets. Björnsson et al. [16] studied the integration of a pyrolysis plant into an existing CHP plant. Mustapha et al. [17] analyzed how the growth of biofuel production in forests affects fuel use in the district heating sector in northern Europe. Duong et al. [18] investigated Acacia mangium solid biofuel characterization and its ash properties. García et al. [19] investigated the joint pelletization of spent fuel and pine sawdust in a continuous pilot pelletizer, which resembles industrial pelletization. The purpose of another study [20] was to evaluate the suitability of residual biomass of conifers and broad-leaved trees to produce quality pellets using an agri-pellet machine activated by the power take-off of a tractor. Nuryawan et al. [21] investigated the main properties of mangrove branches as a raw material for the production of wood pellets and briquettes. Petlickaitė et al. [22] conducted a study of compressed solid biofuel produced from multi-culture biomass. The purpose of article [23] was to determine the variability of the quality parameters of wood chips produced from the most favorable raw material (energy round forest) and under the most controlled operating conditions (pellet mill) as a first step in determining the opportunities to optimize wood chip quality monitoring. Woo et al. [24] studied the characteristics of solid fuel pellets containing spent coffee grounds and wood powder. Souček et al. [25] dealt with the production of mixed fuels, in particular pellets consisting of a mixture of grass and sawdust.

Many studies [26–40] were devoted to the various environmental aspects of using different types of fuel. Kraszkiewicz et al. [26] investigated the effect of ignition techniques on pollutant emissions during the combustion of selected solid biofuels. Zaporozhets [27] carried out a correlation analysis between the energy balance components (the types of energy resources, the transformation sector, and energy-consuming industries) and the emissions of pollutants. Iatsyshyn et al. [28] studied the problem of the impact the storage places of ash and the slag dumps of fuel and energy complex enterprises can have on the environment. Experimental results were obtained from the combustion of raw and torrefied palm kernel shells in a domestic-scale boiler [29]. Zajac et al. [30] analyzed the emission characteristics of a domestic heating boiler (32 kW with automatic fuel loading) fueled with mallow pellets and wood pellets. Duong et al. [31] explored wood pellets for non-industrial applications. Havrysh et al. [32] studied the distribution of input energy and carbon dioxide emissions between the main product and the crop residues during the growing process. Bala-Litwiniak [33] presented an analysis of the combustion of pine husk and sunflower pellets without and with a 5% addition of spent glycerol, and the effect of the addition of spent glycerol on the concentrations of CO_2, CO, and NO_X in the exhaust gases was studied. The aim of another study [34] was to investigate the use of an electrostatic precipitator to control particulate emissions from small heating installations, in particular, solid fuel boilers with a heating output of less than 300 kW. Zhou et al. [35] conducted a study of a cleaner way of burning wood biomass waste on a grate with an emphasis on NO_X emissions. Nong et al. [36] used the GTAP-E-Power model, with additional improvements to include non-CO_2 emissions, to study the impact of increasing environmental taxes on the Vietnamese economy. Wang et al. [37] presented an original interdisciplinary performance-based contract evaluation model for controlling SO_2 emissions in Chinese coal-fired power plants. Wesseh et al. [38] developed a dynamic applied equilibrium model to study the dynamics of CO_2 emissions and assessed how the achievement of environmental policy goals may affect production and productivity in a transition country. Foumani et al. [39] considered how three general emission reduction policies, namely emission taxes, emission benchmarks, and emission trading schemes, can create a competitive environmental sphere. The chemical compositions of 40 samples of wood chips of various genera and origins were analyzed by Rodríguez et al. [40].

Many studies were devoted to the various economic aspects of the study of prospects for the use of biofuels, in particular using the LCOH indicator [41–63]. Coelho et al. [41] analyzed several basic power plants and hybrid biomass options: wood gasification, fuel pellets from garbage, biogas from anaerobic reactor wastewater, landfill biogas, and natural gas. The simulation model developed by Fujii et al. [42] was used to predict the performance of a heat charger, based on which a case study of heat transport between a local steel plant and a hotel was studied, and a comparison of the LCOE with a pellet boiler was made. Gerssen-Gondelach et al. [43] explored the current status and possibility of biomass value chains for energy generation and material manufacturing. They estimated their levelized production costs and emission reduction. Moreover, they found that woodchip combustion and pellets in large power plants and central heating systems are economically and environmentally preferred. Article [44] stated that the combination of geothermal district heating from medium and deep wells with heat from waste incineration creates a synergy that achieves above-average price competitiveness and economic impact. Ruffino et al. [45] estimated the LCOH for the most common heating technologies in Piedmont (NW Italy), i.e., fossil fuels (methane, fuel oil, and liquefied petroleum gas), wood biomass (wood logs and pellets, etc.), and heat pumps (air source and ground source) in both heating only systems as well as heating and cooling configurations. The authors of [46] presented a new approach to the analysis of multi-vector energy systems and proposed the levelized cost of exergy (LCOEx) as a new useful indicator in this field. Technical and economic analyses and a life cycle analysis of the ways of the biochemical transformation of seaweed as a sustainable source of bioenergy were carried out [47]. Kargbo et al. [48] conducted a similar study for fuel from lignocellulosic sources. Article [49] was devoted to the modeling of the cost-optimized technological integration of fuel production using the method of hydrothermal liquefaction. The authors in [50] showed that a price model based on the LCOH can clearly reflect the production cost of heat. Article [51] examined the economic feasibility of commercial heat supply technologies suitable for use in district heating networks. Article [52] analyzed and evaluated the possibilities of using oak bark, oak leaves, and their mixtures for obtaining biofuel. Lehtinen et al. [53] studied the structure of the supply chain of wood chips from harvest to thermal power plant using the example of Finland. Van Stralen et al. [54] analyzed the distribution of different biomass feedstocks in the heat, power, and transport sectors up to 2020 for different biomass use scenarios. Leisen et al. [55] studied new sustainable business models in the energy sector using the example of Germany. Andreoni [56] carried out a comparative analysis of factors influencing the receipt of environmental taxes in 25 EU members from 2004–2016. Zhang et al. [57] studied the impact of a carbon tax on tourism development in terms of energy consumption in China through modeling. Nong [58] proposed a new carbon price mechanism with full emission coverage to improve the ability and accuracy of climate change assessment and energy policy. Kondo et al. [59] proposed green procurement solutions for supplier selection and order quantity to minimize greenhouse gas emissions and costs, taking into account different carbon taxes in different countries. Streimikiene et al. [60] conducted a comparative assessment of the impact of environmental taxes on the indicators of sustainable energy development in three selected countries of the Baltic region (Lithuania, Latvia, and Estonia) during 2005–2015. Nissen et al. [61] proposed a modification of the traditional equalized energy cost formula that takes into account the increase in energy prices. Zang et al. [62] carried out a techno-economic comparative analysis of biomass-integrated gasification combined cycles with and without CO_2 capture. Zang et al. [63] suggested a hypothesis concerning the possibility of developing an integrated methodology for assessing the potential of biogas based on the integration of crop residues and livestock manure.

The studies in [64–66] are most relevant to this study. Bogoslavska et al. [64] determined the LCOH for boilers with a capacity from 100 to 1000 kW. They analyzed different fossil (natural gas and anthracite) and renewable fuels (wood pellets, sunflower husk pellets, straw briquettes, etc.). Specific pollutant emissions were calculated. The authors of [65] showed that the amount of environmental tax in Ukraine does not stimulate the implementation of measures to reduce pollutant emissions, but an increase in environmental tax rates can change it. The purpose of the article [66] was to analyze the impact of the delivery logistics of different types of fuel for low-capacity boilers (0.5 and 1 MW, burning biofuel) on the LCOH. This study showed that the cost of delivering pellets from the producer to the consumer can be up to 20% of their cost.

However, in those conditions when the energy market is changing sharply, the LCOH of biomass boilers and their comparison with conventional boilers are not studied enough. The LCOH structure is also of scientific and practical interest. The purposes of the present study are to analyze the trends of changes in the LCOH for fossil fuel and biofuel boilers in Ukraine, which increases the validity of management decisions in the field of the development of environmentally and economically efficient heat supply systems, and to determine the contribution of the environmental tax and delivery logistic components to the LCOH.

The novelty of this study is its analysis of the LCOH for biomass-based boilers in specific geographical and climate conditions. These conditions are characterized by limited fossil fuel reserves. The territory is predominantly steppe, with sparse forests. Highly developed agriculture is a source of biomass as a raw material for energy production. The study was conducted using the example of Ukraine as a country that satisfies the above conditions.

Two hypotheses were set up:

Hypothesis 1 (H1). *The economic competitiveness of biofuel boilers is stable to the fluctuation of market fuel prices.*

Hypothesis 2 (H2). *The use of agricultural residue-based pellets ensures the lowest LCOH compared with wood and fossil fuels.*

In addition, the authors show that the existing environmental taxation in Ukraine does not stimulate the implementation of measures to reduce the emissions of pollutants. Moreover, we should note that the introduction of a global approach to the taxation of carbon dioxide emissions from biofuel burning, and a significant increase in the share of biofuel boilers in heat supply systems in Ukraine will contribute to both decarbonization and an increase in the country's energy security level.

The rest of this document is as follows: Section 2 describes the formulas and the data for calculations. Section 3 presents the main results of the calculations. A discussion of the obtained results is covered in Section 4.

2. Materials and Methods

2.1. Levelized Cost of Heat

The method of the levelized cost of energy is widely used for economic comparison of energy projects using different fuel types [67]. The levelized cost of heat (LCOH) is used for determining the optimal heating projects [43,45,50,64–66]. This method allows you to compare different heat production technologies. To calculate the LCOH, the following formula is used:

$$LCOH = \frac{\sum_{t=1}^{N} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{N} \frac{H_t}{(1+r)^t}}, USD/GJ, \quad (1)$$

where I_t is the initial investment costs in tth year, USD; M_t is the operations and maintenance costs of the heat supply system in tth year, USD; F_t is the fuel costs in tth year, USD; H_t is the heat generation in tth year, GJ; r is the discount rate; N is the lifetime of the project, year.

The knowledge of the LCOH allows investors to select promising heat generation technologies for any country or region. Moreover, this simplifies the prediction of the cost structure for each technology [66].

As the environmental requirements for boilers and the rate of environmental tax are constantly increasing, the environmental factor must be taken into account when determining the LCOH [64]. We determined the environmental tax based on Chapter VIII of the Tax Code of Ukraine [68].

Biofuel costs comprise their production costs and delivery costs. If we add the environmental tax, Formula (1) is transformed into the following expression:

$$LCOH_{ET+DL} = \frac{\sum_{t=1}^{N} \frac{I_t+M_t+F_t+D_t+E_t}{(1+r)^t}}{\sum_{t=1}^{N} \frac{H_t}{(1+r)^t}}, USD/GJ, \quad (2)$$

where E_t is the environmental tax in tth year, USD; D_t is the fuel delivery costs in tth year, USD.

The impact of the environmental tax and logistic costs on the LCOH is of scientific and practical interest. The change in the LCOH due to the environmental tax ($\Delta LCOH_{ET}$) is determined as follows:

$$\Delta LCOH_{ET} = \left(\frac{\sum_{t=1}^{N} \frac{I_t+M_t+F_t+E_t}{(1+r)^t}}{\sum_{t=1}^{N} \frac{H_t}{(1+r)^t}} \right) - LCOH, USD/GJ. \quad (3)$$

The impact of delivery costs is as follows:

$$\Delta LCOH_{DL} = \left(\frac{\sum_{t=1}^{N} \frac{I_t+M_t+F_t+D_t}{(1+r)^t}}{\sum_{t=1}^{N} \frac{H_t}{(1+r)^t}} \right) - LCOH, USD/GJ. \quad (4)$$

2.2. Discount Rate

The discount rate is used in financial analyses to find the present value of future cash flows. There are three primary methods to calculate the discount rate: the capital asset pricing model (CAPM), the weighted average cost of capital (WACC), and the cumulative method [69]. Scientists substantiated that due to the poorly developed Ukrainian stock market, the cumulative method is more suitable to be applied [69,70].

It must be borne in mind that the transition from fossil fuels to renewables is not considered in commercially invested projects in the world because they curb global warming. In these projects, a social discount rate should be used [71]. In developed countries, a discount rate ranges from 2% to 6% [72]. The major developing countries apply a discount rate of up to 15% [73]. Zuniga et al. [74] revealed that the discount rate of social projects must be around 10%. Therefore, we used a 10% discount rate in this study.

2.3. Logistics

In addition to the choice of boilers and the type of fuel, the correct and efficient organization of delivery is important, which will ensure the timely receipt of orders and the stable operation of boiler plants. Additionally, the transportation process must take into account the characteristics of the fuel and ensure protection from negative external factors (protection of pellets from moisture, precipitation, and mechanical damage). A logistic system impacts the profitability of any heat supply system. The delivery of solid fuel can be carried out in different ways (in bulk, in big bags, in ordinary bags) and by different means of transport (water, rail, and road). The choice of the specific means of transport directly depends on the location of the consumer. Water transportation is the cheapest for long distances. Road transport is relatively expensive for long distances. However, it is convenient and competitive for short distances. Pellets are the most convenient biofuel for transportation and use. They have a constant and high bulk density, which greatly simplifies the process of transporting fuel even long distances, and loading and unloading are easy to automate, which significantly facilitates and speeds up both processes. Bags and bunkers are used to transport pellets. Their prices include production costs, loading, unloading, and transportation costs. The transportation of biofuels is discussed in more detail in the article [35].

We considered pellets packed in big bags (weight—one ton, volume—1.54 cubic meters). Delivery by road transport with a carrying capacity of 20–22 t and a distance of 300 km was considered. This distance is the average within one region of Ukraine.

2.4. Environmental Tax

Environmental taxes are fiscal instruments. They are used for stimulating sustainable development. Therefore, they have a significant impact on the development of heat supply systems and the use of alternative fuels. The environmental tax was calculated based on the annual fuel consumption and the kind of fuel. We used the following information: the thermal power, the thermal efficiency, the annual operating time, the load factor, the lower heating value of fuel, the emission factors, and the environmental tax rate [64–66].

In Ukraine, the heat-generating enterprises that use biofuel are taxpayers for CO_2 emissions, which does not correspond to modern world practice, since biofuel is considered a CO_2-neutral fuel. However, according to the Tax Code of Ukraine [68], the tax base for carbon dioxide emissions is 500 tons/year.

In 2010, Ukraine introduced an environmental tax for carbon dioxide emissions of 0.025 USD/tCO_2. Since 2022, this tax rate has increased to 1.075 USD/tCO_2. The tax rates for different pollutants increase every year.

According to the current Tax Code of Ukraine [68], the environmental tax is paid for the emissions of pollutants by stationary sources; therefore, the tax for the emissions by vehicles was not considered in this article.

The emission factors for the different fuels fired in boilers are presented in Appendix A. The tax rates for the stationary sources of pollution (heating boilers) are presented in Table 1 [68]. Tax rates in EU countries differ tenfold. Poland uses the lowest taxes in the EU, and Sweden has the highest ones (Table 1).

Table 1. Emission tax rates in Ukraine, Poland, and Sweden, USD/t [68,75,76].

Pollutant	Ukraine, 2020	Ukraine, 2022	Poland, 2022	Sweden, 2022
NO_x	87.19	92.27	118.39	697.17
SO_2	87.19	92.27	118.39	394.62
CO_2	0.36	1.08	0.09	153.02

2.5. The Fuel Price and Delivery Costs

Since 2016, in Ukraine, fuel prices have significantly increased (Table 2). The costs and lower heating value of fuels (no delivery costs) are given in Table 2 [77–81].

Table 2. The costs and lower heating values of fuels [64–66,77–81].

Fuel	Lower Heating Value, MJ/kg	Cost, USD/t (USD/1000 m^3)			
		October 2016	September 2020	January 2022	July 2022
Natural gas	33.08	266.11	273.83	1433.69	1008.03
Natural gas (distribution)	-	-	42.67	64.16	60.79
Power coal	22	73.50	99.57	250.90	341.88
Anthracite	27	92.84	124.47	358.42	444.44
Wood pellets	17	96.71	74.68	179.21	273.50
Straw pellets	15.1	38.68	48.01	118.28	136.75
Sunflower husk pellets	18	34.82	42.67	142.65	170.94

Since January 2020, the state regulator has changed the procedure for paying for natural gas distribution services, and a separate payment and tariff for gas distribution (delivery) has been developed [82]. Since August 2020, the retail price of natural gas, in particular for household consumers, is freely set between the supplier and the consumer; that is, it is contractual [83]. In September 2020, the gas delivery rates ranged from 11.95 to 116.5 USD/(1000 m^3) [84], and an average of 42.67 USD/(1000 m^3) was used in our calculations. In 2022, the gas delivery rates varied from 13.66 to 104.98 USD/(1000 m^3) [84], and the average value was 63.66 USD/(1000 m^3). In the heating period of 2021–2022, budget and communal institutions bought natural gas at the price of 1244.67 to 1600.28 USD/(1000 m^3) despite the conclusion of the Memorandum with Naftogaz [85] about the price of 586.77 USD/(1000 m^3) [86]; therefore, in our calculations for January 2022, a natural gas price of 1422.48 USD/(1000 m^3) was accepted. For industry, at the same time, the price was 1891.84 USD/(1000 m^3) [87]. The significant increase in natural gas prices caused an increase in pellet prices. Vehicle fuels and their delivery prices [88] increased less. For trucks with a load capacity of 20–22 tons, the delivery cost was 0.96 USD/km (January 2022) and 1.6–1.78 USD/km in July 2022 [88].

2.6. The Boiler Costs

We studied solid fuel boilers manufactured by Ukrainian companies. They have capacities of 500 and 1000 kW. We analyzed the use of fossil fuels (natural gas and coal) and renewable ones (sunflower husk, straw, and wood pellets). The boiler prices are presented in Table 3 [83,89–91]. As can be seen, their prices rose in price by 49–117% from 2016 to 2022 (Table 3).

Table 3. Main characteristics of boilers and costs in 2016, 2020, and 2022 [33–35,89–91].

The Boiler	Capacity, kW	Efficiency, %	Price, USD			
			October 2016	September 2020	January 2022	July 2022
Solid fuel boilers						
ARS 500 (2016–2020)/KZOT ARS 500 Comfort (2022)	520	85	7117.98	8097.44	10,558.39	10,071.08
ARS 500 BM (2016–2020)/KZOT BRS 500 Comfort BM (2022)	500	84 (coal) 89–92 (pellets)	7644.10	8080.725	10,536.92	10,050.6
Gefest Profi-P 500	500	92	7945.841	7379.09	8903.226	12,556.65
ARS 1000 (2016–2020)/KZOT ARS 1000 Comfort (2022)	1000	85	11,605.42	12,268.85	15,997.99	15,259.62
ARS 1000 BM (2016–2020)/KZOT BRS 1000 Comfort BM (2022)	980/1000	84 (coal) 89–92 (pellets)	11,203.09	11,843.88	15,443.84	14,731.04
Gefest Profi-P 1000 (2016–2020)/(2022)	980/1000	91	12,301.74	13,798.01	16,666.67	23,631.11
Natural gas boilers						
ARS 500 (2016–2020)/Protherm Bison 510 NO (2022)	520/510	90/92	7117.99	8097.44	10,502.62	10,017.88
ARS 1000 (2016–2020)/Protherm Bison 1030 NO (2022)	1000/1030	90/92	11,605.42	12,268.85	19,947.38	19,026.74

3. Results and Discussion

3.1. The Evaluation of LCOH in 2016–2022

The LCOH was calculated at the market prices of 2016, 2020, and 2022. The LCOH comprises the thermal energy costs, the environmental tax ($LCOH_{ET}$), and the delivery costs ($LCOH_{DL}$). The results are shown in Table 4.

Table 4. LCOH and its components in 2016, 2020, and 2022, USD/GJ.

Boiler	LCOH				$LCOH_{ET}$		$LCOH_{DL}$		$LCOH_{ET+DL}$	
	October 2016	September 2020	January 2022	July 2022	September 2020	January 2022	January 2022	July 2022	January 2022	July 2022
Wood pellets										
1. ARS 500 (2016–2020)/KZOT ARS 500 Comfort (2022)	7.27	5.94	13.30	19.79	5.97	13.33	14.30	21.40	14.37	21.44
2. ARS 500 BM (2016–2020)/KZOT BRS 500 Comfort BM (2022)	6.81	5.58	12.37	18.36	5.58	12.44	13.33	19.90	13.41	19.93
3. Gefest Profi-P 500	6.81	5.55	12.33	18.50	5.58	12.37	13.30	20.03	13.33	20.07
4. ARS 1000 (2016–2020)/KZOT ARS 1000 Comfort (2022)	7.16	5.76	13.08	19.59	5.80	13.19	14.12	21.20	14.19	21.30
5. ARS 1000 BM (2016–2020)/KZOT BRS 1000 Comfort BM (2022)	6.62	5.44	12.15	18.15	5.48	12.22	13.08	19.62	13.15	19.73
6. Gefest Profi-P 1000	6.73	5.48	12.29	18.53	5.48	12.37	13.23	20.03	13.33	20.10
Sunflower husk pellets										
7. ARS 500 (2016–2020)/KZOT ARS 500 Comfort (2022)	2.86	3.56	10.22	12.03	3.59	10.29	11.18	13.57	11.25	13.64
8. ARS 500 BM (2016–2020)/KZOT BRS 500 Comfort BM (2022)	3.02	3.77	10.82	12.75	3.81	10.90	11.83	14.36	11.94	14.43
9. Gefest Profi-P 500	2.75	3.34	9.46	11.32	3.38	9.53	10.39	12.79	10.47	12.85
10. ARS 1000 (2016–2020)/KZOT ARS 1000 Comfort (2022)	2.67	3.27	9.89	11.73	3.31	10.04	10.86	13.26	11.00	13.37
11. ARS 1000 BM (2016–2020)/KZOT BRS 1000 Comfort BM (2022)	2.59	3.24	9.43	11.28	3.27	9.53	10.32	12.72	10.43	12.82
12. Gefest Profi-P 1000	3.17	3.81	9.86	11.52	3.88	9.96	10.75	12.92	10.86	13.03
Straw pellets										
13. ARS 500 (2016–2020)/KZOT ARS 500 Comfort (2022)	3.60	4.52	10.14	11.52	4.55	10.22	11.29	13.37	11.36	13.44
14. ARS 500 BM (2016–2020)/KZOT BRS 500 Comfort BM (2022)	3.40	4.27	9.46	10.77	4.30	9.53	10.54	12.44	10.57	12.48
15. Gefest Profi-P 500	3.44	4.30	9.50	10.97	4.30	9.53	10.61	12.72	10.65	12.79
16. ARS 1000 (2016–2020)/KZOT ARS 1000 Comfort (2022)	3.48	4.37	9.93	11.35	4.37	10.04	11.08	13.16	11.18	13.30
17. ARS 1000 BM (2016–2020)/KZOT BRS 1000 Comfort BM (2022)	3.25	4.13	9.21	10.53	4.16	9.32	10.29	12.21	10.39	12.31
18. Gefest Profi-P 1000	3.29	4.16	9.35	10.84	4.16	9.43	10.43	12.55	10.54	12.65
Coal										
19. ARS 500 BM (2016–2020)/KZOT BRS 500 Comfort BM (2022)	6.46	6.19	14.52	19.38	6.47	14.80	15.34	20.72	15.63	20.99
20. ARS 1000 BM (2016–2020)/KZOT BRS 1000 Comfort BM (2022)	6.31	5.97	14.27	19.18	6.26	14.62	15.09	20.44	15.41	20.79
Natural gas										
21. ARS 500 (2016–2020)/Protherm Bison 510 NO (2022)	9.21	9.78	46.67	33.03	9.78	46.67	48.71	34.97	48.71	34.97
22. ARS 1000 (2016–2020)/Protherm Bison 1030 NO (2022)	9.09	9.64	46.52	32.89	9.64	46.56	48.57	34.84	48.60	34.87

In general, the more expensive the fuel, the more expensive the thermal energy. For six years, the heat energy generated by sunflower husk boilers was the cheapest, and straw pellets were slightly more expensive. The LCOH from wood pellet boilers and coal boilers was comparable. Since 2016, the levelized cost of heat has increased by at least four times. The heat generated by natural gas boilers has had the largest increase.

The trend of a significant increase in the price of all types of fuel over the last year is obvious, but there was an exception—from 2016 to 2020, the value of wood pellets decreased by 20%, and the growth rate of their value was the lowest—three times in 5 years. The price of sunflower husk pellets increased the most time, in 5 out of the past 6 years, but the cost of thermal energy obtained from their burning was the lowest. The difference between the minimum and maximum LCOH for the period was 1.5–2.8 times.

The fuel component for biofuel boilers ranged from 68% to 93% in 2016, and from 90% to 97% in July 2022. This increase in the share of fuel components in the LCOH was caused by a significant increase in the cost of all types of fuel. The LCOH was not significantly affected by doubling the boiler capacity. The main reason is that the share of investment costs in the LCOH was less than 5% (Figure 1).

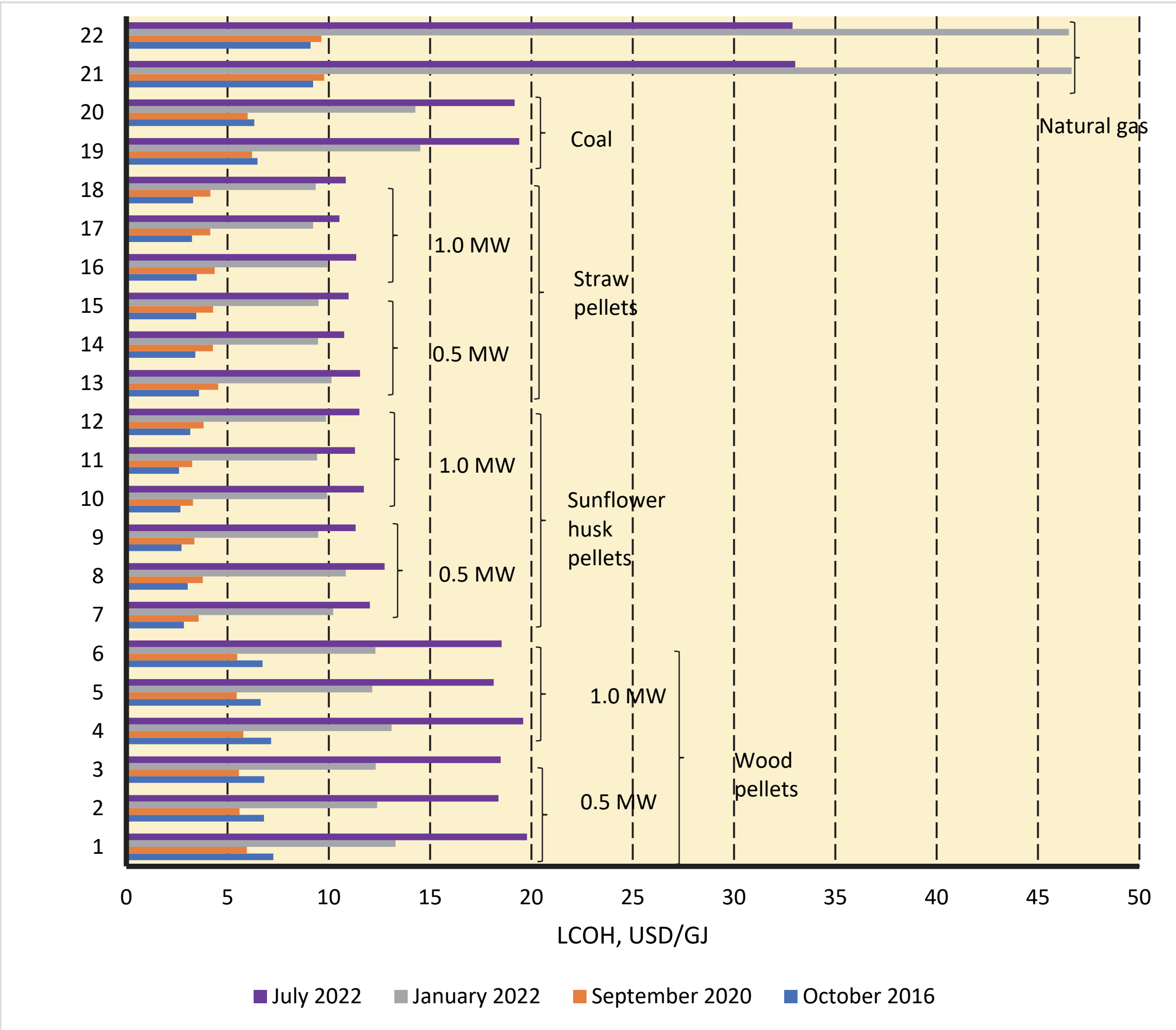


Figure 1. The evolution of LCOH (the number on the x-axis corresponds to the first column in Table 4).

We found that, in Ukraine, the LCOH of biomass-fired boilers ranged from EUR 35.2/MWh to EUR 56.3/MWh. These values were lower than the LCOH for natural gas-fired boilers (EUR 100.2/MWh). This ratio is consistent with European countries. For instance, Ruffino et al. [45] reported that, in Italy, the LCOH of biomass-fired boilers is lower than the LCOH of fossil fuels. Its value ranges from EUR 72.1/MWh to EUR 118.7/MWh. In France, the situation is the same. The LCOH is around EUR 87/MWh [92]. In Poland and Switzerland, the LCOH is somewhat higher [93,94]. The attractiveness of alternative fuels is determined by the ratio of their prices to traditional fuels [95].

3.2. Environmental Tax and Delivery Logistic Components

In 2022, coal boilers had the highest LCOH environmental tax component ($\Delta LCOH_{ET}$) of 0.30–0.34 USD/GJ. Gas boilers had the smallest one of 0.007–0.032 USD/GJ. For biofuel boilers, this component was 0.039–0.114 USD/GJ or 0.26–0.94% of the LCOH. The trend has not changed in the past six years. The environmental tax component had the minimum value for 500 kW boilers that burn wood pellets. In addition, 1 MW boilers firing sunflower husk pellets had the maximum environmental tax component.

According to our calculations, the LCOH logistic component (a transport distance of 300 km) increased from 4.4–11.6% in January 2022 to 5.9–16% in July 2022. The minimum value was for burning natural gas boilers, while the maximum was for burning straw pellet boilers. The smallest component for biofuel boilers was for burning wood pellet boilers.

In January 2022, the LCOH (taking into account environmental taxes and logistics) of solid fuel boilers was more than half as much as from gas boilers (Figure 2). The LCOH from coal boilers was on the same level as the LCOH from the boilers burning wood pellets. In July 2022, the LCOH difference significantly decreased (Figure 3).

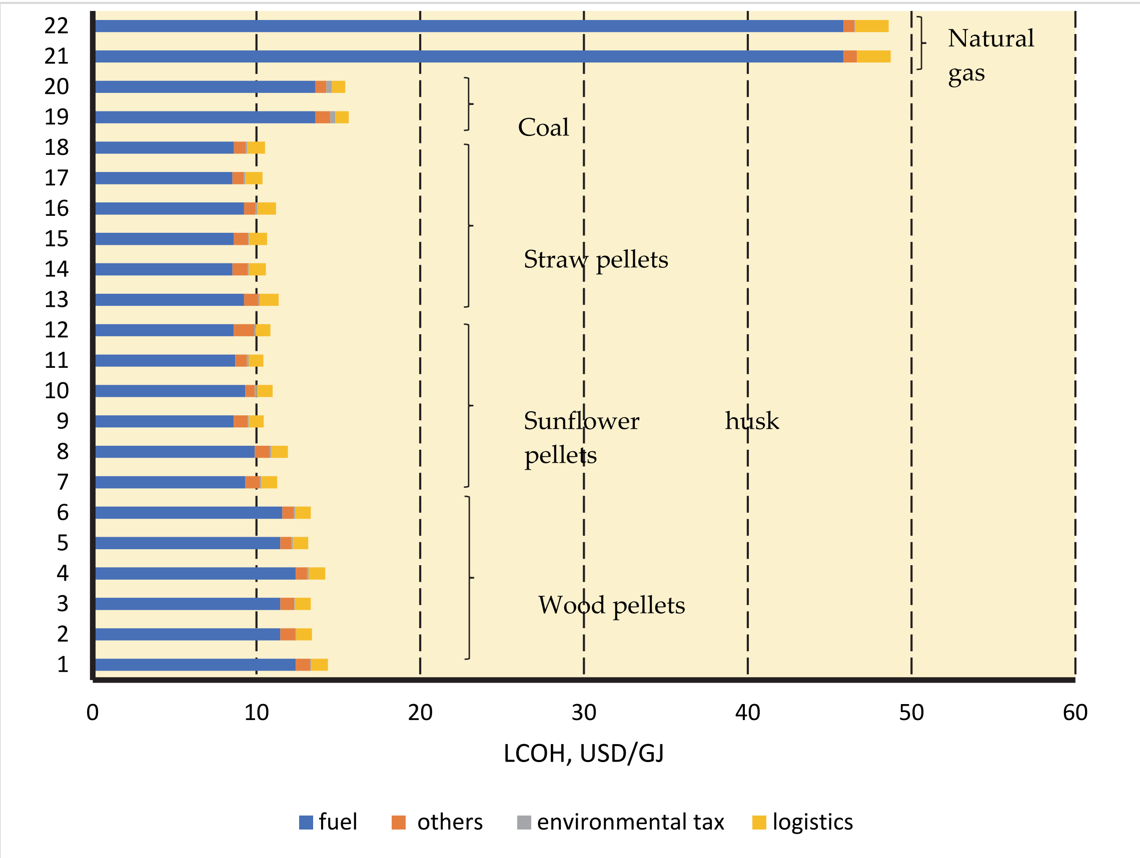


Figure 2. LCOH structure in January 2022 (the number on the *x*-axis corresponds to the first column in Table 4).

The LCOH components of the environmental tax and logistics for biofuel boilers increased during January–July 2022 from 0.96–1.17 USD/GJ to 1.56–1.88 USD/GJ, which in percentage terms was from 7.4–13.5% to 7.7–18%. The LCOH of other non-fuel components did not significantly change and in monetary terms were less than the environmental tax and logistic components (0.59–0.92 USD/GJ in January and 0.59–1.03 USD/GJ in July 2022).

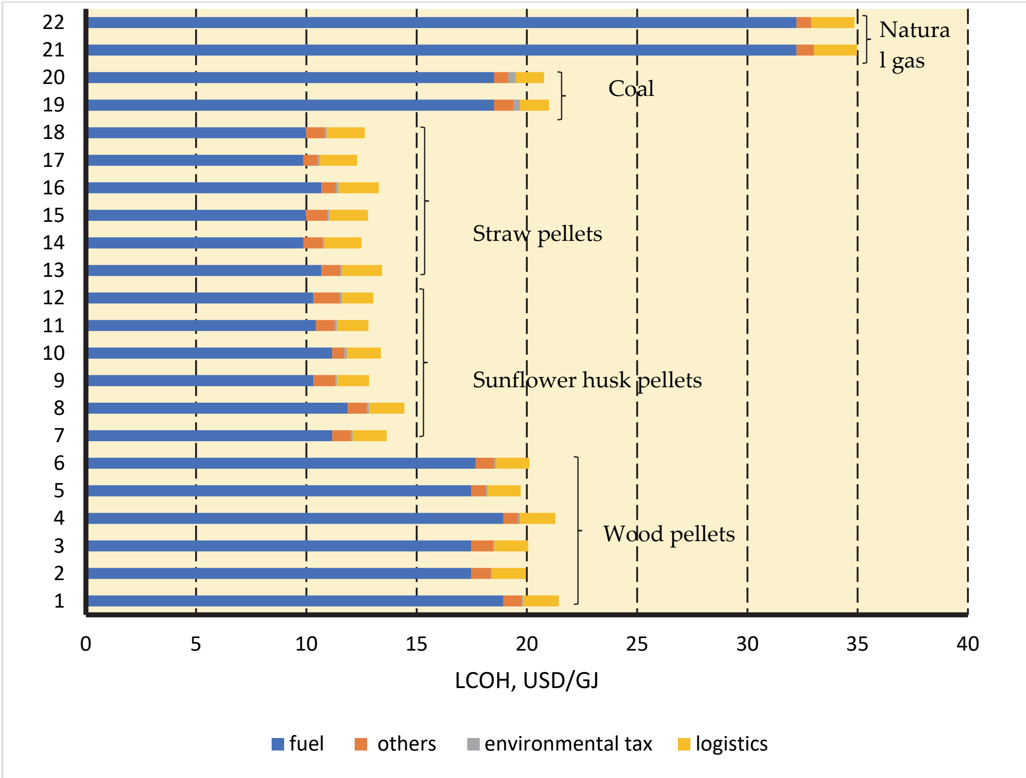


Figure 3. LCOH structure in July 2022 (the number on the *x*-axis corresponds to the first column in Table 4).

The LCOH environmental tax component in Ukraine was insignificant and, therefore, would not stimulate the implementation of measures to reduce the emissions of pollutants.

3.3. LCOH Structure

The LCOH structures for some boilers are shown in Figures 4–8. For biofuel boilers, the LCOH fuel component increased in value terms for the first six months of 2022 from 1.78 USD/GJ for straw pellet boilers (Figure 6) to 7.40 USD/GJ for wood pellet boilers (Figure 4). In percentage terms, this component increased only for wood pellet boilers, for others, including coal boilers, it decreased.

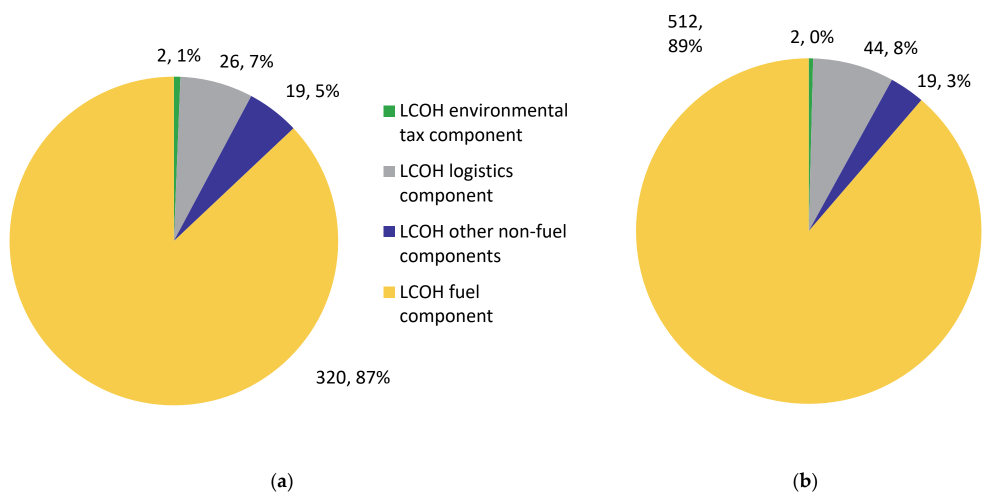
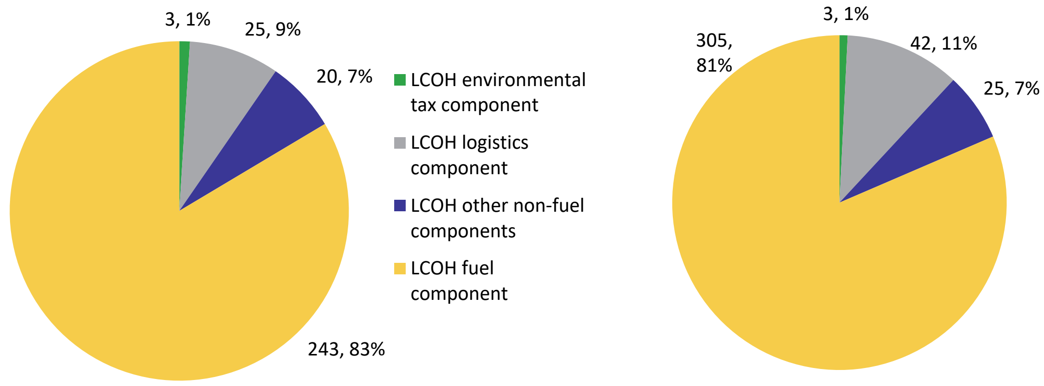
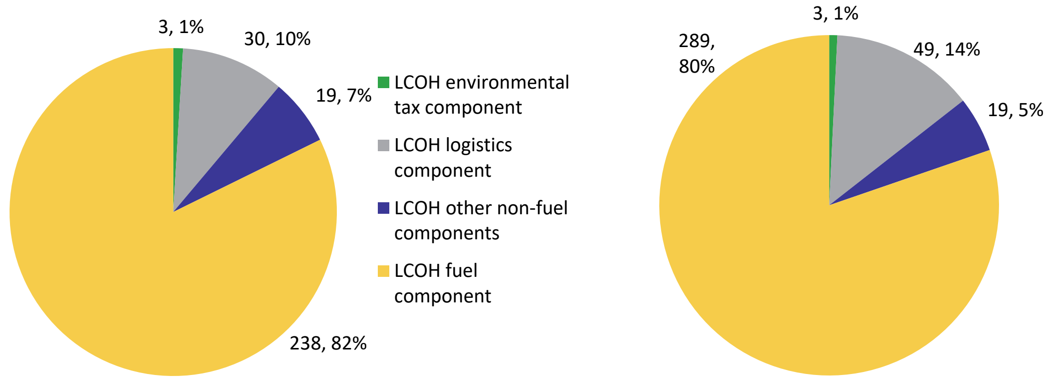


Figure 4. LCOH structure from KZOT BRS 1000 Comfort BM (1 MW) from wood pellets: (**a**) January 2022; (**b**) July 2022.



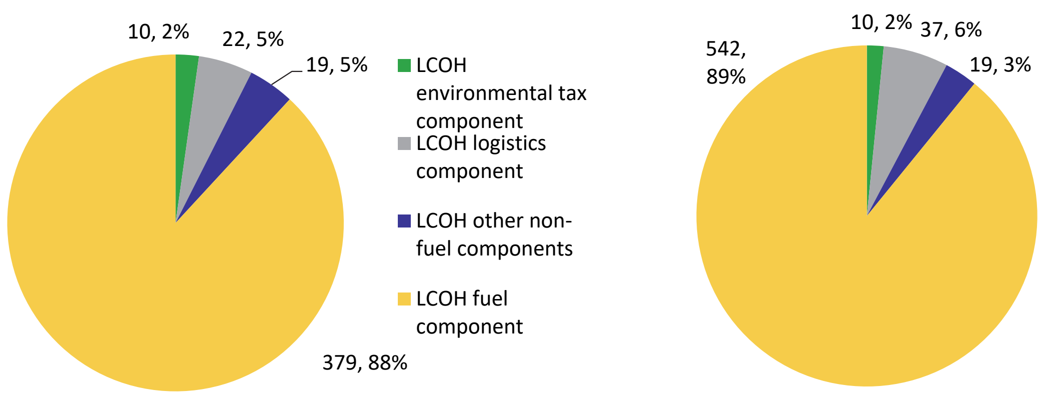
(a) (b)

Figure 5. LCOH structure from KZOT BRS 1000 Comfort BM (1 MW) from sunflower husk pellets: (**a**) January 2022; (**b**) July 2022.



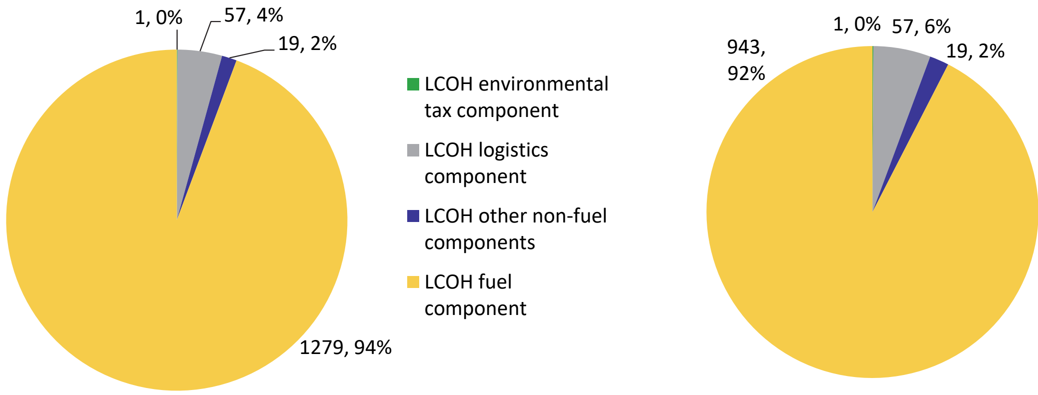
(a) (b)

Figure 6. LCOH structure from KZOT BRS 1000 Comfort BM (1 MW) from straw pellets: (**a**) January 2022; (**b**) July 2022.



(a) (b)

Figure 7. LCOH structure from KZOT BRS 1000 Comfort BM (1 MW) from coal: (**a**) January 2022; (**b**) July 2022.



(**a**) (**b**)

Figure 8. LCOH structure from KZOT BRS 1000 Comfort BM (1 MW) from natural gas: (**a**) January 2022; (**b**) July 2022.

For natural gas boilers, the component significantly decreased, which was because the price of gas was lower in the summer than in the winter. The LCOH logistic component for all biofuel boilers increased, both in percentage terms (by 1–4%) and in terms of value (0.60–0.75 USD/GJ, Figures 4–6). For gas boilers, in terms of value, it almost did not change (Figure 8), but for coal, it increased by 0.53–0.55 USD/GJ (Figure 7). The LCOH environmental tax component in monetary terms did not change during this time. The LCOH of other non-fuel components changed for some boilers, as they became more expensive.

The Development Ukraine Recovery Plan is currently underway. It contains a chapter concerning biofuels such as bioethanol, biodiesel, biomethane, and biomass. It is currently under consideration. After its approval, the authors will investigate the main scenarios for biofuel boilers in Ukraine.

4. Conclusions

The increase in the natural gas price provoked a rise in the cost of biofuels. However, even with a threefold increase in their prices in the past six years, the thermal energy produced by biofuel boilers was cheaper than the thermal energy from fossil fuel boilers.

The cost of fuel delivery can significantly increase the cost of heat energy. For example, a transportation distance of 300 km increases the cost of thermal energy by 6–16%.

The LCOH environmental tax component at Ukrainian environmental tax rates was insignificant and, therefore, would not stimulate the implementation of measures to reduce the emissions of pollutants. A CO_2 emission tax is charged for biofuel boilers in Ukraine. This component was higher for biomass-fired boilers than for natural gas boilers.

The use of biofuel boilers is economically justified in Ukraine and will contribute to the reduction in greenhouse gas emissions, the development of biofuel production, the increase in the number of jobs, and the development of mechanical engineering. The use of biofuels, which are produced in the region of their use, is expedient to reduce the transportation distance.

The LCOH indicator can be used to make decisions about the choice of equipment and the type of fuel in the near term and to optimize the heat supply systems of settlements and the country. For more accurate forecasting of the cost of thermal energy, forecasting models of components, primarily of the cost of fuels, are needed.

Biomass-derived fuels, when sourced in a sustainable manner, are environmentally friendly (CO_2-neutral); however, their combustion results in harmful pollutants and ash. In further research, it is worth determining the ways of handling ash and its effect on the cost of heat energy.

This study confirmed the first hypothesis that biomass-based heat supply systems are stable to the variation in market fuel prices. The second hypothesis is also correct. The LCOH of sunflower husk and straw pellets was lower than those of wood pellets, coal, and natural gas. Its relative value was in the range of 60% (compared with wood pellets) to 35% (compared with natural gas). Therefore, these systems are promising alternatives.

In early 2020, Ukraine's 2050 Green Energy Transition Concept project was presented, which sets its goals close to those of the European Green Deal. Even in the global energy crisis, which began in 2021, the EU and Ukraine should be to make more efforts to develop green energy and increase the share of biofuels for heating. Combined heat supply systems based on heat pumps, wind power, and solar energy are a promising direction. The main scenarios of their development are of significant importance. In addition, a life cycle assessment of carbon dioxide emissions (including transport emissions) is the subject of further investigation.

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Appendix A

The data from the following table were used to determine the environmental tax and the LCOH environmental tax components.

Table A1. Specific pollutant emissions from fuel combustion [33].

Fuel	Specific Pollutant Emissions, kg/t Fuel				Fuel Pollutant Emission Index, g/GJ			
	NO_x	SO_x	CO_2	PM_{10}	NO_x	SO_x	CO_2	PM_{10}
Natural gas	2.127	0	1943.4	0.00	64.31	0	58,748	0
Coal	2.065	51.30	1918.9	47.20	100.9	2506	93,740	2305.9
Wood pellet	1.36	0.187	1700	0.51	80	11	100,000	30
Sunflower husk pellets	1.36	3.2	1816.1	0.091	75.56	207.4	100,893	5.911
Straw briquettes	1.38	2	1544.2	0.171	89.03	127.4	99,624	10.892

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RES Market Development and Public Awareness of the Economic and Environmental Dimension of the Energy Transformation in Poland and Lithuania

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Abstract: Energy transformation in the European Union countries is progressing. Its scope is defined by formal and legal regulations and its effectiveness by the position of decision-makers, legitimised by public support for a particular type of challenge. Both issues are the focus of this article. The promotion of environmental protection measures is currently strongly promoted globally. Hence the widespread acceptance in principle of the changes associated with the implementing of the Green New Deal in the energy sector is not surprising. However, to what extent is knowledge of the solutions constituting the mainstream transition (renewable energy sources) ingrained among communities? Does the level of public awareness influence individual consumer choices, modelling the market? The threads outlined above inspired deliberations focused on analysing the assumptions behind energy transition in the EU, with particular reference to the countries directly bordering the line of the ongoing conflict in Ukraine (Poland, Lithuania), in the light of the resulting and escalating restrictions exacerbating the energy crisis. The immediate neighbourhood of the adopted countries, and their similar socio-economic conditions, provided the basis for comparisons and conclusions. The motivation for the choice of the issue and research area was to fill the clear information gap in this study area, strictly in relation to the adopted configuration of these countries. The research proceedings in the outlined area were primarily based on the methodology appropriate for capture and analysis of economic phenomena, enriched with the results of our own findings (questionnaire survey regarding general knowledge of the ZE market and consumer preferences), in order to assess the economic and environmental dimensions of energy transition in Poland and Lithuania and to assess the level of public awareness in this respect in the countries under study. The presented research is an important complementary element of the authors' series of studies devoted to the analysis of the development of the renewable energy market in Poland and the Baltic States, related to the individual dimensions of RES. Their results give rise to the conclusion that increased social awareness in these countries determines the popularisation of RES solutions in individual use, regardless of their type, stimulating the progress of the energy transformation process.

Keywords: renewable energy; energy transition; energy security; energy policies; electricity prices

1. Introduction

Due to man's negative impact on the environment, irreversible climate change poses a real threat to human existence. Over-exploitation of deposits resulting in an imbalance in ecosystems, combined with critical levels of discharges and emissions of toxic substances—with particular reference to greenhouse gases—are the primary conditions for the global warming taking place, changing the world in an absolutely undesirable direction. Wide-ranging protection of the planet and care for the environment are currently critical priorities in modelling economic changes, finding their outlet in the creation of numerous innovative solutions [1]. These priorities, to a particular extent, refer to energy production, for decades occupying an infamous place in the world ranking of industries with the strongest negative impact on the climate and the planet. The classic methods of energy production—based on fossil fuels and high-carbon technologies—are currently unacceptable. The policy of opening up to ecology and building an innovative approach to energy production based on renewable energy sources has become an absolute necessity.

Overexploitation of natural resources permanently reduces their availability [2]. The prices of fossil fuels are rising and with them the cost of producing 1 KW of energy by conventional means. The increase in energy prices is further stimulated by increasing environmental charges for greenhouse gas emissions. As a result, conventional energy becoming more expensive has significantly burdened the functioning of economic entities which strongly rely on this energy supply formula.

The outbreak of the COVID-19 coronavirus has disrupted the financial economies of both households and businesses. The rising cost of purchasing electricity, coupled with continued high demand for it, began to drain consumer budgets increasingly. The energy crisis was perceptibly aggravated by the outbreak of war in Ukraine and the limited availability of energy resources due to this conflict, pushing up energy prices on world markets. The world faces urgent challenges in finding energy security solutions appropriate for economies and energy consumers. The economic consequences of the increase in energy prices are evident. Prices of products and services are rising, and inflation is skyrocketing. The above applies particularly strongly to countries whose energy supplies are derived most extensively from traditional production, and re-modelling the production formula requires major investment challenges that will, by definition, create additional growth in the market price of energy.

The problem of rising energy prices has been observed in the world for a long time, with the COVID-19 pandemic and the outbreak of war in Ukraine making the situation in the global energy market extremely complicated, essentially reinforcing the negative trend of rising prices, along with a set of economic consequences of these increases, affecting consumers. This situation implies an urgent need to implement measures to limit the growing increase in energy prices and the negative effects of this proces. One of the measures in this field is the promotion of energy from renewable sources and the strengthening public awareness in this regard. With the above in mind, the authors considered it an important research problem to analyse the directions of obtaining green energy in the countries directly bordering the area of the Russian-Ukrainian conflict (Poland, Lithuania), together with an assessment of the degree of knowledge of RES solutions, and of openness to their implementation by the local community. Increasing limitations on the energy market, and deepening of the energy crisis, are the key arguments outlining the current relevance of this issue, the study of which can support the process of social education in the RES sphere, as well as the promotion of this dimension of the energy transition in these countries. The popularisation of RES solutions is a key factor in the development of RES for individual use, which undoubtedly increases the degree of energy independence and reduces the energy cost for individual consumers. The argument above shaped the main objective of the study, which was to analyse the directions of energy market changes based on the review of assumptions of industry reports, and to diagnose the state of knowledge and orientation towards RES by Polish and Lithuanian inhabitants, based on the results of the questionnaire survey. Partial findings were subjected to critical analysis to establish a causal relationship between the level of public awareness and openness to RES.

The research revealed a causal relationship between the level of social awareness and individual use of RES, indicating a more favourable situation in this respect in Lithuania compared to Poland.

It should be emphasised that, within the scope of the study in question—strictly in relation to the adopted configuration of countries—there is a diagnosed information gap, the filling of which may contribute to the improvement of the RES development sphere in individual use. Hence, the research aims to outline the level of public awareness, creating support for implemented changes and motivating individual consumers to reach for solutions increasing energy and financial security—especially important in the realities of the energy crisis.

The available literature is relatively poor in results of current analyses of RES development directions within the scope of the subject of this study and in relation to the adopted configuration of countries. Hence, in the authors' opinion, the results obtained may enrich the existing literature with useful knowledge on the explored topic, enriching the potential to assess the set of challenges regarding renewable energy in Poland and Lithuania, and indicating the benefit of their implementation.

The structure of this paper adopts the following layout: Section 1 is an introduction to the research issue, and Section 2 is a review of the literature addressing the issue of green energy in the global energy market. Section 3 discusses the economic–environmental aspects of the development of the renewable energy market in Poland and Lithuania, considering the formal and legal framework, and the assessments of the local community (results of own research). Section 4 covers discussion and conclusions.

2. Renewable Energy in the World–Literature Review

Public awareness of renewable energy sources is increasing globally [3–5]. The benefits of using green energy are contributing to a change in the energy policies implemented so far [6–8].

The primary motivator for opening up to green energy is to live increasingly in harmony with nature by caring for the environment [9]. This direction is supported by the continuous development of technology and techniques and the increasing availability of the solutions in question, enabling today's consumers (including the energy market) to make informed choices.

The general global openness to the RES dimension is emerging against the background of the need to increase the share of energy from renewable sources in the global energy mix, along with continued growth in global energy demand [10,11]. This results from the search for low-cost and environmentally friendly technologies that combine the expectations of providing adequate energy supply at a reasonable price [12], with the lowest possible adverse environmental impact [13]. RES is therefore a response to contemporary expectations in social as well as economic terms (energy security [14–16], sustainable development [5]). In fact, ensuring energy efficiency at a widely available cost determines the very existence of economies [17], and their development [18,19]. Hence, the energy industry is considered to be a pillar of the world's economies, the capacity of which determines the development of other areas.

The problem of the security of energy production and the energy efficiency of economies in harmony with the expectations of the environment was a fundamental impulse for the creation of the evolving [20] idea of sustainable development. The harmonisation of the economic and socio-economic and socio-environmental dimensions [21], taking into account technical as well as cultural or ethical aspects [22], is intended to secure effective action for a stable present and secure future in terms of energy and environmental security. The formal framework for this concept is set out in the 2015 UN agenda 'The 2030 Agenda for Sustainable Development', which articulates the core objectives of sustainable development, together with a set of sub-targets and a set of metrics [23], outlining a framework for assessing progress at local, regional and national levels—taking into account key aspects that touch on social challenges, economic conditions and environmental requirements [20,21]. The solutions in question correspond to regulations undertaken at the level of international treaties (e.g., European Union regulations), which are transferred to the level of national economies. Securing energy in maximum harmony with nature has become a current priority challenge.

Energy from the sun [24], wind, earth, rivers and oceans, or from biomass, is energy drawn from nature, with enormous renewable potential [25]. They are deposits of energy supply, which are a valuable resource with relatively widespread availability, determined by the geographical position and geo-requirements of the location concerned, with simultaneous availability of the required solutions in the area of technical and technological development. The prism of availability of selected RES sources contributes to the orientation of the world's economies towards obtaining energy from renewable sources, which is referred to in international regulations in the sphere of contemporary approaches to energy production [26]. The area of research and development in this field is strongly promoted, and the popularisation of these solutions is intended to ensure a world that is safe—both in terms of the availability of energy supplies and in terms of existence, by constantly reducing emissions, which are lethal to man and the planet, in connection with energy production [27–30]. Indeed, renewable energy sources represent an important alternative to conventional energy production, offering the possibility to remodel the classical energy supply system and to become independent of fuel supplies from unstable or sanctioned fossil fuel markets. The above assumes particular importance for a number of economies during the current Russian-Ukrainian war and the legacy supply chains restricted as a result, which provides a strong motivation and justification for undertaking the research thread explored within this study.

A number of determinants models the energy market—the geopolitical situation and political considerations [31], international agreements and contracts [32] in the sphere of obtaining energy resources, the public-legal sphere, which defines the energy security model [33] at the level of individual states, and socio-environmental considerations, which determine the energy regulatory systems [34] of various economies.

The energy policies of the world's countries or their agreements (e.g., the energy policy of the European Union [35]) regulate the conditions for undertaking actions oriented towards the development of energy from renewable sources. By defining the scope of the formal and legal framework, they create a space for actions for the reconstruction and development of existing energy systems, directly translating into the system of available solutions—including the area of RES, outlining the field of initiatives both at the level of institutional and individual consumers, the subject of many researchers' inquiries [36–40]. The driving force for change in this area is the broadly understood dimension of research and development in this sphere, but also education and promotion in the subject of existing solutions in this area, together with the dimension of financial support (under government support programmes) in the procedure of implementing the changes in question. The above is an outline of currently important research threads.

A literature review on the subject proves that the problem of energy security based on renewable energy sources is an important topic. However, the search for sources providing answers to questions on specific solutions in individual countries requires significant effort. At the same time, the level of public awareness and social openness to RES in Poland and Lithuania is only hinted at and not sufficiently discussed in this configuration of states. The above inspired the authors to undertake the research threads explored within the framework of this study (in relation to the objective set out in the introduction), in order to fill the gap observed in the literature, by supplementing the research that can be used in decision-making processes or as part of further analyses on the subject.

3. Materials and Methods

The comprehensibility and relevance of these themes determined the scope of the study, which was adopted to maintain the expected informative quality of the results, in order to develop correct conclusions. The above discussion shaped the character of the study, the initial stage of which assumed a conceptual dimension, followed by an empirical-analytical one—for a reliable diagnosis of the state of affairs, taking into account the principles of decomposition and systematisation of phenomena, and substantive conclusions on the subject of the research threads defined in the introduction.

The research was supported by data obtained from sector reports on energy markets in Poland and Lithuania, as well as statistical studies on energy markets of the analysed countries and the European Union.

The research dimension was based on a diagnostic survey method with the use of a questionnaire, the scope of which enabled the measurement of knowledge and the collection of individual opinions on RES among the Polish and Lithuanian communities—inhabitants of both towns and villages. The survey mode took the form of a direct survey among the Polish community and an online survey among the Lithuanian community. The survey focused on RES issues with reference to theoretical aspects and general issues of consumer practice in this field in order to determine public preferences. The survey in question, limited in its scope and subject matter, was conducted in April–May 2022, with a sample of 248 respondents—152 from Poland and 96 from Lithuania. Importantly, the analytical material obtained in the course of the survey in question for the purpose of this article was used only in the required part, and its subsequent dimensions will serve for separate analyses, according to the assumptions adopted by the authors. Hence, the results obtained do not exhaust the scope of the issues explored, providing inspiration and input for further in-depth research in this area.

The presented concept determined the following structure of the research:

1. Analysis of the current literature on energy market issues in the international dimension, with a particular focus on renewable energy. In this regard, the variety of simple methods applicable in the analytical process was used to move from experience in the global dimension to study at the level of the countries accepted for analysis (Poland, Lithuania).
2. Cause-and-effect, situational and comparative analysis of the energy market, including RES, in the countries included in the study (Poland, Lithuania), for critical analysis.
3. Diagnosis of the level of public awareness and analysis of the social openness to RES in Poland and Lithuania, with reference to the results of our own research (questionnaire survey of Polish and Lithuanian communities), to assess the progress of modelling processes in the energy systems of Poland and Lithuania, in line with current trends of change.
4. Easing energy security through gradual decoupling–conclusions and recommendations.

The authors' main goal for this study is to extend and update knowledge in the field of renewable energy technology development to model a vision of energy development in the region in harmony with the environment, using RES solutions In addition, it is important to answer questions such as: to what extent is knowledge of mainstream transition solutions (renewable energy sources) ingrained among communities? Does the level of public awareness influence individual consumer choices modelling the market? In this respect, the quantitative data established during the research process is intended to be useful.

4. Results and Discussion

4.1. The Economic and Environmental Aspects of EU Energy Policy and the Objectives of Poland and Lithuania

In the light of progressive pollution of the environment, decision-makers of individual countries began to adopt an orientation towards the promotion and expansion of the use of energy obtained from renewable sources in economic processes [41]. Sustainable development of the world's economies has become an important topic [42], and its essence is captured in the agenda already referred to in this article signed by the nations associated with the United Nations in 2015—"The 2030 Agenda for Sustainable Development", specifying the headline (16) and sub-goals (169) of the development in question, with correlated measurement indicators (232) [23].

In Europe, especially in countries associated with the European Union, a new energy production approach started to gain momentum. There have been gradual changes in the EU energy legislation concerning electricity generation, e.g., Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market [43], or the use of renewable fuels in transport; eDirective 2003/30/EC of the European Parliament and of the Council of 8 May 2003 on the promotion of the use of biofuels or other renewable fuels for transport [44], which has strongly evolved over the recent years. Renewable energy sources have started to play an important role in modelling the future of energy security of EU Member States. A new look at energy supply which protects the environment to the maximum extent has initiated a trend of transformation of energy systems based on conventional production system, and in 2009 a fundamental goal of the European Union was established in this respect, which stipulated that 20% of energy consumption in the EU Member States should come from renewable sources by 2020 (Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC [45]). The adopted policy will contribute to [42]:

1. An increase in the energy security of EU Member States due to the use of RES.
2. Market integration of energy economies, based on the use of new technologies for the production of cheap and environmentally safe energy.
3. Increasing innovation in and promotion of energy from renewable sources to stimulate progressive change in the energy sector,
4. Increasing energy efficiency using energy supplies from renewable sources,
5. Decarbonisation, in order to protect the environment.

These aspects underpinned the creation of the EU Energy Strategy [46], adopted on 25 February 2015, oriented towards generation security, sustainability and competitive prices in the European energy market [47], creating a clean energy dimension ("Clean Energy For All Europeans") within an energy union [48]. Individual EU member states have established national plans to implement the EU's renewable energy promotion policy, supported by a set of individual targets, reportable on a biennial basis [25]. As of February 2017, the increase in the share of RES in the energy mix of EU Member States contributed to a €16 billion reduction in fossil fuel import expenditure in 2015, giving rise to projections of further savings that could reach €58 billion in 2030 [49].

In 2018, the objectives of the European Union in the energy sphere (Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources [50]) were revised, setting the planned share of energy from renewable sources in the energy mix of the Member States at 32% by 2030, which is expected to directly contribute to increasing the reduction of greenhouse gas emissions and to increasing energy efficiency through the development of RES [26].

The pro-climate activity of the EU is gaining momentum, and the targets for the continuous increase of renewable sources are becoming increasingly ambitious. In 2019, the "European Green Deal" [51] was adopted, on the way to energy neutrality for the European continent. In 2021, it was proposed to change the adopted target for the share of RES in the energy mix of EU countries to 40% by 2030 [25], Moreover, member states have agreed to reduce emissions by 55% by 2030 compared to the 1990 results [52]. A key determinant of the promotion of the above actions is their financing. This dimension of actions is regulated by a number of formal and legal instruments, including, among others, Commission Implementing Regulation (EU) 2020/1294 of 15 September 2020 on an EU Renewable Energy Financing Mechanism [53], oriented to support initiatives related to the established targets—in the overall EU dimension and at the Member State level, by feeding in investment activities in the area of RES.

The EU Member States are obliged to implement the current provisions, and the strategies adopted in this respect should be consistent with the objectives set for these countries.

The European Union's energy objectives established in this way have posed a huge transformation challenge for many countries, including Poland. The Polish energy sector, 70% of which is based on coal, has faced major challenges associated with the need to remodel the existing energy system towards less harmful methods of generating energy. It should be stressed here that the coal-based power industry in European Union countries is a major contributor to carbon dioxide emissions, accounting for almost a quarter of total emissions. Among the potential directions of actions in order to achieve the established EU targets, the following were indicated at that time [54]:

- modernisation of coal-based power generation towards Carbon Capture and Storage technology, oriented towards capturing about 90% of CO_2 and its storage in the energy production process,
- nuclear power generation,
- renewable energy sources,
- improvement of energy efficiency (increasing the degree of energy use in the process of transmission and consumption).

In the area of RES solutions implementation, Poland has committed itself to [55]:

- achieve a 15% share of renewable energy sources in the country's energy balance by 2020, with an option, in the event of failure to meet environmental targets, to purchase 'green certificates' from countries that have generated a surplus of clean energy with respect to the thresholds set by the EU [56],
- increasing the share of biofuels on the market to 10% in 2020, including stimulating the use of generation II biofuels (transport),
- increasing the diversity of sources of supply and developing infrastructure for domestic production based on available energy sources (orientation towards distributed energy).

Following the above, the directions of green energy generation in Poland were mainly conventional biomass power plants and hydroelectric power plants (with a share of approximately 75% in renewable energy sources in Poland), as well as the opening up of wind power plants, strongly developed in the period 2007–2011, with an increase in their capacity in this period by 829% to 1180 MW [52]. Among the RES sources in Poland, the share of solar energy (photovoltaics) and geothermal energy (geothermal) in the energy portfolio also started to be marked. Furthermore, efforts were oriented towards:

- promotion of the construction of agricultural biogas plants with the assumption of one commune/one biogas plant,
- establishment of formal and legal conditions for undertaking investment activities in relation to the construction of offshore wind farms,
- support for technical and technological development, including in particular the development of RES concepts and production in the area of RES solutions,
- financial support of activities related to the construction of RES installations, including drawing on European funds, environmental protection funds, or preferential rates or tax exemptions,

In order to:

- reduce the country's dependence on energy imports,
- diversify the structure of energy supply sources,
- strengthening local energy development based on renewable energy sources,
- environmental protection due to the use of green technologies [57].

These are extremely important aspects of energy policy, oriented toward the security of supply and affordability of energy in a competitive energy market.

The energy policy of Lithuania is fully in line with the EU energy strategy. Lithuania is orientating its activities in this field [55]:

- Increasing energy security through gradual decoupling from the energy supply based on raw materials imported from Russia (e.g., by cutting off the "Brell" transmission ring) and diversification of energy sources—including strengthening of the role of domestic energy production coupled with the policy of increasing the share of renewable energy sources in its energy mix,

- Participation in the market integration of energy economies, with a focus on the electricity and gas sectors (synchronisation with the European transmission network by 2025),
- development of innovation in the energy sphere and increasing the degree and scope of utilisation of new technologies in energy production processes based on renewable sources—environmentally safe and attractive in terms of production costs
- stimulation of RES increase in the energy mix and improvement of the country's energy efficiency,
- reducing consumption of energy derived from conventional forms of production and increasing the level of environmental protection (decarbonisation).

These actions outline the specific dimension of Lithuania's energy transition, oriented towards the path of energy self-sufficiency and strengthening of energy security in the region through energy production for export to the Baltic countries, including Finland and Poland. It is worth noting that a few years ago the level of domestic electricity production estimated in relation to its final consumption in Lithuania was only about 5%, thus the outlined path towards increasing the competitiveness of the state energy sector in Lithuania is a necessary but very costly measure—the implementation of the energy development objectives requires significant investment and modernisation efforts, related to the provision of technical facilities for the efficient and effective functioning of the energy market, taking into account the capacity and security of supply chains. The cost of the process of synchronisation of the Lithuanian energy system with the European energy transmission grid is an investment burden oscillating around EUR 1.5 billion. At the same time, the EU strongly supports this activity, and 75% of the financing source for this project is from EU funds [58]. It is worth mentioning that, for this transformation only in the period 2014–2020, the European Union has allocated funds in the amount of 564.4 million euros, and the modernization of infrastructure in the period until 2027 will burden the leading network and gas pipeline operator with investments to the value of about 2.1 billion euros, hence Lithuania's ambitious goals in this regard [58]:

- to increase the share of renewable energy sources in Lithuania's final energy consumption to 45% by 2030 and 80% by 2050,
- to change the relationship in the energy balance by RES share in energy production to 70% by 2030 (with EU targets of 32%) and 100% by 2015.

The correctness of this direction of action is confirmed by the growing interest in purchasing of Lithuanian energy in the region (e.g., by Poland), along with the opening up to investments in RES, implemented via international cooperation, including with Poland (mainly wind farms).

The energy policy of the European Union is oriented towards creating a low-emission energy market—safe for energy consumers (availability of energy at affordable prices) and the environment (reducing greenhouse gas emissions, limiting the extraction of non-renewable resources disturbing the functioning of ecosystems, etc.). The directions of the challenges undertaken at the level of Member States in their assumptions directly relate to the established main objectives of the EU in this area, which can be undoubtedly confirmed based on the analysis of the cases of Poland and Lithuania. They constitute a path for improving the efficiency of energy supply mechanisms at the country level in line with sustainable development, strengthening the energy security of economies and the competitiveness of the European Union energy market.

4.2. RES Development Directions in Poland and Lithuania

The Polish and Lithuanian energy sectors are facing a number of challenges in the energy transition of their respective economies. Growing energy demand makes the transformation processes absolutely necessary, and the implementation of RES solutions is becoming increasingly important in the modelling of energy systems in line with contemporary socio-economic expectations. The above assumes particular importance in the realities of the currently observed energy crisis and rising energy prices, particularly significant in the recent period affecting Poland.

There are a number of possibilities for obtaining energy from renewable sources. These include solar energy, wind energy, and energy from the Earth's interior, etc. Among the sources mentioned above, photovoltaics is becoming increasingly popular in achieving sustainable development goals. Currently, the total installed capacity of photovoltaic (PV) systems in Poland is estimated at over 8.76 GW (which, according to forecasts, may reach 12 GW by 2024), which currently accounts for approximately 48% of this source of energy supply in the Polish structure of RES sources [58] and for over a 3% share in the Polish energy mix [59]. To a significant extent, the growth of photovoltaic solutions is related to the increasing interest of Poles in small PV installations (private micro-installations with a limited connection power of up to 10 kWp [53], driven by friendly formal and legal instruments in this field, directed to a wide range of potential investors who are individuals (e.g., "My Current", "Clean Air", "Thermomodernization Relief"), economic entities (e.g., "Energia Plus") or farms (e.g., "Agroenergia").

The development of the photovoltaic installation market also concerns the Lithuanian market. As in Poland, PV micro-installations, dedicated to private users at a household level, enjoy a significant interest in this country, while the market also shows business interest in constructing high-power photovoltaic farms. This, motivated by government support programmes, has contributed to the fact that the share of PV in the energy mix in Lithuania is 2.3% and, according to forecasts, the connection capacity of PV installations may reach 1 GW by 2025 [51].

Another dimension of RES that is being rapidly developed in Poland and Lithuania is wind energy. Currently, the installed capacity of wind installations (the on-shore dimension of wind energy) in Poland has reached 7.18 GW, which gives a 40% share of the RES energy structure [58]. The connection capacity of wind installations in Lithuania exceeds 0.53 GW, giving more than 11% of the energy volume consumed in Lithuania [60]. Both in Poland and Lithuania significant attention is focused on offshore wind energy. This is a reasonable direction, as the offshore wind energy potential is estimated at 90 GW with an estimated capacity for Poland of 5.6 GW and for Lithuania of 0.7 GW (25% of electricity demand) for 2030, when energy from offshore wind is expected to flow into the power grids of these countries [61]. This is a very important dimension of activities in the area of energy transformation of these economies. The potential of offshore wind is recognised as an important instrument for reducing carbon dioxide emissions, as per the European Green Deal principles.

The potential of wind energy is increasingly being exploited. However, the needs of consumers interested in small wind installations are still worthy of attention, along with the support of market activities and from the area of regulation and support (arrangement of formal and legal frameworks) under the criterion of ensuring broader knowledge and access to the solutions in question [61].

An important, dimension of the implementation of solutions oriented at drawing energy from renewable sources is geothermal energy, drawing energy from the heat of the Earth. The energy potential of the Earth is huge, but the availability of the Earth's heat for utilisation varies from country to country. Due to Poland's favourable geothermal conditions, energy is successfully drawn from deep and shallow geothermal sources, supporting Poland's energy security (share in RES less than 1%). In the case of deep geothermal, plants with maximum water temperature of 61–86 °C, with a share of geothermal power in the total installed capacity ranging from 0.3 to 40.7 MW and with a share of geothermal power in the installed capacity ranging from 31–100%, are in operation [62]. In the case of Lithuania, the availability of geothermal resources is relatively limited to the western regions of the country, outlining the future potential for their development in this area [63]. However, there is availability of 150 °C deposits in the form of rock heat at a depth of several kilometres, from which a heat plant in Klaipėda draws energy, with an installed capacity of 17 MW and a useful temperature of 38 °C [64].

The potential of the Earth's energy is described as the absolute future of RES development, which, according to the authors, will be more widely used in the area of deep geothermal, after solutions giving higher economic efficiency drawing from geothermal deposits of different quality have been worked out. Undoubtedly, a more widely developed practical solution for tapping energy from the earth is shallow geothermal energy, using low-temperature heat from the earth due to drilling, creating a market for heat pumps of various types (water-air, air-air, others), which are widely available. The installed capacity for drawing from Earth's heat in direct mode in 2020 in Poland was 756 MWt, while in Lithuania it was 125.5 MWt [65]. The interest in heat pump installations up to 390 MW with an annual capacity level of 2000 TJ is steadily growing [66]. A particularly intensive growth of heat pumps is observed in the Polish market (173,146 pump installations installed in 2019, with the share of air heat pumps in relation to ground heat pumps in the ratio of 2:1), with a significant share in Lithuania (7456 pump installations in 2019 with the predominant share of air pumps in the total pump volume) [67].

The study results conclude that renewable energy sources are an important subject relating to the challenges of implementing of the European Green Deal policy in Poland and Lithuania. An interesting observation is the growing demand for solutions from small-scale, generally widely available installations drawing from renewable sources—photovoltaics, shallow geothermal energy or interest in domestic wind installations. The above testifies to the growing social awareness in the field of energy from renewable sources and the need to function in accordance with current pro-environmental trends. This is a very positive public orientation, indicating a cause-and-effect relationship between increased public awareness and the popularisation of RES solutions for individual use.

4.3. Social Openness to RES in Poland and Lithuania—Research Results

Conventional energy production contributes to the overexploitation of fossil fuels, which are limited resources [68,69]. The prism of limited goods creates a higher cost of acquisition, which in turn increases the cost of energy production and increases the market price of 1 KW of energy. Complementing the above with the environmental aspect [70] and charges for discharges and emissions of harmful substances, the economic justification of maintaining conventional energy production in the long term raises a number of doubts. Hence, the search for alternative energy production solutions was oriented towards the aspect of environmental safety correlated with the economic safety of the consumer. In this respect, the role and importance of renewable energy sources in energy production is widely exposed [71] in modern environmental and economic realities. This is because renewable sources are considered a reliable, safe and cost-effective way to achieve the objectives of sustainable development of economies [72].

A strong increase in the price level per 1 KW is currently affecting a number of countries. This situation is created by the increase in the demand for energy as a result of the increase in the consumption of electricity globally, including the countries of the Baltic Sea region, the increase in the cost of CO_2 emission allowances and, absolutely, the state of the Russian-Ukrainian war which changes the current functioning of the energy market [73]. In the outlined situation, the orientation towards RES is fully justified. Consumers are looking for access to energy at a competitive price, hence the production of green energy must be based on technologies that justify this action from the economic side [74]. At the same time, it is worth emphasising that energy derived from RES, excluding investment outlays, is considered as cheap. This perspective drives sustainable energy development, basing on RES the challenges of optimising the cost of energy production and distribution costs. The above is an important goal for the transformation of this economic dimension [75].

The success of implementing these changes is created by understanding and accepting the needs of the environment, regarding the actions taken. Hence, public education and promoting solutions beneficial to the environment and consumers plays an important role in the implementing of sustainable development and its objectives. Increased public awareness contributes to increased interest in RES solutions for individual use, strengthening the development of the green energy market, which is confirmed by the conducted research "Analysis of RES solutions in Poland and Lithuania" (April–May 2022), based on a diagnostic survey formula. The results of the research (survey of knowledge and consumer preferences regarding RES, Table 1) indicate that 79% of the surveyed Polish community is in favour of the development of the green energy market globally, while only 54% associate the issue of sustainable development with energy transition. In this regard, a survey of the Lithuanian community revealed that 97% of respondents support a global orientation towards RES, and 73% link this activity with the idea of sustainable development.

Table 1. Consumer knowledge and preferences in the field of Renewable Energy Sources—research results.

Research Thread	Poland % of Indications	Lithuania % of Indications
Support for the development of green energy in the world	79	97
Linking the issues of sustainable development with the energy transformation	54	73
The justification for green energy as the basic direction of the development of the energy market	64	71
Justification for price changes resulting from restrictions due to the transformation process	28	72
Positioning renewable energy sources in the group of environmentally safe	96	98
Recognition of RES as a source of cheap energy (excluding investment outlays)	16	18
Recognition of financial support for RES investments as a key factor in the development of the green energy market	86	91
Confirmation of individual preferences for the selection of energy sources from RES	22	38
Assessment of progress in the implementation of renewable energy sources in the country at an average or poor level	60	91
Assessment of the progress in the implementation of renewable energy sources in the country compared to other European Union countries at an average or weak level	48	73

On the subject of attitudes towards restrictions on conventional energy production in connection with the transition, and rising energy prices in connection with this measure, only 28% of Polish respondents found these justified, stressing, however, that green energy should be the primary direction of development of the energy market in Poland (64%). In the case of the Lithuanian community, 72% of respondents considered the introduction of restrictions in this area as justified, and almost the same percentage (71%) considered RES energy as the basic and appropriate direction for the country's energy transformation.

The vast majority of Polish respondents (96%) confirmed that renewable energy sources are oriented towards obtaining energy in an environmentally safe manner, with only 16% classifying the production of green energy—excluding investment in RES installations—as cheap. In the case of respondents from Lithuania, as many as 98% of respondents confirmed RES-based energy production as pro-environmental, while only 18% classified it (excluding investment expenditure) as cheap energy generation.

In this survey, respondents also indicated that financial support for projects is the main motivator for RES investment activities. This position is confirmed by 86% of Polish and 91% of Lithuanian respondents, with a lack of opinion on this issue indicated by approximately 6% of the total surveyed population.

An important aspect of this research is to capture the cause-effect relationship in terms of advocacy for RES development, with a simultaneous declarative interest in choosing the direction of solutions in this area. A hypothetical need to invest in this type of solutions was articulated by 22% of Polish respondents and 38% of Lithuanian respondents, indicating a coupling between the increasing level of social awareness and individual interest in RES investments and confirming the research assumptions made in this respect.

In addition to the presented scope, an interesting strand of research is the assessment of the progress of sustainable development implementation in the energy sphere. In Poland, 60% of respondents rated this process as average compared to progress in other Baltic Sea countries. When comparing the struggle in question to the results other EU member states achieved, Poland's results were assessed by an equal percentage (48%) as average or poor. For Lithuanian respondents, on the other hand, 91% assessed the effects of RES implementation in Lithuania against the background of the Baltic States as average, while 73% considered the results against the background of the EU Member States as average.

The study's results clearly indicate that the Lithuanian community is more open to green energy sources, ahead of Poland in the ranking in this area, and also more strongly emphasises the role of RES in the ongoing energy transition than Poland. A slightly higher percentage of the Lithuanian community described production based on renewable sources as cheap. The survey's results on the progress of RES implementation in the Baltic States and in the EU area can be considered relatively comparable—in the case of both countries, in the social assessment the results are at an average level.

The results of the assessment of the level of information in the RES sphere are similar to those presented above. In Poland's surveyed community, 37% positively assessed the quality and availability of general information on RES, compared to 63% of the Lithuanian community. On the other hand, only 23% of the surveyed community in Poland assessed as positive the access to information in the sphere of financing RES installations—including analyses of their economic justification, while in Lithuania 61% assessed this scope positively (Table 2).

Table 2. Assessment of quality and access to information in the RES sphere—survey results.

Research Strand	Poland % Indications	Lithuania % Indications
Good assessment of the quality and availability of general information on RES solutions	37	63
Good assessment of the availability of information on RES funding—including analyses of their economic justification	23	47

The visible differences in the Lithuanian community's approach to RES issues, determined by the theoretical and practical knowledge of RES solutions and their essence in supporting the operation of the RES market, can be juxtaposed with the general level of the share of RES sources in the energy mix of the studied countries, which for Poland, with regard to solar energy, wind energy, heat pumps and geothermal energy, currently fluctuates at around 18%, while for Lithuania it exceeds 25%. This is an interesting observation, as the practical activity of Poland, compared to that of Lithuania in the examined dimension of RES solutions (photovoltaics, wind energy, geothermal), is strongly marked in the energy market, although, in the final analysis (in relation to the size of the countries and energy demand), the sustainable development goals facing Poland still pose a major challenge.

With regard to the findings, it should be pointed out that the opening up to RES, motivated by the public's aversion to harmful and expensive conventional production, may contribute to formal and legal decisions taken by decision-makers, promoting a course of action at the national level that coincides with the Green Deal. In addition, as public awareness increases, so does the popularisation of RES solutions in individual use, which undoubtedly reinforces the progressive transformation of the energy market. The above coincides with the observation noted in the literature that the mode of energy transition in individual EU countries is implemented according to the individual approach of the countries [76]. Furthermore, the literature signals the importance of public awareness for the development of RES sources in practical use [77], pointing to its insufficient level as one of the main barriers to green energy development [78].

The observed average 25% difference in the rating at the positive level in relation to the quality and availability of general information on RES solutions and availability of information on RES financing, taking into account the analyses of economic justification in terms of the results of the survey of the Lithuanian community compared to that of the Polish community, translates into an average 14.65% better results in the sphere of consumer knowledge and preferences in terms of renewable energy sources. The strongest difference in this area (44%) emerges in the justification of price changes resulting from restrictions in the energy transition process, with the acceptance of the Polish community at a level of 28% and in the Lithuanian community at a level of 72%. The detailed distribution of differences in indications of the Polish and Lithuanian communities is presented in Figure 1.

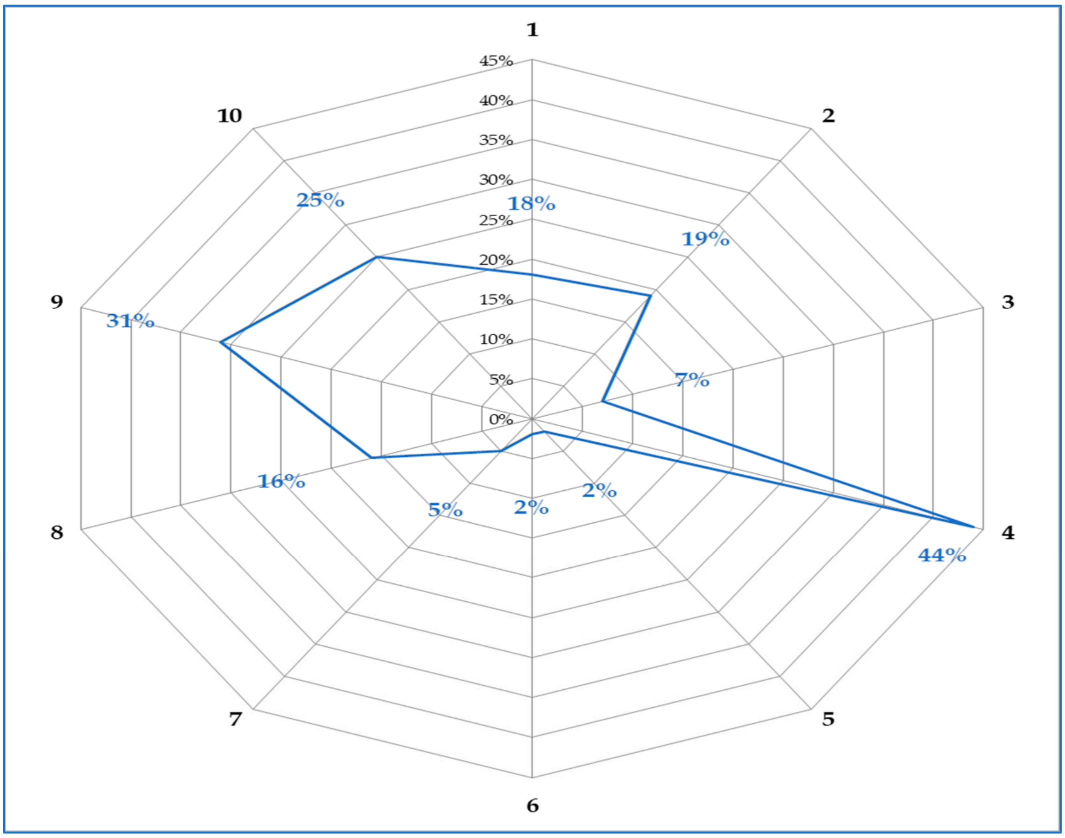

Figure 1. Distribution of differences in indications of Polish and Lithuanian communities in terms of knowledge and preferences and assessment of the quality and access to information in the RES sphere—survey results. Legend: (1) Support for the development of green energy in the world; (2) Linking the issues of sustainable development with energy transformation; (3) The justification for green energy as the basic direction of the development of the energy market; (4) Justification for price changes resulting from restrictions due to the transformation process; (5) Positioning renewable energy sources in the group of environmentally safe sources; (6) Recognition of RES as a source of cheap energy (excluding investment outlays); (7) Recognition of financial support for RES investments as a key factor in the development of the green energy market; (8) Confirmation of individual preferences for the selection of energy sources from RES; (9) Assessment of progress in the implementation of renewable energy sources in the country at an average or poor level; (10) Assessment of the progress in the implementation of renewable energy sources in the country compared to other European Union countries at an average or weak level.

The analysis of quality and availability of general information on RES solutions and their financing reveals the importance of access to information, creating the level of social awareness. Hence, the findings of the research presented in this article in the sphere of social preferences in relation to the forms of obtaining information in this sphere that strengthen knowledge about RES may prove to be significantly useful. Practical orientation to the key issues in social education in the RES field may contribute to improving the results obtained. Findings in this regard were made in the framework of our own research presented in this article. Respondents from the surveyed countries indicated in 95% of cases that the most useful sources of knowledge in the RES sphere are industry portals (articles and blogs available on the web), and the most demanded are RES consulting points (84%). In addition (with multiple choices), professional industry publications (75.5%), thematic seminars (58.5%), conferences (50%), and distributed information materials (91%) were indicated. The detailed distribution of indications in this area by country is presented in Table 3.

Table 3. Publicly demanded sources of information in the RES sphere—survey results.

Publicly Requested Information Sources on RES	Poland % Indications	Lithuania % Indications
Renewable Energy Action Points	86	82
Thematic seminars	56	61
Information material distributed	47	44
Industry portals (RES)	93	97
Conferences	56	44
Professional sector publications (RES)	78	73

With regard to the findings made in the article, it should be pointed out that the opening up to RES is motivated by public aversion to harmful and expensive conventional production. This orientation may contribute to the formal and legal decisions taken by decision-makers, promoting a course of action at the national level that coincides with the Green Deal. In addition, as public awareness increases, so does the popularisation of RES solutions in individual use, which undoubtedly reinforces the progressive transformation of the energy market. The above positions the social awareness factor in the system of determinants of renewable energy market development.

5. Conclusions

Actions drawing energy from available renewable resources is a green alternative to classical solutions in the field of energy production. The orientation towards increasing this share in the energy supply system is a challenge for many modern economies. Consistent implementation of RES solutions undoubtedly increases the chances of Poland and Lithuania achieving their goals in the area of EU energy policy, changing the orientation from the solutions practiced in these countries for years, characteristic of a centrally planned economy—based on a single energy source (Poland—coal, Lithuania—nuclear energy) [53]. The review of the assumptions of the energy transformation of the European Union and the assessment of the ongoing changes in the energy systems in Poland and Lithuania carried out in this study indicates that the energy transformation direction adopted by the EU, and consequently by Poland and Lithuania, is in the direction of the improvement of the region’s competitiveness through strengthening energy security, correlated with the improvement of the quality of social and economic life—considered through the prism of innovativeness of applied solutions, as well as the greening of energy supply routes, together with the optimisation of generation costs shaping the market price per 1 KW. In addition, the above should be complemented by the aspect of stimulating an increase in energy efficiency, in connection with increasing the rationality of energy use in places of its consumption, as well as limiting losses in the process of its transmission, which can be emphasised in the regulations [53]. The elements outlined above create sustainable development, oriented towards seeking and implementing solutions that balance environmental protection objectives with supply security objectives in a competitive energy market (availability of green energy at an affordable price).

The energy transition process in Poland and Lithuania is progressing. Increased awareness among consumers, who are orienting their energy choices towards renewable energy sources, is driving this change. This awareness grows out of knowledge of the essence of pro-environmental actions, captured in the energy policies of modern economies, corresponding to the assumptions of sustainable development. The promotion of a mode of functioning in harmony with nature, together with the system of instruments supporting pro-environmental solutions, assumes a fundamental significance here, confirmed by research.

The system of changes in the energy market strongly concerns the development of formulas for obtaining green energy. In particular, the importance of individual use of RES solutions is highlighted, where popularisation of this direction is seen in both social education and financial support; hence it is necessary to nurture and strengthen the dimensions of social education in the RES sphere and available RES investment financing instruments. This is because the level of social awareness determines individual consumer choices, modelling the energy market. The above confirms the research assumptions adopted for this study. Moreover, the above is in line with the position generally articulated in the literature on education and support for the local community in the process of green transformation [79], which sees it as a driving force for stimulating its effectiveness.

In view of the above, the authors believe that it is worth strengthening or remodelling the dimension of educational undertakings in the RES area, taking into account the broad promotion of solutions applicable at the level of individual households, as this may improve the practical interest of investors in these solutions in the country, which has been pointed out among the determinants of consumers' investments in the RES sphere, articulating the need for research in this area [80]. The above conclusion coincides with the position noted in the literature about the need for changes in the formula of knowledge transfer [29,81] on the topic of RES potential [82] and its active promotion [83]. Hence, the creation of educational programmes dedicated to different social groups would be worth considering. Furthermore, the need to ensure the availability of information on financial instruments in the field of RES financing, including professional counselling to benefit consumers' potential, is particularly important. The above conclusion is strengthened by the observation of the information deficit of RES customers [59].

Drawing on renewable energy is the most appropriate way to green the energy economy, in line with the idea of sustainable development and strengthening the financial security of energy consumers. An important determinant of the development of this dimension is public awareness of RES. This is an important condition, which should be properly developed at the level of economies, hence it is worthwhile designing solutions in the sphere of RES education to refer to the current preferences of the RES market's potential customers.

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The Impact of Natural Gas, Oil, and Renewables Consumption on Carbon Dioxide Emissions: European Evidence

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Abstract: Natural gas has returned to prominence in the agenda of European countries since the beginning of the invasion of Ukraine by Russia in 2022. However, natural gas is a fossil source with severe environmental implications. This paper aims to verify the impact of natural gas on carbon dioxide (CO_2) emissions for a European panel from 1993 to 2018 for sixteen countries. An Autoregressive Distributed Lag (ARDL) model in the form of an unrestricted error correction model was used to identify the short-run impacts, the long-run elasticities, and the speed of adjustment of the model. The results indicate that in the short-run, natural gas has a negligible impact on CO_2 emissions when faced with oil consumption (6.7 times less), whereas the consumption of renewables and hydroelectric energy proved to be able to decrease the CO_2 emissions both in the short- and long-run. The elasticity of oil consumption is lower than the unit, indicating that efficiency gains have been achieved during the process of the energy transition to clean energy sources. If economies use non-renewable energy, governments must continue to prefer natural gas to oil. Renewables and hydroelectric consumption must be used to revert the path of CO_2 emissions. Given the unstable scenario that has been caused by the War in Eastern Europe, politicians should focus on accelerating the transition from fossil to renewable energies.

Keywords: natural gas; carbon dioxide emissions; economic growth; consumption of renewables

1. Introduction

The development of the natural gas market in the European Union (EU) happened gradually. Firstly, with the Single European Act entrance, in force since 1986, the target of creating the internal market until 1992 was established. This market would develop an inter-institutional relationship of political cooperation and community competence among the European countries.

Liberalizing the natural gas market would protect consumers' interests in the final price, the quality of service, environmental sustainability, access to information, and supply security. Furthermore, natural gas is essential for citizens' lives in both electricity production and residential consumption. According to the article "EU energy mix and import dependency" from Eurostat [1], the European Union (EU) received more than 46% of its natural gas imports from Russia. Other important providers are Norway, Algeria, Qatar, the United States of America, the United Kingdom, Nigeria, and Libya making up collectively with Russia 90% of the EU's total natural gas imports.

In Figure 1, we show the energy imports dependency, namely natural gas in % of the total energy needs:

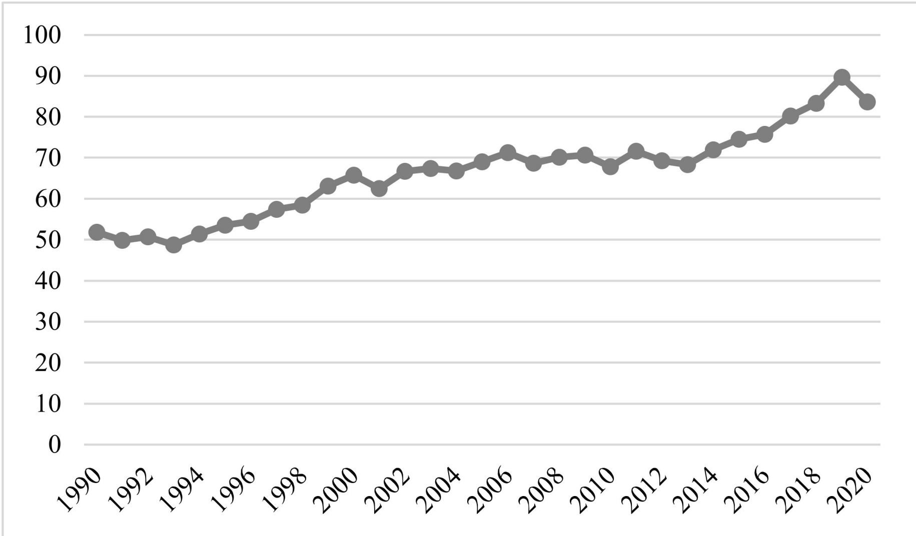

Figure 1. Natural gas in % of the total energy needs. Source: [1].

The numbers that are shown in Figure 1 suggest that some European countries are highly dependent on natural gas imports. However, due to the current scenario of War in Eastern Europe (invasion of Ukraine by Russia) and the strong European dependence on Russian natural gas, in parallel with all targets for reducing global warming, the replacement of natural gas with clean sources of energy is once again a matter of emergency. Finally, considering important aspects that were addressed by [2], such as energy efficiency, energy security in the EU, the living conditions of the population, and the conditions for economic development.

The European Union economy is increasingly using energy that was obtained from renewable energy sources [3]. Nonetheless, regarding the relevance of natural gas for the EU, this research aims to identify the impact of natural gas consumption on carbon dioxide (CO_2) emissions, analyzing an EU countries' panel.

The criteria for selecting countries for this research were: (a) being a member of the EU, a sophisticated natural gas market; (b) having data for a long-time horizon for the series; and (c) availability of data for all the variables. These rules resulted in annual data, a time horizon from 1993 to 2018, and sixteen EU countries.

After the Autoregressive Distributed Lag (ARDL) model estimation, the results support the Kuznets curve's presence, revealing a negative impact on the gross domestic product (GDP) per capita (PC) in curbing the carbon dioxide (CO_2) emissions and evidence of the impact of renewables consumptions on reducing CO_2 emissions. The results, as expectable, also reveal that the consumption of natural gas and other fossil energy sources has different environmental impacts. However, the natural gas contribution to increasing CO_2 emissions is very small compared to other fossil energy sources. These results provide a better comprehension of the liberalization of natural gas in the European common market and sets a scientific basis for further comprehension of the phenomenon of CO_2 emissions in the EU.

The research is organized as follows: The first section shows the introduction. The second section (literature) reviews the existing literature about CO_2 emissions and the liberalization of natural gas in the EU. Section three (methodology) describes the data, the methods, and the model that was used. The empirical results and discussion are presented in Section four. Finally, the conclusions and policy recommendations are shown.

2. Literature

There have been significant changes in the integrated energetic gas and electricity market in the last decades. According to the Fact Sheets of the Internal Energy Market [4], the 1990's directives are the starting point for the liberalization of the internal market for natural gas and electricity since, at this time, the major part of the national markets for electricity and gas were objects of monopoly [4]. The United Kingdom and Wales were the first countries to establish liberalization measures (e.g., [5,6]).

Newbery [5], in his analysis of the liberalization of the British electricity market, points out that the main factors that led to this were the little government incentive for the good use of available resources, in addition to the choice, often by political influence, by managers that were not qualified to take on projects in the area. In addition, liberalization was looking for a system to deliver energy efficiently, safely, and sufficiently at competitive prices [5].

This liberalization in Great Britain was positive, as [7] points out. For example, in the first five years after opening to the private market, the costs decreased by 6%, labor productivity more than doubled, the actual cost of fuel that was used to create energy dropped substantially, and new and important investments were made at a much lower cost (per unit of energy) than the cost before liberalization [7].

Thus, there were significant changes in the energy markets [8–10]; competitive markets replaced monopolies of public services, and the traditional public management tended to disappear, with its place being taken over by the private administration [5,10].

State members of the EU decided to open their markets gradually to the competition. In 1996, measures were adopted that predicted the countries would establish the rules as the electricity market liberalization until 1998. While for the gas market liberalization, the measures were adopted only two years later and predicted the establishment of legislation until the year 2000 [4].

According to information from the European Commission [11] in 2009, legislation about the energy market, known as the third package of energy, was approved. The package aimed to improve the internal energy market's functioning and resolve structural problems in the energy sector [11]. Again, according to the European Commission [12], difficulties were found in entering new companies. The increased competition in the energy market failed due to the huge number of regulated prices that are still practiced by the countries.

According to the European Parliament [13], new measures were adopted in June 2019, named the directive 2019/944/EU, and three regulations (Electricity Regulation (2019/943/EU); Risk Preparedness Regulation (2019/941/EU); Regulation EU 2019/942/EU establishing an Agency for the Cooperation of Energy Regulators (ACER)). These measures introduce rules in the energy market to adapt to the necessity of renewable energies, besides attracting new investments. In addition, incentives for consumers and the introduction of the Member States' obligation to prepare emergency plans to deal with possible electricity crises are also highlighted.

De Campos [14] also points to the importance of the Community Directive 98/30/EC, which approved the opening of the internal gas markets and reported topics such as transportation, infrastructure, storage, organization, and operation of the sector. Ref. [8] stated that these changes over time are attributed to good regulation, which solved unforeseen problems in the proceedings.

The dependence on natural gas from foreign suppliers is very high in the European Union, leaving countries in a unique situation regarding supply security [15]. The EU is dependent on imports of natural gas from an oligopoly of important producers [16].

Hulshof et al. [17] warned that the number of gas suppliers to the European market is limited. The author points out that the market faces periodic shocks in both supply and demand, which is one reason for the price distortion [17]. Given the dependence of Member States on gas imports, following the Russian-Ukrainian dispute (for natural gas) in 2009, the European Parliament established specific regulations (for further details on the regulations please access measure No 994/2010 [4]) that created ways to ensure gas imports [13].

Natural gas has a great advantage over electricity because it can be stored [18,19]. In addition, [20] reports that natural gas, contrary to electricity, does not have what can be described as "captive uses", forcing natural gas to be market competitive with its substitutes, at least in industrial, domestic, and tertiary sectors.

Golombek et al. [21] pointed out the various effects of partial liberalization of energy markets and stresses that liberalization causes higher CO_2 emissions using fossil fuels. Based on extended tests of the proposed model, there would be an increase of approximately 8% in CO_2 emissions from Western Europe in a scenario of complete liberalization. Also, according to the model, even with the increase in emissions, the proportion of the overall increase in welfare that would be generated by liberalization is valid [21].

The International Energy Agency [22] highlights that the substitution of coal with natural gas leads to a reduction in the emission of CO_2 and methane in the energy sector by 50% and by 33% in the heating sector. In addition, natural gas is the cleanest source compared to other non-renewable energy sources [18]. Another advantage is the backup function for electricity production when renewable sources do not operate [23].

All over the world, several contemporary authors have studied the relationship between natural gas consumption and economic growth. See Table 1.

Table 1. Literature on gas consumption and growth.

Author(s)	Features
[2]	Natural gas and electricity were the main sources of energy that were consumed by the EU industrial sector between 1995 and 2019
[24]	Natural gas consumption provided economic growth in China, but no relationship between these variables occurred in India in the short-run. However, there is a two-way causal relationship between natural gas consumption and economic growth in the long run.
[25]	A non-linear programming approach predicts the wider inter-regional and inter-industry impacts of natural gas flow disruptions. The impacts on GDP are positive for the European Union and negative for Russia.
[26]	The natural gas shortage reduced Mexico's annual GDP growth rate by 0.28 percentage points in the second quarter of 2013. In addition, a 10% increase in natural gas supply shortages reduces industrial production by 0.32%.
[18]	Gas consumption and gross domestic product (GDP) growth are cointegrated. Therefore, there is feedback causality between gas consumption and long-run GDP growth.
[27]	The results provide evidence of the growth hypothesis in Iraq, Kuwait, Libya, Nigeria, and Saudi Arabia. Conservation hypothesis Algeria, Iran, United Arabian Emirates, and Venezuela. Further evidence suggests hypotheses of neutrality in Angola and Qatar.
[28]	The results indicate a positive relationship between economic development and natural gas consumption. In contrast, the relationship between natural gas consumption and economic development in the European Union is negative.
[29]	There is a cointegration relationship between natural gas consumption and economic development in China and Japan. In China, the results indicated the existence of a unidirectional causality of natural gas consumption to economic development. In Japan, there is a two-way causality between natural gas consumption and economic development.
[30]	Granger's causality test revealed two-way causality between natural gas energy consumption and GDP growth.

Table 1. *Cont.*

Author(s)	Features
[31]	Iran is considered a major world producer of natural gas. However, natural gas prices negatively and significantly impact natural gas consumption in Iran. Therefore, there is a positive impact on gas consumption growth.
[32]	Natural gas consumption, capital, labor, and exports positively affect Pakistan's economic growth. Therefore, the hypothesis of natural gas consumption growth is also supported, and it is suggested that natural gas conservation policies may delay economic growth.

The enormous importance of natural gas for the development of nations goes beyond the articles and its importance in world geopolitics. For example, the main gas-producing countries, such as Iran, have their economy strongly influenced by their price, as the increase in price harms domestic gas consumption, which in turn harms economic growth [31]. Alcaraz & Villalvazo [26] present another example of this direct relationship between the availability of natural gas and the country's growth in Mexico, which, in 2013, faced a severe lack of gas supply due to a significant increase in consumption, which was not accompanied by investments in infrastructure. This lack of supply was responsible for a 0.28% reduction in the Mexican GDP in the second quarter of 2013 alone.

Due to its direct relationship with economic growth and the increased regulation of CO_2 emissions, natural gas consumption has been represented in many countries as an important source of electricity generation [18]. Table 2 shows the relationship between electric energy consumption and economic growth.

Table 2. Literature on electricity consumption and economic growth hypotheses.

Author(s)	Features
[33]	The increasing production of economic activities consumes much energy. Consequently, this leads to an increase in CO_2 emissions.
[34]	The energy field plays a critical role in countries' growth
[35]	Energy use is essential to promote economic activity but generates environmental problems.
[36]	Proposes that new variables be related to nexus energy-growth.
[37]	Within the extended Nexus of Fuinhas & Marques (2019), the authors relate carbon dioxide emissions and economic growth to domestic credit to verify its effect on self-income economies.
[38]	Link the globalization process and its dimensions with energy consumption levels with the analysis of urbanization and economic growth.
[39]	Analyze the impact of renewable energy consumption on economic welfare using panel data techniques.
[40]	It is a recent study on the link between energy consumption and economic growth.
[41]	Perform a meta-analysis of 51 published studies, given worldwide since 1949, on the relationship between energy consumption and GDP growth.
[42]	Panel analysis. Relationship between economic growth and pressure on nature from environmental sustainability.
[43]	Forecast 2005–2035, China will replace the United States as the world's leading embodied energy consumer by 2027, when per capita energy consumption will be a quarter of the United States.
[44]	Study of the use of renewable energy in European countries, through panel data techniques.

Table 2. *Cont.*

Author(s)	Features
[45]	Studied the assumptions associated with the causal relationship between electricity consumption and economic growth.
[46]	The literature between growth and energy is not conclusive on the main hypotheses.
[47]	The causality test is applied to examine the causal relationship between primary energy consumption (EC) and actual gross domestic product (GDP) for Turkey during 1970–2006.
[48]	It is a pioneering test to prove the US's causal relationship between Energy and GDP.

Several studies from several countries report the importance of the relationship between electricity consumption and economic growth. The neutrality, feedback, growth, and conservation hypotheses are usually tested and verified for sets of countries or time-series analyses. Belucio & Fuinhas [49] stated that, in a certain way, electricity consumption can be considered a proxy variable for the general sophistication of a society/economy.

The concern to promote economic development allied with gas emissions control passes through great environmental responsibility goals. In 2019, at COP 25 in Madrid, the need to take even more extreme measures than those that were agreed upon in Paris 2015 during COP 21 was noted, where world leaders accepted the measures that were proposed by the UN (United Nations Organisations) to reduce greenhouse gas emissions [50–52].

However, there was no consensus on the measures to be taken. The discussion was postponed since several developing countries, such as Brazil and China, are unwilling to take drastic measures to reduce CO_2 emissions. Another significant change in the global scenario was the USA's departure, the second-largest CO_2 emitter in the world, from the Paris Agreement in 2017, seriously compromising the viability of the goals set so far.

Natural gas is an important fuel source for Europe and is expected to remain so for the next decades [53]. However, the way this gas is extracted has changed in recent years, with a significant increase in the extraction of so-called shale gas. According to the Energy Information Administration [54], shale gas is natural gas that is trapped in small pores inside shale formations (more frequent), sandstone, and other sedimentary rocks.

The world's reserves of shale gas are vast and also, according to the Energy Information Administration [55], it is estimated that only in technically recoverable reserves outside the USA, there are 6914.1 trillion cubic feet (195.79 trillion cubic meters) of shale gas, with China having the most significant reserves. However, the United States is now the world's largest producer, which pioneered the development of extraction technologies and increased the percentage of extracted shale gas concerning the total natural gas produced from 1.6% in 2000 to 23.1% in 2010 [26].

Also, in 2019 the Energy Information Administration [54] estimates that dry shale gas production amounted to 25.28 trillion cubic feet (715.85 billion cubic meters), accounting for 75% of the total dry natural gas production in the USA (the main gases on the market are wet natural gas and dry natural gas. Wet gas is composed of several other gases besides methane, making its use as fuel unfeasible. It does not reach the consumer without going through the processing that turns it into dry natural gas, composed almost solely of methane. This, in turn, is the gas that runs through pipelines and is delivered to the final consumer). This significant increase in production caused a drop in the price of natural gas in the USA market, from $7.7 per thousand cubic feet (28.31 cubic meters) in 2007 to $3.8 in 2012 [26].

In the environmental aspect, there is much discussion about the increase in shale gas extraction to the increase in greenhouse gas emissions [56]. According to [57], fugitive (fugitive emissions are the diffuse emissions that occur during the process of extraction, refining and transport of gas, mainly through leaks) greenhouse gas emissions from shale gas extraction in 2010 corresponded to 3.6% of all emissions that related to natural gas.

According to an analysis of methane emissions from shale gas extraction, between 3.6% and 7.9% of the extracted methane escapes into the atmosphere during the lifetime of an extraction well [58]. Also, according to this research, the environmental impact of methane greenhouse gases is greater than that of conventional gas or petroleum for any time horizon observed, especially from 20 years [58].

3. Methodology

3.1. Data

The time horizon comprises of data from 1993 to 2018 for sixteen countries (Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Luxembourg, Ireland, Italy, Netherlands, Poland, Spain, and Sweden). Initially, 25 countries were considered for the study, but the reduction was inevitable due to the lack of statistical data.

Table 3 shows, in detail, the variables that seek to explain the phenomenon of emissions, the origin of the data, and the transformations to which the variables were submitted.

Table 3. Variables.

Variables	Abbreviation	Base	Unit	Transformations
CO_2 emissions	CO_2pc	BP	Million tonnes	It is divided by the population to transform the variable into its per capita (PC) value.
Natural gas consumption	ngcpc	BP	Millions of tons of oil equivalent	It is divided by the population to transform the variable into its per capita (PC) value.
Renewables and Hydroelectric consumption	rchcpc	Author, own calculations based on BP	Millions of tons of oil equivalent	It is the sum of renewable and hydroelectric consumption. It is divided by the population to transform the variable into its per capita (PC) value.
Oil consumption	ocpc	BP	Millions of tons of oil equivalent	It is divided by the population to transform the variable into its per capita (PC) value.
Gross Domestic Product	gdp	World Bank	Constant LCU	It is divided by the population to transform the variable into its per capita (PC) value.

Notes: The population data were obtained from the "World Development Indicators" of the World Bank (WB) and are measured by the total number of persons; the renewables and hydroelectric consumption data was retrieved from the BP "Statistical Review of World Energy" and are both measured in millions of tons of oil equivalent.

In Table 4, the descriptive statistics are presented. The acronyms "l" and "dl" in front of the variables mean that they were transformed into natural logarithms and first differences, respectively. Again, the number of observations makes it possible to confirm that the panel is balanced.

Table 4. Descriptive statistics.

Variable	Obs.	Mean	Std. Dev.	Min.	Max.
lCO_2pc	416	2.20569	0.3777207	1.456253	3.331839
lgdppc	416	11.13046	1.37738	9.54555	15.19928
lngcpc	416	−0.4648637	0.9243719	−5.483719	0.9595549
locpc	416	−13.32239	0.5286551	−14.78923	−11.88321
lrchcpc	416	−15.53361	1.396328	−19.22397	−12.95452
$dlCO_2pc$	400	−0.0090524	0.0509482	−0.2076705	0.1845551
dlgdppc	400	0.0190884	0.0280064	−0.0942888	0.2149944
dlngcpc	400	0.0162301	0.1318025	−0.6753016	1.404376
dlocpc	400	−0.0005098	0.0454565	−0.1489391	0.1560745
dlrchcpc	400	0.067968	0.1579153	−0.5162868	1.026718

It is possible to measure the degree of linear association between the variables by the correlation matrix (Table 5), in which we can have three possible results: (i) negative correlation, that is, when one increases, the other always decreases; (ii) positive correlation, shows that the variables vary in the same direction; and (iii) neutral, when the variables do not depend linearly on each other.

Table 5. Correlation Matrix.

	lCO_2pc	lgdppc	lngcpc	locpc	lrchcpc
lCO_2pc	1.0000				
lgdppc	−0.2070	1.0000			
lngcpc	0.4397	0.0102	1.0000		
locpc	0.6721	−0.2885	0.2944	1.0000	
lrchcpc	−0.2449	−0.1119	−0.2457	0.1987	1.0000
	$dlCO_2pc$	**dlgdppc**	**dlngcpc**	**dlocpc**	**dlrchcpc**
$dlCO_2pc$	1.0000				
dlgdppc	0.3305	1.0000			
dlngcpc	0.3669	0.1532	1.0000		
dlocpc	0.5675	0.4843	0.1770	1.0000	
dlrchcpc	−0.2375	0.0502	−0.1182	−0.0551	1.0000

The matrix of correlations shows an apparent absence of collinearity since all the coefficients are below 70%. Although, in order to confirm the existence or not of multi-collinearity, we also conduct the VIF (variance inflation factor) test. Multicollinearity can cause distortions in the results, so it is always important to check the statistics. The results of the VIF statistics are shown in Table 6.

Table 6. VIF Results.

Dependent Variable: $dlCO_2pc$			Dependent Variable: lCO_2pc		
Variables	**VIF**	**1/VIF**	**Variables**	**VIF**	**1/VIF**
dlocpc	1.33	0.750125	locpc	1.30	0.766698
dlgdppc	1.33	0.753464	lngcpc	1.23	0.810356
dlngcpc	1.05	0.949279	lrchcpc	1.16	0.858642
dlrchcpc	1.03	0.975430	lgdppc	1.10	0.906230
Mean VIF	1.18		Mean VIF	1.20	

Table 6 confirms that multicollinearity is not a problem for estimating the model, given that the VIF values were all slightly above 1, not reaching the usually accepted benchmark of 10 (if they surpassed this value, multicollinearity could be a problem).

We also conducted Pesaran's [59] cross-sectional dependence (CD) test (Table 7). Again, the test's null hypothesis, cross-sectional independence, was rejected, meaning that our panel countries share an interdependency and are susceptible to the same shocks.

Table 7. Cross-sectional independence.

Variable	CD-Test	*p* Value	corr	abs(corr)
lCO_2pc	38.58	0.000	0.691	0.702
lgdppc	48.37	0.000	0.866	0.866
lngcpc	28.24	0.000	0.505	0.563
locpc	17.88	0.000	0.320	0.538
lrchcpc	43.59	0.000	0.780	0.780
$dlCO_2pc$	17.78	0.000	0.325	0.347
dlgdppc	35.14	0.000	0.642	0.642
dlngcpc	24.49	0.000	0.447	0.451
dlocpc	14.93	0.000	0.273	0.292
dlrchcpc	5.06	0.000	0.092	0.239

Note: The CD test has N(0,1) distribution under the H_0: cross-sectional independence.

Finally, the unit root tests showed that our data are constituted by I(0) and I(1) variables and that no variable showed signs of being I(2). The details of the unit root tests are shown in Table A1 in the Appendix A. The unit root testing was conducted by using the Pesaran [60] CIPS test, which is robust to the phenomenon of cross-section dependence.

3.2. Methodology

This study's methodological approach was based on the autoregressive distributed lag (ARDL) model in the form of an unrestricted error correction model (UECM). This approach enables us to inquire about the explanatory variables' short- and long-run effects on the dependent variable. Additionally, the ARDL model has the advantage of being appropriate in the presence of cointegration and endogeneity, produces efficient estimates with relatively small or moderate samples, and allows the incorporation of I(0) and I(1) variables in the same estimation. This last point is especially important given that the unit root tests (Table A1) indicated the presence of variables in both integration orders (I(0) and I(1)). In Equation (1), we present the ARDL model specification in the form of an unrestricted error correction model (UECM):

$$\begin{aligned} dlco2pc_{it} = {} & \alpha_{1i} + \beta_{1\,1} dlgdppc_{it} + \beta_{1\,2} dlngcpc_{it} + \beta_{1\,3} dlocpc_{it} + \\ & \beta_{1\,4} dlrchcpc_{it} + \gamma_{1\,1} lco2pc_{it-1} + \gamma_{1\,2} lgdppc_{it-1} + \gamma_{1\,3} lngcpc_{it-1} + \\ & \gamma_{1\,4} locpc_{it-1} + \gamma_{1\,5} lrchcpc_{it-1} + \varepsilon_{it} \end{aligned} \tag{1}$$

where the α_i represents the intercept, β_{it} and γ_{it}, with t = 1, ... , 5 denotes the estimated parameters, while ε_{it} represents the error term. Again, the prefixes "l" and "dl" denote natural logarithms and first differences, respectively. After this brief explanation of the methodological approach, in the following section, we will present the results from our model and their subsequent discussion.

4. Results and Discussion

Before proceeding with the model estimation, some specifications need to be checked. First, the Hausman test [61] translates into a clarification of which specification is the most correct for the proposed data panel analysis: the rando effects (RE) or the fixed effects (FE)? The test has the following null hypothesis: the random effects are the most suitable specification. If we reject the null, the fixed-effects specification is the most suitable. The outcomes of the Hausman test, with (chi2(9) = 42.00 with Prob > chi2 of 0.000) and without (chi2(9) = 46.41 with Prob > chi2 of 0.000), the Stata sigmamore option (which reflects more robust results), were unanimous, indicating the fixed effect specification has the most suitable one. Next, we computed a series of specification tests to decide on the best-suited estimator to conduct the analysis. Table 8 presents the results of the specification tests.

Table 8. Specification's tests.

Test	Statistics
Modified Wald's test	347.72 ***
Pesaran's test	8.350 ***
Friedman's test	85.412 ***
Wooldridge's test	32.875 ***
Breusch-Pagan LM test	228.321 ***

Notes: H_0 of Modified Wald's test: sigma(i)ˆ2 = sigmaˆ2 for all I; H_0 of Pesaran's test: residual are not correlated; H_0 of Friedman's test: residual are not correlated; H_0 of Wooldridge's test: no first-order autocorrelation; H_0 Breusch-Pagan LM test of independence is that residuals across entities are not correlated; *** denotes statistical significance at 1% level.

In Table 8, we show the results from the modified Wald's test [62], Wooldridge's test [63], Pesaran's [59], and Friedman's tests [64] for cross-sectional independence, and the Breusch-Pagan Lagrange multiplier (LM) [65]. All the tests reject the null at the 1% level, meaning there is evidence of heteroscedasticity, first-order autocorrelation, and contemporaneous correlation in the model. Given these results, the use of the Driscoll & Kraay [66] estimator (fixed effects (FE)-DK) seems to be the most suitable option, given that it "*is capable of producing standard errors robust to the disturbances being cross-sectionally dependent, heteroskedastic, and autocorrelated up to some lag*" [67].

Before presenting the results, we should refer to that in the first model estimation, the variables "dlgdppc" and "lngcpc" were not statistically significant. Consequently, they were excluded from the model estimation. Therefore, the most parsimonious model has now the following specification (Equation (2)):

$$dlco2pc_{it} = \alpha_{2i} + \beta_{2\,1} dlngcpc_{it} + \beta_{2\,2} dlocpc_{it} + \beta_{2\,3} dlrchcpc_{it} + \gamma_{2\,1} lco2pc_{it-1} + \gamma_{2\,2} lgdppc_{it-1} + \gamma_{2\,3} locpc_{it-1} + \gamma_{2\,4} lrchcpc_{it-1} + \varepsilon_{it} \quad (2)$$

Additionally, six dummy variables were included in the model to correct the outliers that were detected in the residual's analysis (e.g., [68]). There were three dummies for Denmark (den1996, den2003, and den2006, for the years 1996, 2003, and 2006, respectively); two for Finland (fin2005 and fin2006, for the years 2005 and 2006, respectively); and one for Luxembourg (lux1995, for the year 1995) that were used. For Denmark, the explanations for these outliers were a peak in coal consumption and an increase in oil and gas in 1996, and peaks in coal consumption in 2003 and 2006. Finland experienced a sharp drop in coal consumption in 2005. However, it is unclear what caused the 2006 abnormal increase in CO_2 emissions (it may just be the effect of returning to the pre-existing situation). Luxembourg faced a sharp drop in coal consumption in 1995. In Table 9, we display the results from the model estimation (the specification tests from Table 8 were remade to ensure that the results concerning their null hypotheses stayed the same for this most parsimonious model). Moreover, we also present the results with the FE estimator to see the differences in using the FE-DK estimator.

Table 9. Estimation results.

Dependent Variable: $DLCO_2PC$	Coef.	FE	Coef.	FE−DK
Constant	2.4081	***	2.4081	***
den1996	0.1654	***	0.1654	***
den2003	0.1504	***	0.1504	***
den2006	0.1667	***	0.1667	***

Table 9. *Cont.*

Dependent Variable: $DLCO_2PC$	Coef.	FE	Coef.	FE−DK
fin2005	−0.1491	***	−0.1491	***
fin2006	0.1725	***	0.1725	***
lux1995	−0.1338	***	−0.1338	***
dlngcpc	0.0845	***	0.0845	**
dlocpc	0.5666	***	0.5666	***
dlrchcpc	−0.0497	***	−0.0497	***
$lCO_2pc(-1)$	−0.1473	***	−0.1473	***
lgdppc(−1)	−0.0382	**	−0.0382	*
locpc(−1)	0.1326	***	0.1326	***
lrchcpc(−1)	−0.0065		−0.0065	*
	Diagnostic Statistics			
N	400		400	
$\mathbf{R^2}$	0.6321		0.6321	
F stat	F(13, 371) = 49.04		F(13, 24) = 2065.38	
Prob	***		***	

Notes: ***, **, * denote statistical significance at 1%, 5%, or 10% level, respectively; the Stata command *xtscc* was used to estimate the models; The model was tested with the trend, but it was not statistically significant.

With the analysis of the results (Table 9), we see that the estimated coefficients have the expected signal according to economic theory. The ECM coefficient has the expected (negative) sign, which is within the expected range [−1; 0], being statistically significant at the 1% significance level.

Although the information is displayed in Table 9, we should note that the long-run elasticities are not shown in this table. This is because they had to be calculated by dividing the coefficients of the variables by the lCO_2pc (ECM) coefficient, both lagged once, and then we had to multiply this ratio by (−1). Table 10 shows the short-run impacts, the model speed of adjustment, and the computed long-run elasticities.

Table 10. Elasticities and speed of adjustment.

Dependent Variable: $DLCO_2$	Coef.	FE	Coef.	FE−DK
Short−run impacts				
dlngcpc	0.0845	***	0.0845	**
dlocpc	0.5666	***	0.5666	***
dlrchcpc	−0.0497	***	−0.0497	***
Long−run elasticities				
lgdppc(−1)	−0.2590	**	−0.2590	**
locpc(−1)	0.9002	***	0.9002	***
lrchcpc(−1)	−0.0442	*	−0.0442	*
Speed of adjustment				
ECM	−0.1473	***	−0.1473	***

Notes: *, **, and *** denote statistical significance at the 10%, 5% and 1% levels, respectively; the ECM denotes the coefficient of the variable LCO_2 lagged once.

As we can see by the results from Table 10, the impact of natural gas consumption on CO_2 emissions is positive and statically significant, but only in the short -un. This fact is not in line with, for example, the results from [69], who analyzed a similar relationship for the case of 14 Asia-Pacific countries, and whose results pointed to the existence of a short- and long-run relationship between natural gas consumption and CO_2 emissions. Nevertheless, this result probably derives from the fact that although for many years, natural gas has been seen as a precious energy source, the natural gas development in Europe has been suffering a deceleration due to environmental concerns, with policy-makers starting to primarily focus on the investment on renewable sources of energy [28]. This contrasts with the situation of Asia-Pacific countries, where it is predicted that natural gas consumption will continue to grow steadily in the future [70]. In addition, there is also the case of the extreme dependence of the European countries on, for example, Russian natural gas, a fact which also contributed to cooling the consolidation of natural gas in the energy mix of many European countries due to economic and political reasons [28]. Moreover, the fact that natural gas presents a positive coefficient is not surprising, given that although natural gas emits less CO_2 when it is compared with oil or coal, it still emits some amount of CO_2 [71].

Nevertheless, in the short-run, we see a great difference in terms of oil consumption vs. natural gas impacts. More precisely, when compared with oil consumption, natural gas has an impact that is 6.7 times lower on CO_2 emissions. Moreover, we should also stress that contrary to natural gas, oil consumption has also presented a positive and statistically significant effect on CO_2 emissions in the long run. This result was far from unexpected, given that oil consumption is considered one of the major contributors to CO_2 emissions increase [72].

Another result that is far from unexpected is the one from renewable and hydroelectric energy consumption. As we can see in Table 10, the energy consumption from this type of source negatively impacts CO_2 emissions both in the short- and long-run. However, in the long-run, the coefficient is only statistically significant at the 10% level. Despite this last fact, we can say that the estimation results corroborate the already widely accepted view that investment in renewables is one of the major strategies to reduce emissions in the short- and long-term [73].

Regarding the GDP, the results point to, in this group of countries, economic growth had been grounded in a way that contributes to the decrease in CO_2 emissions. More precisely, looking at Table 10, we see that the coefficient of GDP is revealed to have a negative sign and to be statistically significant at the 1% level in the long-run. This result is similar to the one from Dogan & Aslan [74], who analyzed a similar relationship for the case of a panel of EU countries and candidate countries. The authors also found a negative coefficient for the case of the effect of GDP on emissions, with this result following the Environmental Kuznets Curve (EKC) hypothesis. Indeed, the authors state that since their sample is primarily composed of high-income and upper-middle-income countries, the countries from their panel should be beyond the threshold level, enabling "increases in real income lead to environmental improvements" [74].

Finally, the ECM coefficient (i.e., the model's speed of adjustment) is negative and statistically significant at the 1% level, as it should, and has a value of 14.73%, which is fast enough for the model to achieve the equilibrium in the medium-run.

5. Conclusions

A per capita analysis of natural gas' impact on carbon dioxide emissions was performed for sixteen European countries from 1993 to 2018. An autoregressive distributed lag (ARDL) model in the form of an unrestricted error correction model, controlling for the variable's renewables and hydroelectric consumption, oil consumption, and gross domestic product was used to conduct the analysis. The ARDL approach is a robust econometric technique that identifies the short-run impacts, the long-run elasticities, and the speed of adjustment in the variables' relationships.

Denmark (in 1996, 2003, and 2006), Finland (in 2005 and 2006), and Luxembourg (in 1995) suffered shocks in CO_2 emissions that can be related to changes in their energy mix. Furthermore, these outliers can be related to atypical coal consumption, stressing that alterations in the energy mix favoring coal use result in additional environmental damage. To cope with these outliers, "country-year" impulse dummies were included in the models' estimation. This artifact allows for modeling of the relationships without being disturbed by the anomalous events on CO_2 emissions.

The results from the ARDL model were essentially the following: (1) natural gas consumption has a positive impact on carbon dioxide emissions in the short-run; (2) oil consumption has a positive impact on carbon dioxide emissions both in the short- and long-run; (3) renewables and hydroelectric energy consumption have a negative impact on carbon dioxide emissions both in the short- and long-run; and (4) the GDP has a negative impact on carbon dioxide emissions in the long-run.

Due to these results, we can state that, first, it seems that this group of countries is being able to reduce the environmental impacts (measured by CO_2 emissions) of their economic activity. The fact that GDP presents a negative coefficient in the long-run highlights the environmental improvements that are made in these economies and follows the EKC hypothesis (we should not forget that the countries from our sample are mostly high-income or upper-middle-income economies). In this sense, these countries should continue on this path. More appropriately, these countries' governments should continue to promote the energy transition process in their respective economies. The importance of such a transition becomes clear when we look at the impacts of oil consumption vs. renewables/hydroelectric consumption on CO_2 emissions. Suppose these countries want to decrease their level of emissions. In that case, they need to continue to support the promotion of low carbon energy sources, with the increase of the share of renewables in their energy mix and, at the same time, reduce the dependence of their economic activity on fossil fuels, as well as the incentives to the use of this type of energy (e.g., fossil fuel subsidies). Regarding natural gas consumption, we can state that the lack of a statistically significant long-term effect does not fully allow us to develop more profound political implications regarding this energy source. Strictly speaking, although theoretically natural gas is seen as an effective alternative to reduce greenhouse gases (it emits a significantly lower level of emissions during combustion when compared with oil and coal), the lack of a long-run relationship between this energy source and CO_2 emissions does not allow us to completely corroborate this hypothesis for the sample of countries under study. However, even with the absence of a statistically significant effect in the long-run, if we compare the overall effects of natural gas and oil on CO_2 emissions, it seems that the use of natural gas is indeed less harmful to the environment than oil (in the short-run, natural gas has an impact that is 6.7 times lower on CO_2 emissions). Thus, we can say that, by the results that were achieved, it appears that having to use non-renewable energy, governments should continue to prefer natural gas over oil.

Given this last issue/limitation (the lack of a statistically significant effect from natural gas in the long run), future investigations on this thematic should be centered on a panel of European countries where natural gas already has a considerable weight in their energy mix and where the natural gas industry is already at an adequate level of development. This approach is required to obtain more robust results regarding the impact of natural gas on CO_2 emissions.

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Appendix A

Table A1. Unit roots test Pesaran [61] Panel Unit Root test (CIPS).

Without Trend				With Trend			
Variable	**Lags**	**Zt−bar**	***p*-Value**	**Variable**	**Lags**	**Zt−bar**	***p*-Value**
lCO_2pc	0	−3.259	0.001	lCO_2pc	0	−3.062	0.001
lCO_2pc	1	−2.110	0.017	lCO_2pc	1	−1.861	0.031
lgdppc	0	1.643	0.950	lgdppc	0	1.573	0.942
lgdppc	1	−1.599	0.055	lgdppc	1	−1.683	0.046
lngcpc	0	−3.092	0.001	lngcpc	0	−4.825	0.000
lngcpc	1	−1.553	0.060	lngcpc	1	−4.028	0.000
locpc	0	0.443	0.671	locpc	0	−3.233	0.001
locpc	1	1.354	0.912	locpc	1	−2.053	0.020
lrchcpc	0	−3.525	0.000	lrchcpc	0	−3.193	0.001
lrchcpc	1	−1.93	0.027	lrchcpc	1	−1.185	0.118
$dlCO_2pc$	0	−13.29	0.000	$dlCO_2pc$	0	−11.987	0.000
$dlCO_2pc$	1	−9.44	0.000	$dlCO_2pc$	1	−7.86	0.000
dlgdppc	0	−5.770	0.000	dlgdppc	0	−3.805	0.000
dlgdppc	1	−3.938	0.000	dlgdppc	1	−2.137	0.016
dlngcpc	0	−11.614	0.000	dlngcpc	0	−9.811	0.000
dlngcpc	1	−8.741	0.000	dlngcpc	1	−6.51	0.000
dlocpc	0	−12.596	0.000	dlocpc	0	−11.217	0.000
dlocpc	1	−7.988	0.000	dlocpc	1	−5.849	0.000
dlrchcpc	0	−13.933	0.000	dlrchcpc	0	−12.567	0.000
dlrchcpc	1	−8.284	0.000	dlrchcpc	1	−6.534	0.000

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The Impact of Energy Policies on the Energy Efficiency Performance of Residential Properties in Portugal

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Abstract: The effect of energy policies on the energy performance of residential properties/houses in nineteen Portuguese districts from 2014 to 2021 was investigated. A linear random-effects model regression was used as the method in this empirical investigation. The empirical results indicated that the income per capita has a negative effect on residential properties with high energy efficiency certificates (e.g., **A+**, **A**, and **B**) and a positive impact on residential properties with low energy efficiency certificates (e.g., **C**, **D**, **E**, and **F**); the codes and standards energy policies for energy efficiency have a positive effect on residential properties with high energy efficiency certificates (e.g., **A**, **B**, and **B−**) and residential properties with low energy efficiency certificates (e.g., **C**, **D**, **E**, and **F**); the fiscal and financial incentive policies for energy efficiency have a positive effect on residential properties with high energy efficiency certificates (e.g., **A+**, **A**, and **B**) and a negative effect on residential properties with B− energy certificate, and also a negative effect on residential properties with low energy efficiency certificates (e.g., **C** and **D**) and a positive effect on residential properties with an F energy certificate; the information and education policies of energy efficiency have a positive effect on residential properties with high energy efficiency certificates (e.g., **A+**, **A**, and **B**) and residential properties with low energy efficiency certificates (e.g., **C**, **D**, and **E**); and, finally, the consumer credit per capita has a positive effect on residential properties with high energy efficiency certificates (e.g., **A+**, **A**, and **B**) and a negative effect on residential properties with low energy efficiency certificates (e.g., **C**, **D**, and **F**), as well as a positive effect on residential properties with an F energy certificate.

Keywords: energy efficiency; econometrics; EPCs; incentive policies; Portugal

1. Introduction

Although energy consumption is a key element of economic development, high energy consumption has caused climate change and greenhouse gas emissions. Thus, countries, including those in the European Union (EU), have based their policies on energy efficiency. In most countries, a significant percentage of the total final energy consumption is related to the residential sector. Although energy consumption in the building sector of Europe has not increased significantly in recent years, 40% of the total energy consumption in Europe, about one-third of the emissions of greenhouse gas, and 36% of the carbon emissions, which all cause climate change, are due to energy consumption in the residential sector (e.g., De- Boeck et al. [1], Wang et al. [2], Li et al. [3], and the European Commission [4]). Numerous factors affect energy consumption in the residential sector, which has made this sector complex [5]. So, the residential sector is the main target of many EU energy efficiency policies and an excellent opportunity to decrease energy consumption. Indeed, the residential sector has made the most progress in energy efficiency compared to other sectors. On the other hand, the most economical method of reducing energy consumption in buildings is achieved through energy efficiency measures (e.g., Ramos et al. [6], Pablo-Romero et al. [7], and Palma et al. [5]). Given the impact of the building sector on the environment, the study of energy efficiency in this sector should focus on energy policies.

Southern European countries, such as Portugal, have different economic, cultural, and climatic characteristics than northern European countries. The final energy consumption for cooling and heating in the residential sector is very different in European countries, and southern European buildings are less adaptable to severe climate change than northern European buildings. In addition, there are many concerns about energy efficiency in southern European countries due to the increasing demand for cooling and heating systems [5]. Therefore, the study of southern European countries can provide different and important results for implementing policies. On the other hand, a case study is necessary to provide policies following the climatic characteristics of each country. In a southern European country (Portugal), the residential sector consumes 18.2% of the total energy consumption [8].

The Energy Performance Guidelines for buildings are a popular policy initiative proposed by the European Union to address climate change and energy efficiency issues. One of these measures is the directive for using energy performance certificates (EPCs) to analyse the residential sector energy performance (e.g., Abela et al. [9] and Lee et al. [10]). The European Commission introduced the EPC building directive in 2002, which required member countries to implement EPC certifications [11]. The purpose of providing these guidelines is information transparency and reducing asymmetries in the information concerning the energy efficiency of residential units, to achieve the goals of improving energy efficiency and reducing the energy consumption of buildings [12]. Transparency of information on energy efficiency leads owners of residential units to provide EPC certification to potential buyers and tenants at the time of sale and rent. With EPCs, buyers and tenants can easily access fast, reliable, and accessible information (e.g., Lee et al. [10], Gouveia and Palma [13], Dell-Anna et al. [14], and Franke and Nadler [15]). Therefore, EPCs evaluate the performance and energy efficiency of the building. In addition, an EPC can encourage people to renovate their buildings to save energy [3].

Residential property owners are interested in getting higher EPCs because buildings with higher EPCs have higher prices due to higher energy efficiency (e.g., Brounen and Kok [16], Cajias and Piazolo [17], Hyland et al. [18], Fuerst et al. [19], and Stanley et al. [20]). On the other hand, according to the European Commission, renovation can save up to 46% of the energy consumption [4]. Therefore, the EPC rating process encourages the owners to save energy by upgrading their building energy efficiency. It also presents an occasion to train them about energy efficiency and recommends various actions that can quickly improve the energy performance of residential units to owners. With a small investment in energy efficiency, technologies can easily be upgraded to a higher EPC (e.g., Collins and Curtis [12] and Comerford et al. [21]). Unfortunately, there is no standard framework for EPC delivery in member countries [14].

The building energy certification system was implemented in Portugal in 2008, where all new residential buildings were required to have an energy performance certificate [22]. Moreover, since 2009, it is mandatory in Portugal that all buildings have a valid energy certificate. Therefore, the EPCs became mandatory in the country with Decree-Law no. (118/2013) of 20 August 2013, which follows Directive (2010/31/EU). As a result, Portugal issued 13,799 certificates in 2008, and in 2020 issued 198,090 (see Figure 1 below).

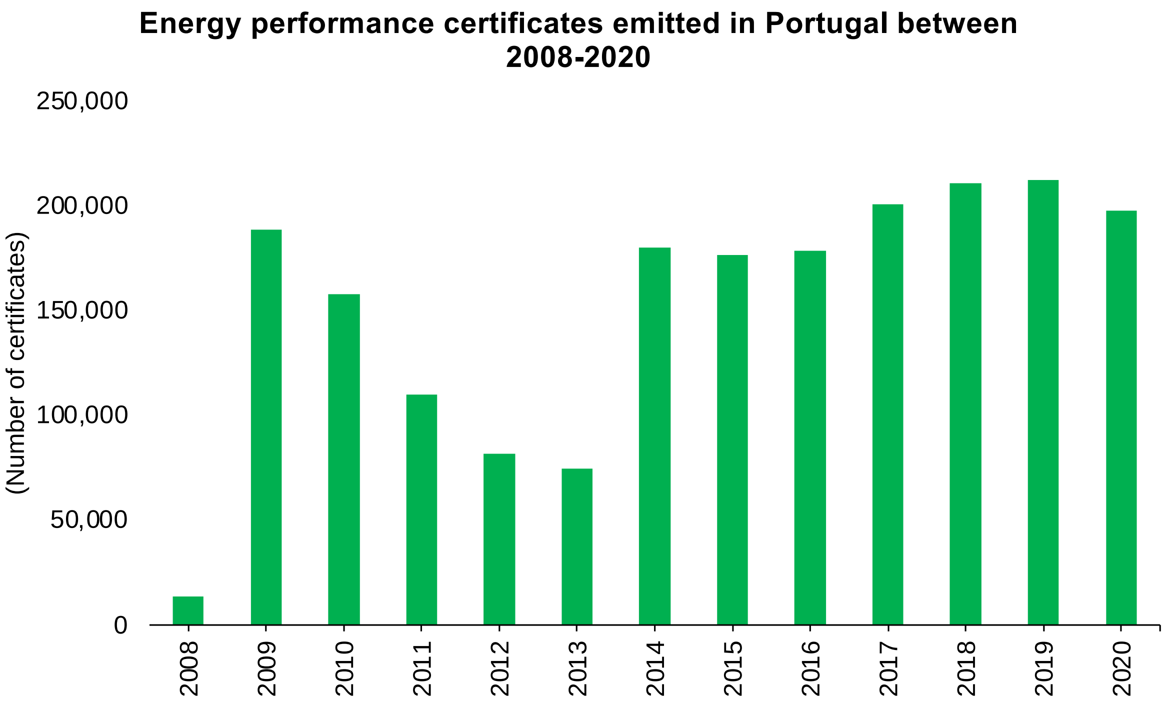

Figure 1. EPCs issued in Portugal between 2008 and 2020. This figure was created with data from *Observatório da Energia* [23].

Indeed, when we address the number of issued energy certificates by energetic class in Portugal, we can see that in 2008 the energy certificate with ratings **B** and **B+** were the most issued, with 4164 and 1635 certificates, respectively, while there were issued 141 for rating **C**, 75 for rating **D**, 14 for rating **E**, 4 for rating **F**, and 11 for rating **G**. In 2014, the energy certificates with a rating of **C** and **D** were the most issued, with 58,209 and 46,661 certificates, respectively, while there were issued 1893 for rating **A+**, 7018 for rating **A**, 12,950 for rating **B**, 19,171 for rating **B−**, 24,379 for rating **E**, and 9758 for rating **F**. Moreover, in 2020, the energy certificates with ratings of **C** and **D** were the most issued, with 41,347 and 34,961 certificates, respectively, while there were issued 31,185 for rating **B**, 20,155 for rating **B−**, 21,720 for rating **E**, and 12,933 for rating **F** (see Figure 2 below).

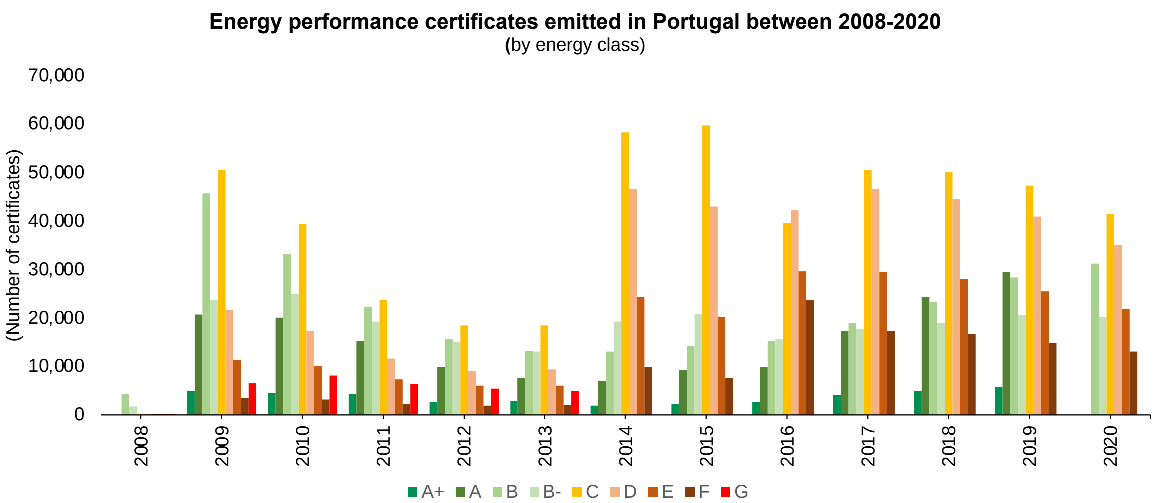

Figure 2. EPCs issued by type of energy class in Portugal between 2008 and 2020. This figure was created with data from *Observatório da Energia* [23].

Indeed, the increase in the number of energy certificates with high ratings (e.g., **A+ A**, **B**, and **B−**) is essential for Portugal to reduce the household energy consumption, where this sector consumed (18.2%) of the total energy consumption in 2019 (see Figure 3 below).

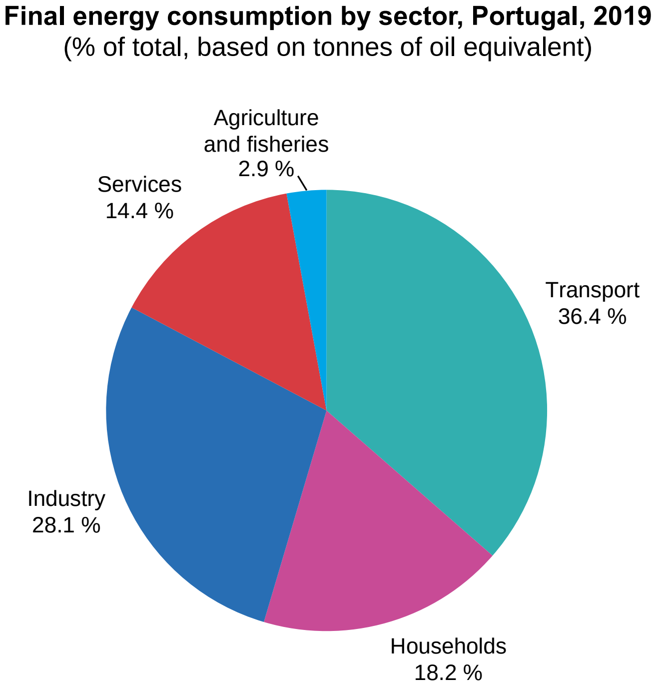

Figure 3. Final energy consumption by sector in Portugal in 2019. This figure was created with data from PORDATA [24].

Moreover, in 1990, the consumption of energy from the household sector was 2301.6 Mtoe, and in 2000 this value reached 2820.9 Mtoe, and in 2019 reached a value of 2891.3 Mtoe. During the period between 1990 and 2019, the consumption of energy from the household sector increased 26% despite the 6.51% drop in 2011, 3.04% drop in 2012, and 2.28% drop in 2013 caused by the financial and economic crisis that occurred in this period (see Figure 4 below).

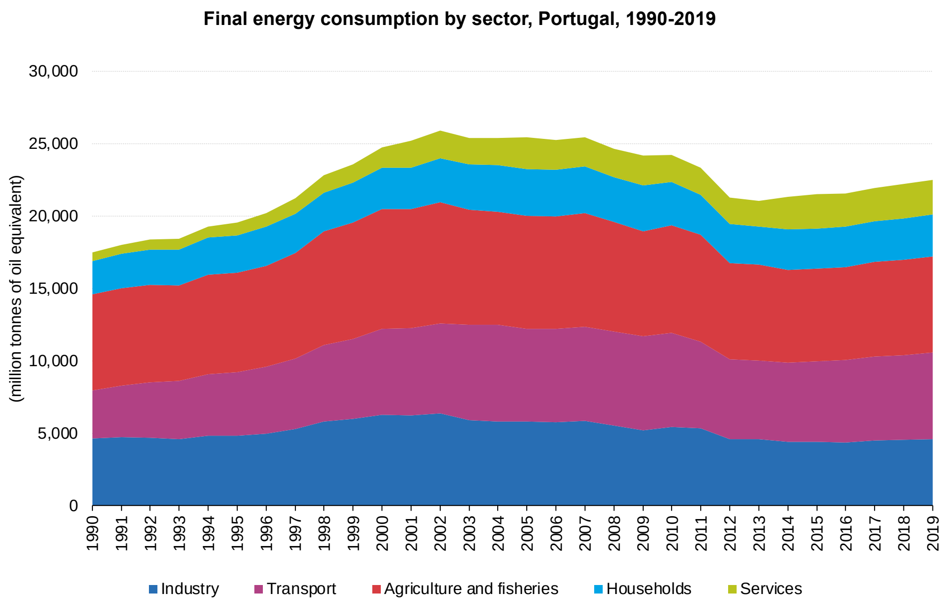

Figure 4. Final energy consumption by sector in Portugal between 1990 and 2019. This figure was created with data from PORDATA [24].

Indeed, when we addressed the gross inland energy consumption by fuel in Portugal, we identified that the oil and petroleum products had a 42.6% share in the energetic mix, while for the EU, this value is 34% in 2019. Solid fossil fuels had a share of 11.2%, natural gas 21%, and renewables and biofuels 25.2%, while in the EU, these values are 11.6%, 23.1%, and 15.8%, respectively (see Figure 5 below).

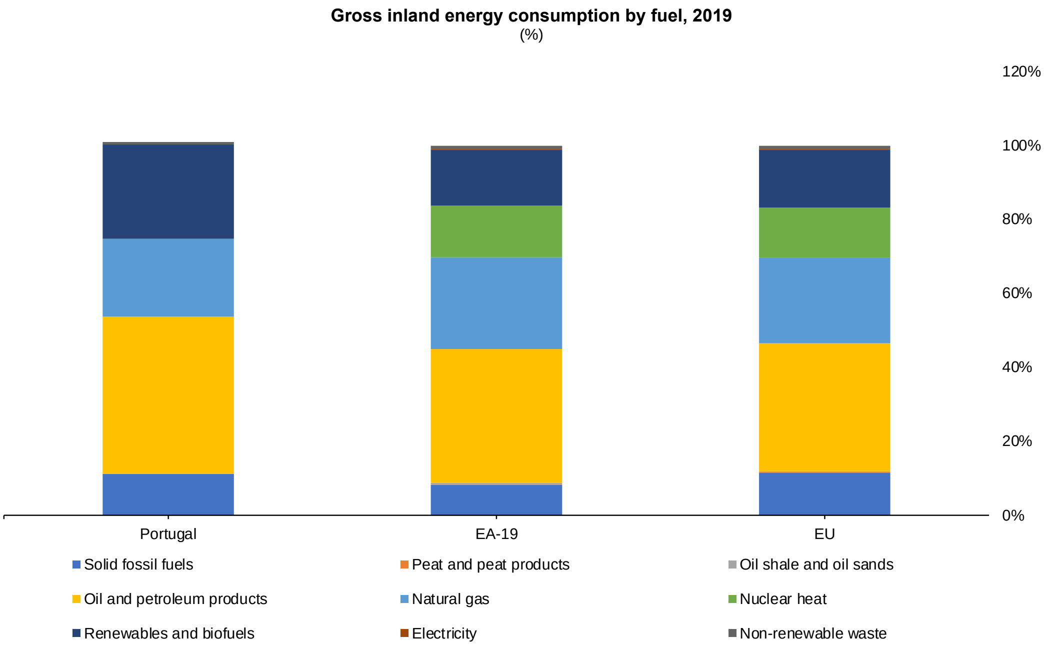

Figure 5. Final energy consumption by sector in Portugal between 1990 and 2019. This figure was created with data from Eurostat [25].

As shown in the figure above, the fossil fuel energy source share represented 74.8% of the energy mix of Portugal in 2019. For this reason, the adoption of EPCs is essential to reduce energy consumption by households in order to mitigate climate change.

Previous studies have analysed various energy efficiency policies (e.g., energy efficiency labels, standards and codes, financial and credit incentives, information policies, and regulatory standards) in the EU and different countries. Some studies have suggested that financial and credit incentives increase energy efficiency (e.g., Noaily [26], Filippini et al. [27], and Trotta et al. [28]). Financial instruments were introduced in 2017 to support investment in urban rehabilitation and renovation of buildings, insulation, and efficient equipment purchase [8]. Some studies have shown that regulatory standards and major renovations reduce energy demand [29]. Broin et al. [30] argued that information policies increase energy efficiency. Another solution is to achieve higher energy efficiency in the residential sector through building codes [28].

Despite the rapid release of EPCs and similar tools, no studies are examining the impact of energy efficiency policies on the energy performance of residential properties in Portugal. This study uses energy codes and standards related to buildings, information policies, financial incentives, and residential sector credit as proxies for energy efficiency policies. In addition, the effect of per capita production on buildings' energy performance was studied. Increasing household per capita income also improves energy efficiency because wealthier households renovate buildings and install heating and cooling systems and air conditioning with better and newer technologies in energy consumption (e.g., Saussay et al. [31] and Broin et al. [30]).

A case study to match the specific characteristics of each country can offer different scales of space and time and provide new policies and insights for other countries [32]. Portugal is a good and interesting case study for several reasons: (1) The level of access to EPC databases varies in different European countries, but the Portuguese database is one of the first databases. (2) Many Portuguese buildings are old and were built before 1990, affecting energy consumption. About 50% of buildings in Portugal need renovation, so some studies have considered the issues and problems related to Portugal's energy shortage to be related to its residential sector (e.g., Simoes et al. [33], Gouveia et al. [32], and Palma et al. [5]). Portugal was one of the first countries to adopt the EPC guidelines and implement them fully and correctly in its own country. So, consumers in Portugal have much information about EPCs. In addition, Portugal is warmer than northern European countries, which significantly affects consumer preferences for EPC properties. The residential sector's final energy consumption per capita of Portugal is lower than the European mean, even in countries with comparable climates such as Spain and Italy (e.g., Ramos et al. [6] and Palma et al. [5]). Therefore, a case study of Portugal can provide interesting and meaningful results for policymakers.

Most studies of European countries have examined one or two variables of energy efficiency policy. In this study, to complete the previous studies and fill the gap of prior studies, the effect of several energy efficiency policies on energy performance in the residential sector of a southern European country was considered. To our knowledge, our study is the first one that analyses the impact of energy efficiency policies on residential properties' energy performance in Portugal. This study, therefore, goes a step further and develops an analysis of energy efficiency policies.

According to the above, in this paper, we seek to answer whether energy efficiency policies affect the energy efficiency performance of residential properties/houses in nineteen Portuguese districts from 2014 to 2021. Which energy efficiency policy variables have the most significant effect on energy efficiency in the Portuguese building sector? To answer this question, the main purpose of this study is to investigate the impact of energy efficiency policies on the energy performance of residential properties in Portugal. While the analysis in this article is specific to Portugal, it has far-reaching policy implications. Any success, challenge, or impact of energy efficiency policies on EPCs in a country is a helpful lesson for officials in other European countries similar to Portugal to improve the energy efficiency of residential properties. In addition, the policy implications of this article help direct investment in optimal opportunities to improve Portugal's energy efficiency. This study also provides insights and helpful information for national and local stakeholders and political decision-makers.

This investigation is divided into six sections. Section 2 presents the literature review; Section 3 describes the data and model used in this empirical investigation; Section 4 shows the empirical results; Section 5 presents the discussion; and, finally, Section 6 presents the conclusions and policy implications.

2. Literature Review

This section reviews previous studies on energy efficiency policies in the housing sector. Past studies revealed that different policies had been implemented to increase energy efficiency (e.g., Alberini and Bigano [34], Aydin and Brounen [35], Charlier [36], Dubois and Allacker [37], Filippini et al. [27], Lopes et al. [38], and Ramos et al. [6]). These policies include, for example, energy performance standards; required labels of energy efficiency for appliances and building standards; fiscal, regulatory, and information policies; tax credits; energy certificates; energy feedback programs; subsidies for renovation; and subsidies for building new houses.

Most studies conducted to review energy efficiency policies in the housing sector have been conducted for a panel of countries. However, some studies have evaluated energy efficiency policies in the housing sector for EU countries. For example, Filippini et al. [27] explored the impact of energy policy instruments on energy efficiency in the EU housing sector during 1996–2009. In this research, econometric approaches of energy demand modelling and boundary analysis have been used. The empirical analysis revealed that financial incentives and energy performance standards play a crucial part in promoting energy efficiency.

In contrast, the enlightening actions do not affect it. Thonipara et al. [29] examined the energy efficiency policies of residential buildings in the European Union. The results showed that construction regulations are an effective policy tool to reduce energy consumption in residential buildings. However, the impact of regulatory standards for new buildings and major renovations is only visible over more extended periods. Carbon and energy taxes are effective in improving energy efficiency. Broin et al. [30] examined the energy efficiency policies of the EU housing sector during the period 1990–2010. The effects of policies have generally been discussed in fiscal, regulatory and information policies. The correlation between real demand decline and the estimated impact of regulatory policies is stronger than the correlation with the implications of fiscal and information policies. Given the energy efficiency market barriers in the residential sector, the results support that the regulatory policy is the main concern in designing successful paths in the direction of the EU's broader targets for heating energy.

Several other studies that examined a panel of countries evaluated European countries and the Organisation for Economic Co-operation and Development (OECD). Aydin and Brounen [35] examined the impact of residential energy efficiency policies on household energy consumption across Europe from 1980 to 2016. In this study, electrical and non-electrical energy consumption was examined separately because households usually use these items for different purposes (appliances and heating) and are subject to different energy efficiency policies. They focused on two distinct mandatory energy efficiency labels for household appliances and building standards. It was revealed that home appliances' strict building regulations and energy labelling requirements reduce residential energy consumption. Bertoldi and Mosconi [39] studied the impact of energy efficiency policies on energy storage in 29 European countries during 1990–2013. Their results show that in the absence of energy efficiency policies, energy consumption in Europe in 2013 would have been about 12% higher. Finally, Costantini et al. [40] examined the impact of policies on energy efficiency technologies for the residential sector in 23 OECD countries from 1990 to 2010. Evidence showed that innovation in energy efficiency technologies is driven by both demand policy tools and technological pressure. Most importantly, the evidence presented shows that the simple adding of an uncontrolled number of policy tools simultaneously can reduce the effectiveness of the policy mix.

In other studies, researchers compared the effectiveness of energy efficiency policies between the two countries. Kern et al. [41] examined policy instruments to stimulate energy efficiency in Finland and the United Kingdom from 2000 to 2014. The results show that both countries increasingly have complex policy mixes that include various goals and tools and use a wide range of different tools to encourage users to reduce their energy consumption. Huang et al. [42] compared energy-saving policies in the housing sector between Japan and China. Related policies fall into four categories: control and regulatory instruments, economic/market-based instruments, financial and information instruments, and voluntary measures. The effect of the policy analysis showed that energy-saving policies in the housing sector led to energy savings in both Japan and China. Comparing the barriers showed that Japan and China have many barriers, including high transaction costs and a lack of usable methods. Compared to Japan, China suffers from more obstacles, such as inefficient implementation, insufficient information and awareness, and an immature financial regulation system.

In the meantime, several studies on energy efficiency policies have been conducted nationally. Beerepoot and Beerepoot [43] examined their government's strict regulations to motivate improvements in energy performance in the Dutch building sector during the period 1996–2003. The results show that energy performance policy in the Netherlands has not helped to disseminate or develop innovations in hot-water technologies. To some extent, it helps to improve the efficiency of conventional hot-water production technologies. Related factors, such as changes in gas prices or housing investment, also have hardly impacted incremental or new energy consumption in the Dutch residential building. Boonekamp [44] examined the results of the Netherlands household energy efficiency policies from 1990 to 2003. The author also deals with the quantitative analysis of the interactions between three main measures: (i) the regulatory energy tax; (ii) investment subsidies; and (iii) gas regulation used to heat the place. The results showed that combining two or three policies is 13–30% less effective than all the effects of individual measures. In another study for the Netherlands, Murphy [45] used policy tools to improve the energy efficiency in private homes. The results showed that the current tools to create a long-run energy-saving plan for present homes are weak. In addition, most tools appear and disappear over short periods and cannot form a coherent and integrated strategy that continuously targets existing dwellings.

Yu et al. [46], in a study considering the Global Change Evaluation Model, examined the growth in the building sector and the impact of building energy policies in Gujarat (India). The results show that without developing energy incentive policies, the energy consumption could strongly increase in commercial and residential buildings from 2010 to 2050 in Gujarat. Indeed, realising the Energy Saving Building Law can increase energy efficiency in commercial buildings and reduce building electricity consumption in Gujarat by 20% by 2050. Contrasted to the no-policy scenario, having energy codes for commercial and residential buildings can save 10% electricity consumption. Alberini and Bigano [34] examined the motivations for promoting residential energy in Italy. The study used data collected from 3000 Italian landlords between May and June 2013. The results showed that non-monetary incentives have little effect on increasing energy efficiency and monetary incentives are generally not cost-effective, even under the optimistic assumptions contained in Italy's tax credit program. Li and Shui [47] conducted a comprehensive analysis of building energy efficiency policies concerning improving energy performance, the standard of living, and mitigating climate change in China. The results showed that the analysis emphasises the importance of ensuring policy compliance within the current regulatory framework to maximise the effectiveness of energy efficiency policies in the Chinese-made environment. Kamal et al. [48] researched the energy efficiency policies' roles in the housing sector in Qatar using the system dynamic method. Seven energy efficiency policy measures based on renovation and new constructions were evaluated for these buildings to see their effects on electricity consumption. The results showed that building energy-intensive facilities and renovating old buildings every ten years could save more than 4700 gigawatt-hours of electricity by 2050.

Ramos et al. [6] review the empirical evidence focusing on energy certifications, feedback programs, and energy audits. As the findings revealed, the energy certifications and feedback programs could be successful. Nevertheless, this only will occur if they are carefully designed. In contrast, the evidence supports that the effectiveness of energy audits is mixed. Charlier [36] examined the impact of tax credits and energy burdens on the energy efficiency costs of the residential sector. Due to the complexity of studying decision-making to invest in energy-saving renovations, a two-variable Tobit model was used to compare decisions about energy-saving. The findings confirmed that tax credits were unsuccessful in distributing incentives. Therefore, the government public policy should focus on low-income residents. Finally, Dubois and Allacker [37] evaluated the efficacy of three economic instruments to increase energy efficiency in the housing sector: (i) reconstruction subsidies; (ii) demolition and reconstruction project subsidies; and (iii) the construction of new housing subsidies. The results show that renovation subsidies, with low energy gains, worsen the overall housing energy consumption due to inefficient energy homes. Therefore, the use of policy tools requires structural changes.

Pasichnyi et al. [49] analysed the data quality assurance method for energy performance certificates (EPCs). The analysis showed that EPC data could be improved by adding or revising the EPC features and ensuring the interoperability of the EPC dataset. Shen et al. [50] researched the current development of policy instruments to promote energy efficiency (compulsory enforcement instruments, economic incentives, and voluntary design instruments) (BEE) by examining their performance in seven selected countries and regions. The results showed that different countries had made good progress in building energy efficiency by adopting different policy instruments. Boza-Kiss et al. [51] stated that while specific instruments such as product standards and labels can achieve the greatest energy savings, in terms of cost-effectiveness, it is not possible to prioritise the policy instruments under consideration. McCormick and Neij [52] collected policy instruments for energy efficiency in buildings in Nordic countries. This study focuses on policy instruments, including building codes, subsidies, labels and flyers, information campaigns, and taxes.

Trotta et al. [28] had identified policy instruments and private initiatives in five European countries (Finland, Hungary, Italy, Spain, and the United Kingdom). The results show that the British government has implemented better policies with private sector initiatives to improve energy efficiency. However, Finland's scarcity of effective and directed policies has raised energy consumption. In Hungary, Italy, and Spain, interesting initiatives were found (for example, financial incentives). Nair et al. [53] analysed the factors affecting the energy efficiency investment in the Swedish construction sector. The findings showed that personal characteristics, for instance, income, education, house age, thermal discomfort, past investment, and perceived energy cost, affect the homeowners' preference for a particular energy efficiency measure. Amstalden et al. [54] examined the effects of policy instruments on energy efficiency in the Swiss residential sector. The findings indicated that Swiss policy instruments drive investments to increase energy efficiency.

Houde and Aldy [55] examine the increasing impact of energy subsidies on the presence of policy expression in the United States. The results showed that, in general, the impact of this subsidy program on long-term energy demand is probably negligible. Tambach et al. [56] examined Dutch energy policy instruments for the building sector. The results show that although Dutch energy policy instruments for present housing appear to meet local executive demands largely, complementary policy instruments are required to encourage and pressure the current modernisation regime. Lindén et al. [57] stated that policy instruments had enhanced the energy efficiency behaviour in Sweden, namely, extensive information campaigns during the oil crisis of the 1970s and the labelling of household energy. Finally, Murphy et al. [58] reviewed policy instruments to improve energy performance in the Dutch construction sector. The results indicated that the existing instruments are not outfitted to create a long-run energy-saving plan for current homes.

As can be seen, although previous studies have used variables, methods, countries, regions, and time series to explain the impact of energy efficiency policies on energy performance in the housing sector, gaps in the literature have been found and need to be filled. This study's energy efficiency policy variables include standard energy policies and codes, financial incentives, and information policies. Given that in most previous studies only one or two of these policies have been used to examine the impact of energy efficiency policies, extensive use of the number of policies to explore their effect is one of the main innovations of this study. On the other hand, there is no research on the impact of energy efficiency policies on energy performance in the household sector in Portugal. The research that has been done so far, with the exclusion of Portugal, was mainly based on the European Union, OECD, India, and China. The following section presents the data and methods used in this research.

3. Data and Method

This section briefly describes the data and variables, the panel of countries, and the methodological approach used in our tentative analysis.

3.1. Data

As mentioned before, in this subsection, we will present the data/variables utilised in this empirical analysis. Nineteen districts of Portugal were selected (**Aveiro**, **Beja**, **Braga**, **Bragança**, **Castelo Branco**, **Coimbra**, **Évora**, **Faro**, **Guarda**, **Leiria**, **Lisboa**, **Madeira**, **Portalegre**, **Porto**, **Santarém**, **Setúbal**, **Viana do Castelo**, **Vila Real**, and **Viseu**), assessed for the period between 2014 and 2021. The district of **Azores** was not selected due to the inexistence of data. Figure 6 below shows the districts that were selected in Portugal.

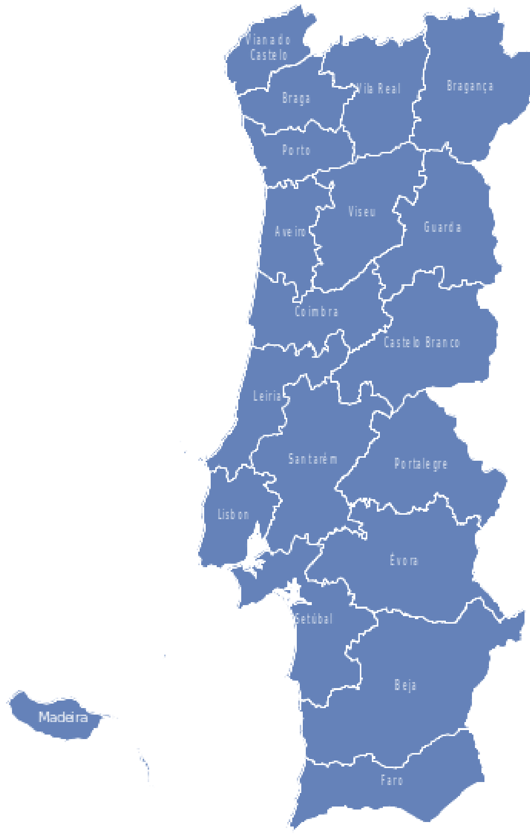

Figure 6. Portuguese districts. The authors created this figure.

We selected Portugal to realise this investigation because this country has a severe energy poverty problem caused by low income and access to energy efficiency technologies, as caused by the inefficiency of public policies. Indeed, Portugal has a significant problem with families' access to residential properties with high energy efficiency certificates (**A+**, **A**, **B**, and **B−**) compared to Scandinavian countries. Additionally, we selected Portugal as our object of study because we need to understand the fundamental problem. Finally, this country has detailed and daily updated data, unlike other countries in Europe. The variables used in this empirical investigation are shown in Table 1 below.

The study uses data from 2014 to 2021. Data availability for the variables was the main criteria to establish the period used, for example, (i) the energy performance certificates (**A+**, **A**, **B**, **B−**, **C**, **D**, **E**, and **F**). This investigation used only issued EPCs for new and existing residences/houses. Moreover, the number of EPCs issued were constructed in accumulated form for each Portuguese district until November 2021; and (ii) **CSEPA**, **FFIPA**, and **IEPA**, the national-level policies in force. This investigation opted to use the policies at the national level because the Portuguese districts do not have the autonomy to legislate or create their own energy policies. Therefore, these variables were generated until November 2021. Indeed, each policy is represented by the sum over policies throughout its useful life or end. Therefore, for the variables **CCPC** and **IPCC** (an estimation of GDP per capita, for 2020, was used), this investigation used data until 2020.

Table 1. Description of the variables.

Variables Used	Description of Variables	Time	Source
Dependent Variables of the Model			
A+	Energy performance certificates issued with rating A+	2014–2021 (Certificates issued in accumulated form until May 2021)	Sistema de Certificação Energética dos Edifícios (SCE) [59]
A	Energy performance certificates issued with rating A	Id.	Id.
B	Energy performance certificates issued with rating B	Id.	Id.
B−	Energy performance certificates issued with rating B−	Id.	Id.
C	Energy performance certificates issued with rating C	Id.	Id.
D	Energy performance certificates issued with rating D	Id.	Id.
E	Energy performance certificates issued with rating E	Id.	Id.
F	Energy performance certificates issued with rating F	Id.	Id.
Independent variables of the model			
CSEPA	Codes and Standards Energy policies for energy efficiency in the residential sector.	2014–2021 (Policies in Force in accumulated form until November 2021)	IEA [11]
FFIPA	Fiscal/financial incentive policies to promote energy efficiency. These policies are destined for the residential sector. Moreover, this variable comprises the following policies (e.g., subsidies, tax relief, and grants).	Id.	IEA [11]
IEPA	Information and education policies of energy efficiency directed to the residential sector. This variable comprises the endorsement label and comparison label policies	Id.	IEA [11]
IPCC	Gross domestic product (GDP) per capita constant (Euros)	2014–2020	PORDATA [60]
CCPC	Consumer credit per capita (Euros)	2014–2020	Id.

Notes: Id. denotes Idem.

In Portugal, EPCs are used to summarise the energy efficiency of residential properties. Furthermore, in Portugal, the residential properties are given a rating between **A+** (Very efficient) and **F** (Inefficient) (see Figure 7 below).

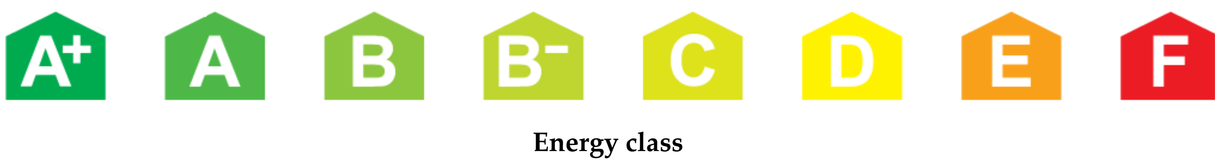

Figure 7. Energy performance certificates (EPCs) in Portugal. This figure was retrieved from *Sistema de Certificação Energética dos Edifícios* (SCE) [59].

Moreover, in Portugal, the EPCs consider several aspects of a residential property to classify the energy efficiency. For example, the EPCs take into account (i) the energy consumption characteristics of home appliances; (ii) hot water and measures to mitigate the energy consumption; (iii) the property's location; (iv) the floor and the area; (v) the year it was built; and (vi) the configuration of its surroundings (i.e., roofs, walls, floors, and window glazing). Therefore, all these aspects influence the energy class.

Moreover, the EPC scale is calculated in Portugal by dividing a residential property's primary energy demand (Ntc) and the corresponding limit value (Nt). Indeed, the new residential properties must be above class B−, the reference consumption (100%). Existing residential properties can have any class, and the various classes are the percentage intervals of the reference consumption. For example, a class C residential property consumes between 100% and 150% (between 1 and 1.5 times) of the reference consumption (see Table 2, below).

Table 2. Consumption by energy class in a residential property.

Energy Class		R = (Ntc/Nt)	Residential Energy Consumption in (%)
Residential property with high energy efficiency	A+	$R \leq 0.25$	(25%) or less
	A	$0.25 < R \leq 0.50$	Between (25%) to (50%)
	B	$0.50 < R \leq 0.75$	Between (50%) to (75%)
	B−	$0.75 < R \leq 1.00$	Between (75%) to (100%)
Residential property low energy efficiency	C	$1.00 < R \leq 1.50$	Between (100%) to (150%)
	D	$1.50 < R \leq 2.00$	Between (150%) to (200%)
	E	$2.00 < R \leq 2.50$	Between (200%) to (250%)
	F	$R > 2.50$	More than (251%)

Notes: This table is based on data from the *Sistema de Certificação Energética dos Edifícios* (SCE) [59].

Moreover, the variables **CSEPA**, **FFIPA**, and **IEPA** were generated as an accumulated variable, where each new policy is the sum of the policies during its useful life or until its end. This method was developed by Fuinhas et al. [61] and Koengkan et al. [62]. Finally, the variables were transformed into natural logarithms to make them more symmetrical and reduce their volatility and the influence of outliers.

After showing the variables used in our empirical investigation, we can demonstrate the descriptive statistics (see Table 3 below). Natural logarithms were used to linearise the relationships between the model variables [62]; also, Log denotes variables in the natural logarithms, and the Stata command *sum* was used to perform the descriptive statistics.

Table 3. Descriptive statistics.

Variables	Descriptive Statistics				
	Observations	Mean	Standard Deviation	Minimum	Maximum
LogA+	133	4.687	1.353	1.099	7.086
LogA	133	5.909	1.442	2.773	8.804
LogB	133	6.284	1.038	4.159	8.819
LogB—	133	5.898	1.086	4.127	8.400
LogC	133	6.711	1.324	4.615	9.725
LogD	133	6.951	1.173	5.106	9.569
LogE	133	6.725	0.933	4.860	9.061
LogF	133	6.335	0.826	2.890	8.498
LogCSEPA	133	1.482	0.111	1.387	1.609
LogFFIPA	133	1.557	0.227	1.099	1.792
LogIEPA	133	1.880	0.077	1.792	1.946
LogIPCC	133	9.821	0.045	9.757	9.892
LogCCPC	133	8.708	0.135	8.510	8.935

This investigation used variable codes and standards, fiscal, and information policies. According to Trotta et al. [28], the standards for buildings and energy-related products ensure that the desired energy performance of the building components and (especially) heating equipment is achieved even when its purchaser has been related to the existence of credit and policies for support.

Indeed, according to Noailly [26], the energy efficiency policies show that, for example, the energy efficiency standards policies (codes and standards) have been one of the main drives of innovation and energy efficiency in buildings and residential properties. Moreover, Bleischwitz et al. [63] add that this type of policy is the preferred option in the European Union to reduce the barriers to energy efficiency in residential properties. An empirical proof that the energy efficiency policies increase the residential sector was found by Broin et al. [30]. The authors used panel data of fourteen European Union countries to estimate the efficiency standard policies' impact on space heating demand in the residential sector from 1990 to 2010. The authors pointed out that the efficiency standard policies are more effective than the European Union's fiscal/financial or informative policies. These findings agree with earlier studies of Filippini et al. [27] and Saussay et al. [31].

Considering the fiscal/financial incentive policies, Trotta et al. [28] mentioned that fiscal incentive policies encouraging energy efficiency in residences include several measures to lower the taxes paid by consumers. Indeed, the same authors add that these policies are instruments that European countries can use to promote and facilitate efficient energy use among domestic customers. For example, in European Union countries, this policy covers (i) reducing the heating demand by overall upgrading of the building's energy performance; (ii) improving the building's thermal insulation (replacement of windows, including blinds and fittings, and insulation of roofs, walls, and floors); (iii) installing solar thermal panels; (iv) replacing winter heating systems (with condensing boilers or heat pumps); and (v) replacing electrical water heaters with heat pump water heaters. In the literature, the evidence that policies such as fiscal and financial incentives can boost energy efficiency was found by several authors (e.g., Broin et al. [30], Filippini et al. [27], and Saussay et al. [31]).

Regarding the information policies, Trotta et al. [28] comment that the information and educational policies induce a change in the consumer's behaviour by providing information about potential energy savings from energy-efficient products or investments and including programmes to give feedback to consumers about their energy consumption. In the literature, this variable was used by some authors, such as Trotta et al. [28], Broin et al. [30], and Filippini et al. [27], to explain the effect of information and education policies on energy efficiency. All these authors find a positive impact of information and education policies on energy efficiency in European Union countries.

This investigation used the GDP per capita because the income increase allows the households to invest in renovating buildings/residences and sustainable building/residence construction, installing energy-efficient heating systems, and purchasing more energy-efficient equipment. Moreover, in the literature, this variable was used by several authors (e.g., Broin et al. [30], Filippini et al. [27], and Saussay et al. [31]) to explain the effect of income on energy efficiency. Indeed, all these authors find a positive impact of income on energy efficiency in European Union countries.

Finally, this empirical investigation used credit variables (consumer and house credit). As Trotta et al. [28] mentioned, soft loans are commonly used to encourage energy efficiency improvements by lowering the inhibitive upfront costs faced by households. In Portugal, families commonly use two types of credit (consumer and home credit) to renovate buildings/residences and for sustainable building/residence construction, installing energy-efficient heating systems, and purchasing more energy-efficient equipment. Some authors have investigated the effect of credit or capital on energy efficiency. For example, Zhang et al. [64] studied the impact of credit access on energy intensity (a proxy of energy efficiency) for China between 2011 to 2013. The empirical results indicate that the firms with access to credit are associated with lower energy efficiency. In other words, firms with credit access tend to have significantly higher energy use per unit of output. Koengkan [65] investigated the effect of capital stock development on renewable energy investment in Latin America and the Caribbean region between 1990 and 2016. The author found that increasing public credit reduces the financing costs and encourages the development and investment in renewable energy technologies and energy efficiency.

3.2. Method

In this section, we present the estimation method and the pre- and post-estimation tests made to assess the quality of the econometric model. To assess the impact of the previously described covariates on the number of issued EPCs, the next panel estimation was estimated for each energy performance certificate scale.

$$LogEPC_{k_{i,t}} = \alpha^k + \beta^k X_t + c_i^k + u_{i,t}^k, \tag{1}$$

where $LogEPC_{k_{i,t}}$ is the natural logarithm of the cumulative number of issued energy performance certificates scale, k (k = **A+**, **A**, **B**, **C**, **D**, **E**, and **F**), for district i in the year t; $X_t = [LogCSEPA_t LogFFIPA_t LogIEPA_t LogIPCC_t LogCCPC_t]$ denotes the vector of the natural logarithm of the explanatory variables at time t; α^k is the constant term for the regression k and β^k are the explanatory variables' coefficients; and c_i^k and $u_{i,t}^k$ are the district-specific random effect for district i in the regression k and the individual-specific random effect for equation k, respectively.

Before estimating Equation (1), it is essential to perform several preliminary tests to assess the data's statistical properties and identify the adequate estimation method. Thus, we conducted the following tests:

(i) Skewness/kurtosis test for normality (D'Agostino [66])—the null hypothesis states that data is normally distributed. By combining skewness and kurtosis, this test has higher power to test for normality.
(ii) Shapiro–Wilk test for normality (Shapiro and Wilk [67])—the null hypothesis states that the data is normally distributed. Moreover, this test is based on the first two moments of the order statistics.
(iii) Variance inflation factor (VIF)—a high value for the VIF suggests that the variables are highly correlated, which leads to imprecise and unstable coefficient estimates.
(iv) Levin–Lin–Chu (LLC) panel unit root test (Levin et al., [68])—the null hypothesis is that the variables are non-stationary. Moreover, stationarity in the models is necessary to prevent estimating a spurious regression [62].
(v) Hausman test (Hausman [69])—this test is built on comparing random effects (RE) and fixed-effects (FE) estimates. The test has the null hypothesis of consistency of

the random effects estimator. Moreover, in this test, the null hypothesis fails once the unobserved effect is correlated with the covariates. In this situation, a fixed-effects estimator is preferable [62].

The residuals' statistical properties were tested after estimating Equation (1). Thus, the non-appearance of some characteristics, such as heteroscedasticity, autocorrelation, and cross-sectional independence, were tested. When one of these violations occurred, it biased the estimated standard errors. In this case, it is advised to use an estimator that can compute robust standard errors [62].

(i) Wooldridge's autocorrelation test (Wooldridge [70])—the test examines if the idiosyncratic estimation residuals are correlated. The test has the null hypothesis of no autocorrelation.
(ii) Breusch–Pagan's heteroscedasticity test (Breusch and Pagan [71])—the test has the null hypothesis that the idiosyncratic errors are homoscedastic [62].
(iii) Cross-sectional dependence test (Pesaran [72])—the null hypothesis presupposes that the idiosyncratic residuals are cross-sectionally uncorrelated. The alternative hypothesis assumes that residuals could be correlated across units [62].

The following section reveals the empirical findings of this research.

4. Empirical Results

As mentioned before, this section will focus on the empirical results of our investigation. In other words, the preliminary tests, main model regression, post estimation tests, and robustness check. The first step before the model regression is the realisation of the preliminary tests, such as (i) the normal distribution tests (e.g., skewness/kurtosis test and Shapiro-Wilk test); (ii) VIF test; (iii) Unit root test; and (iv) Hausman test.

Therefore, to test the presence of normality in the variables, the normality of distribution was tested with the skewness/kurtosis test—first separately and then combined, and with the Shapiro–Wilk test (see Table 4 below). The Stata commands *sktest* and *swilk* were used to perform the normal distribution tests.

Table 4. Test for a normal distribution.

Variables	Observations	Skewness	Kurtosis	Skewness and Kurtosis		Shapiro–Wilk	
				Probability > X^2		Probability > z	
LogA+	133	0.000	0.762	0.003	***	0.000	***
LogA	133	0.713	0.013	0.049	**	0.173	
LogB	133	0.342	0.038	0.076	*	0.118	
LogB−	133	0.016	0.232	0.034	**	0.000	***
LogC	133	0.036	0.007	0.007	***	0.000	***
LogD	133	0.030	0.041	0.018	**	0.000	***
LogE	133	0.051	0.126	0.052	**	0.003	**
LogF	133	0.001	0.000	0.000	***	0.0000	***
LogCSEPA	133	0.404	0.000	0.000	***	0.992	
LogFFIPA	133	0.000	0.769	0.001	***	0.000	***
LogIEPA	133	0.161	NA	NA		1.000	
LogIPCC	133	0.161	NA	NA		0.178	
LogCCPC	133	0.577	0.000	0.001	***	0.019	**

Notes: ***, **, * denote parameters statistically significant at the 1%, 5%, and 10% levels, respectively; NA denotes not available.

Table 4 above shows that the data is slightly positively skewed ($_1 > 0$) and with a lighter tail ($\beta_2 < 3$); that is, in the direction of a higher-rated housing certificate or more policies and with fewer extreme values. For **LogA** and **LogCCPC**, the distributions of the scores were more highly skewed. The D'Agostino et al. [66] skewness/kurtosis test allows us to reject the null hypothesis of a normal distribution of the data. Furthermore, when testing normality with the Shapiro–Wilk test, the returned values suggest the null of normal distribution for **LogA+**, **LogB−**, **LogC**, **LogD**, **LogE**, **LogFFIPA**, and **LogCCPC** can be rejected; the other variables are normally distributed in the model. Therefore, the data are not normally distributed in the model. After realising the normality distribution tests, it was necessary to assess multicollinearity between the model's variables. To this end, the variance inflation factor (VIF) test was realised (see Table 5 below). The Stata command *vif* was used to perform the VIF test.

Table 5. VIF test.

Model	Mean VIF
The model with the dependent variable (A+)	7.60
The model with the dependent variable (A)	7.60
The model with the dependent variable (B)	7.60
The model with the dependent variable (B−)	7.60
The model with the dependent variable (C)	7.60
The model with the dependent variable (D)	7.60
The model with the dependent variable (E)	7.60
The model with the dependent variable (F)	7.60

The results from Table 5 point that the variance inflation factor is in the range of 1.0 to 10, signifying a relatively high but tolerable collinearity among the predictor variables in the regression [63]. The repeated VIF value shows that the income and policy variables are repeated for each cross, as the policies are determined at the national level. After identifying high multicollinearity between the variables, it was time to identify the unit roots. The first-generation LLC panel unit root was computed to achieve this objective (see Table 6 below). The Stata command *xtunitroot llc* was used to perform the unit root test.

Table 6. Panel unit root test.

Variables	LLC-Test				
	Without Trend			With Trend	
	Lags	Adjusted t		Adjusted t	
LogA+	1	−10.3574	***	−35.9503	***
LogA	1	−5.9879	***	−9.4100	***
LogB	1	−5.7227	***	−25.6855	***
LogB−	1	−21.1892	***	−18.6313	***
LogC	1	−71.5136	***	−55.9105	***
LogD	1	−16.1621	***	−17.0379	***
LogE	1	−13.2848	***	−61.0671	***
LogF	1	−38.5522	***	-1.1×10^2	***
LogCSEPA	1	−1.3447	*	−12.6552	***
LogFFIPA	1	−6.8679	**	2.5922	
LogIEPA	1	−5.4166	***	−5.2045	***
LogIPCC	1	−12.5721	***	43.0495	
LogCCPC	1	10.8918		-1.3×10^2	***

Notes: ***, **, * denote parameters statistically significant at the 1%, 5%, and 10% levels, respectively.

In Table 6, the first-generation test for the unit roots developed by Levin, Lin, and Chu [59] is displayed. They show that most panels are stationary; that is, I(0). In turn, some panels (**LogFFIPA**, **LogIPCC**, and **LogCCPC**) are near-stationary; that is, on the boundary between the I(0) and I (1) order of integration. The stationarity of the variables is due to low temporal variation in the variables, leading to random effects. Therefore, the next step of this investigation is to search for individual effects. To this end, the Hausman test, which compares the random (RE) and fixed effects (FE), was computed (see Table 7 below). The Stata command *hausman* was used to perform the Hausman test.

Table 7. Hausman test.

Model	Probability > chi2(5)
The model with the dependent variable (A+)	0.00
The model with the dependent variable (A)	0.00
The model with the dependent variable (B)	0.00
The model with the dependent variable (B−)	0.00
The model with the dependent variable (C)	0.00
The model with the dependent variable (D)	0.00
The model with the dependent variable (E)	0.00
The model with the dependent variable (F)	0.00

According to Koengkan et al. [62], when the data fails to meet the asymptotic assumptions of the Hausman test, the results of the Hausman test contrast with the use of the RE or FE models (see Table 7); it can be concluded that the RE model is present. According to the same authors, when this occurs, it is an indication of the non-systematic difference in coefficients.

The second step after the preliminary tests is the realisation of the random-effects linear regression model. Table 8 below show the outcomes of the linear RE model. The Stata command *xtreg* with the option *re robust* was used to perform the linear random-effects model regressions.

Table 8. Linear random-effects model regressions.

Independent Variables	**Dependent Variables**							
	Residential Properties with High Energy Efficiency							
	High Bound				**Low Bound**			
	A+		**A**		**B**		**B−**	
LogIPCC	−5.9800	***	−5.9775	***	−6.3608	***	0.7478	
LogCSEPA	0.1221		1.0136	***	0.7854	***	0.4683	**
LogFFIPA	0.7443	***	0.7541	***	0.5637	***	−0.5159	**
LogIEPA	3.2752	***	3.0084	***	2.3000	***	−0.4703	
LogCCPC	1.8077	***	2.2404	***	1.8800	***	0.4199	
Constant	40.1812	***	36.7750	***	46.019	***	−4.1113	
Obs	133		133		133		133	
Independent variables	**Residential properties with low energy efficiency**							
	High bound				**Low bound**			
	C		**D**		**E**		**F**	
LogIPCC	4.8506	***	4.1309	***	2.7596	***	−2.0946	***
LogCSEPA	0.4840	***	−0.3828	**	−0.6129	***	−1.4099	***
LogFFIPA	−1.0325	***	−0.3335	**	0.1681		1.7562	***
LogIEPA	0.4781	**	0.5541	*	0.7396	**	0.2950	
LogCCPC	−0.9788	***	−1.0356	***	−0.6731	***	0.2696	***
Constant	−32.4140	***	−24.5571	***	−15.2606	***	23.3589	***
Obs	133		133		133		133	

Notes: ***, **, * denote parameters statistically significant at the 1%, 5%, and 10% levels, respectively.

The random-effects linear regression analysis (see Table 8 above) shows that most policies have a significant, differentiated effect on residential energy efficiency choice. For example, the variable **LogIPCC** impacts negatively the residential properties with higher energy efficiency; that is, with high energy efficiency performance certificates (e.g., **A+**, **A**, and **B**). It supports that Portuguese personal income is low and prevents the investment in residential properties with high energy efficiency, making consumers prone to prefer the least expensive, lower-efficiency residential properties; that is, with low energy efficiency performance certificates (e.g., **C**, **D**, and **E**).

Regarding the energy policy effect on the choice of energy efficiency of the residential properties, results are not uniform. Consumer credit (**LogCCPC**) positively impact higher-efficiency residential property and negatively impact lower-grade certificates. Consumers may decide to use credit for higher-efficiency housing when facing a budget constraint. For fiscal policies (**LogFFIPA**), the impact is also positive for the higher-grade certified residential property (e.g., **A+**, **A**, **B**, and **B−**) and negative for the lower-efficiency residential property (e.g., **C** and **D**). Taken together, this may suggest that consumers are encouraged to take on credit because of fiscal policies—a tax reduction in the interest rates—for purchases of higher-efficiency housing. These differentiating effects of personal income, credit, and fiscal policies on residential energy efficiency suggest that incentives are narrowly targeted to higher energy-efficient homes. Indeed, they effectively incentivise higher-efficiency housing purchases, thus leading to greater differentiation in the residential sector concerning energy efficiency.

It should be noted that the effects of consumer credit and fiscal policies in the **F** category do not follow the general tendency described above. Regarding income per capita, the negative impact shows that consumers tend to not choose the lowest-efficiency residential property as income rises. However, fiscal and credit policies have positive effects, suggesting that consumers use credit with comparatively higher interest rates. Codes and standards policies (**LogCSEPA**) are significant and positive for higher-grade efficiency residential property (e.g., **A**, **B**, **B−**, and **C**). They are negative for lower-efficiency housing (e.g., **D**, **E**, and **F**) but insignificant for **A+** housing, suggesting that these policies cannot incentivise the choice for the highest-efficiency residential property. Information and education policies (**LogIEPA**) positively affect most energy efficiency category housing, with the greatest impact on higher-grade housing (e.g., **A+**, **A**, and **B**). The exception for grade **B−** housing, for which information policies and personal income are insignificant, may signify consumers choose average energy efficiency residential property without policy incentives.

After the linear random-effects model regression, it was required to realise the post-estimation tests; that is, in this investigation, the following tests will be computed: (i) Wooldridge's test; (ii) Breusch and Pagan LM test; and (iii) Pesaran's test. Table 9 below points to the results of the post-estimation tests. The Stata commands xtserial, xttest0, xtcsd, and pesaran abs were used to perform the post-estimation tests for the linear random-effects of the models.

Table 9. Post-estimation diagnostic tests for the linear random-effects model.

Models	Wooldridge's Test	Breusch and Pagan LM Test	Pesaran's Test
The model with the dependent variable (A+)	7.769 **	350.12 ***	−1.400
The model with the dependent variable (A)	6.083 **	383.48 ***	1.467
The model with the dependent variable (B)	21.126 ***	382.72 ***	−1.572
The model with the dependent variable (B−)	9.77 ***	372.88 ***	2.271 **
The model with the dependent variable (C)	0.820	386.05 ***	16.922 **
The model with the dependent variable (D)	3.387 *	388.49 ***	−0.387
The model with the dependent variable (E)	1.380	373.95 ***	3.579 ***
The model with the dependent variable (F)	1.468	294.45 ***	24.831 ***

Notes: ***, **, * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

Table 9 reveals several diagnostic tests. The Breusch and Pagan LM test [71] rejects homoscedasticity, supporting that the random-effects model is preferable compared to the OLS one. Woolridge's [70] test found diverse results for panel autocorrelation. Autocorrelation was found in the energy efficiency certificates for the grades **A+**, **A**, **B**, **B−** and **D**, but not in certificate grades **C**, **E**, and **F**. Pesaran's [72] test for residuals reveals cross-sectional dependence for the energy EPC of grades **B−**, **C**, **E**, and **F**. In contrast, the energy EPC of **A**, **B**, and **D** shows cross-sectional independence.

Figure 8 below reviews the independent variables' impact on the dependent ones. Therefore, this figure was created with the results from Table 8 above.

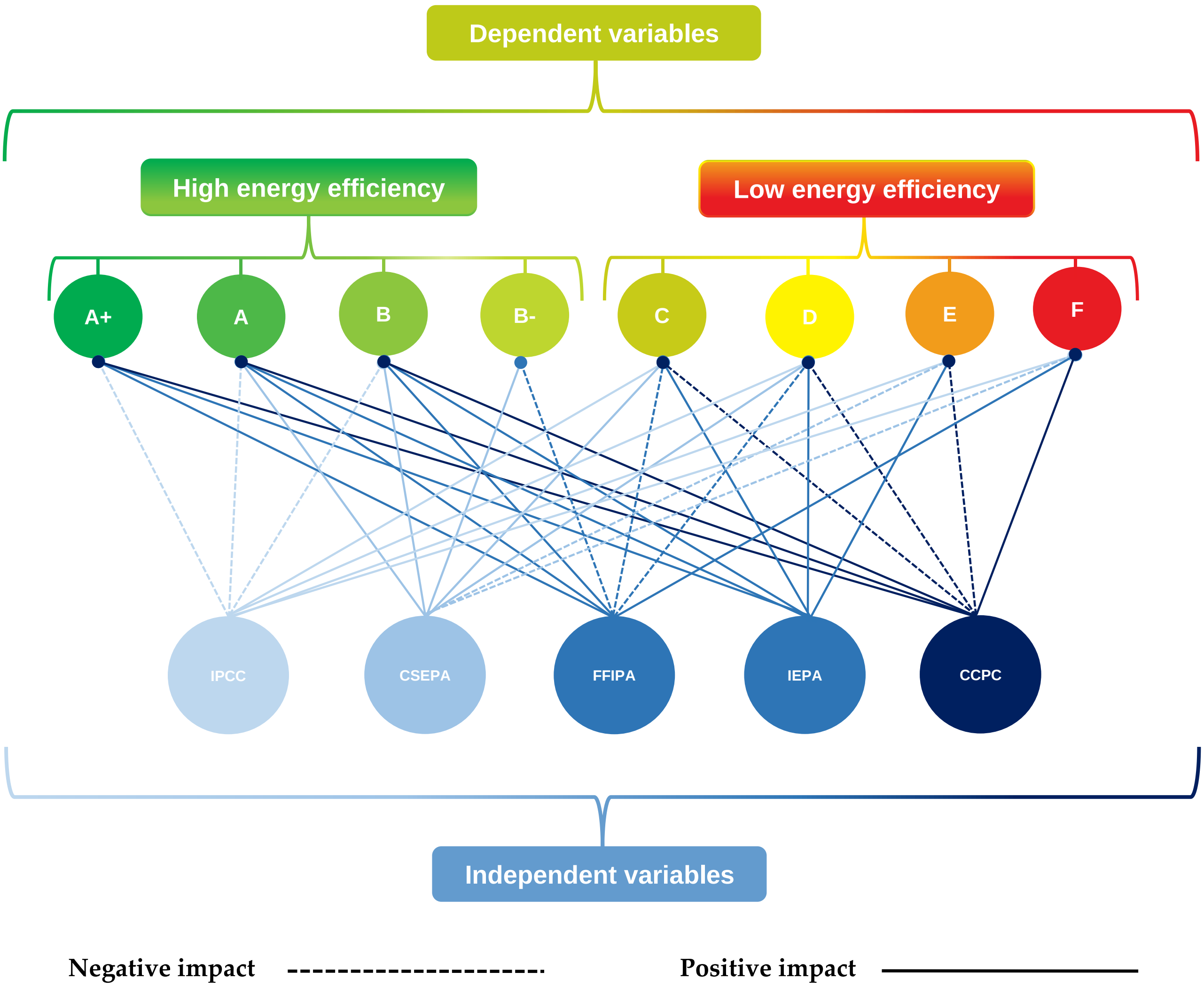

Figure 8. Outline of the independent variables' effect. The authors created this figure.

5. Discussions

Discussing our main results, we can see that energy policies indeed play a meaningful role in promoting the energy performance of residential properties in Portugal.

Talking about the codes and standards policies (**LogCSEPA**) and information and education policies (**LogIEPA**), since 1 January 2009, all residential buildings in Portugal must have an energy certificate [22]. Following Fragoso and Baptista [73], excluding the information campaigns that were conducted "to provide a better understanding to the building owner of the building features that can be improved when considering the potential energy reduction or achieving costs savings", an energy certificate is, undoubtedly, a central source of information. Indeed, it is a friendly and user-oriented document. Beyond the evaluation of the energy efficiency of a property, it also provides owners with information on the measures that will enable a reduction in energy consumption, a comfort improvement, cost reduction, and an increase in the property valuation. It is also important to stress that, in the real estate market, any advertisement of buildings or apartments needs to present the energy label of the building since December 2013 [73]. In addition to the previous information, the creation of programs such as "CINERGIA—Energy Information Centre" and the ADENE (Portuguese Energy Agency) initiative, under the "Portugal Energia" (Portugal Energy) measure of the SIMPLEX+2017 program, was also crucial to the increase in energy literacy in the Portuguese society [73].

All these factors may lead to an enhanced awareness of the owners on the advantages of increased building energy efficiency, leading them to take the necessary measures to turn their properties into high-grade housings (**A+**, **A**, and **B**). Indeed, following the data from the Portuguese Energy Agency (ADENE), in 2014, only 1828 certificates for residential houses were **A+**, 6135 were **A**, and 9337 were **B**, which contrasts with 2021, where 3370 of the issued certificates were **A+**, 12,472 were **A**, and 10,050 were **B** [59].

According to "The Energy Efficiency Watch Survey Report 2020" [74], Portugal's progress in energy efficiency policies has been significant. Experts recognise the valuable progress made in promoting energy efficiency in this report. Indeed, in industry, transport, and buildings, with energy labelling of products, energy efficiency requirements for buildings, and energy certification of buildings being pointed as the most effective specific policy measures.

However, the models' results reveal strong restraints limiting the Portuguese investment in highly energy-efficient housing. Indeed, Portugal has a household income that can be considered low [75]. Therefore, the policy has been used to lessen the budget constraints of Portuguese households. Indeed, to support energy efficiency projects, the execution of fiscal and financial incentive policies (LogFFIPA) is of major relevance. "The Energy Efficiency Watch Survey Report 2020" [74] already referred to the ineffectiveness of Portuguese policies.

Furthermore, many experts (46%) consider financial incentives ineffective [62] in promoting investments energetically efficient. Consequently, it is far from unexpected that the effect of consumer credit (LogCCPC) is of higher magnitude than the one from fiscal and financial incentive policies (LogFFIPA). Therefore, one can consider that, in the absence of appropriate fiscal and financial incentives, households will recur to credit to materialise their projects to achieve energy efficiency in their houses.

Nevertheless, the Portuguese government seems to recognise that failure. To deal with the goals of "Plano Nacional Energia e Clima 2030" (National Energy and Climate Plan 2030), the "Programa de Apoio Edifícios mais Sustentáveis" (More Sustainable Buildings Support Program) was created by the Portuguese government. It was assigned 4.5 million euros in 2020/2021 to implement the first phase. This first phase intended to establish procedures and actions to boost (i) rehabilitation; (ii) decarbonisation; (iii) energy efficiency; (iv) water efficiency; and (v) buildings' circular economy. Indeed, the initial endowment of 4.5 million euros was soon exhausted, requiring the addition of 5 million euros. Furthermore, the Portuguese government publicised the program's second phase, "Plano de Recuperação e Resiliência" (Recovery and Resilience Plan), in the summer of 2021. This phase incentivises projects to improve the energy sustainability of houses. Consequently, the government is supporting this investment with a further 30 million euros.

6. Conclusions and Policy Implications

This article addressed the impact of energy efficiency policies on EPCs for residential properties, identifying whether energy policies effectively promote the residential properties' energy efficiency in Portugal. It is essential to highlight that the characteristics of buildings are fundamental in determining the energy needs and identifying possible ways to enhance energy efficiency.

The increase in energy consumption is a consequence of the development of societies. However, this increase can be significantly reduced through responsible use of energy. The residential sector is one of the biggest energy consumers in Portugal. Energy consumption in habitations depends on several factors, such as construction quality, location, insulation level, and equipment types.

Buildings are responsible for considerable environmental impacts throughout their life cycle, as they cause the occupation and use of land and changes in local ecosystems. When applied to residential buildings, energy certification allows future owners to know the energy performance of habitation even before its purchase and use. In this way, the importance of builders using more efficient construction solutions and equipment, from an energy point of view, is highlighted.

Energy inefficiency is caused by excessive energy consumption in the habitations. Several factors contribute to excessive consumption, such as thermal comfort, the number of equipment used and its energy efficiency, the local climatic conditions, and the economic conditions of the families.

The findings of this article can support policymakers in choosing measures with the most significant potential for implementation in the housing sector and which may be the target of public and private support and financing for the improvement and development of Portugal's housing park. It is important to promote sustainable energy consumption based on renewable energy sources, adopting public policies to promote energy efficiency together with environmentally conscious decisions. Thus, it is necessary to implement changes in the design phase of buildings and their use phase, studying their energy performance and improvement strategies to realise sustainable construction.

Portugal is taking several measures to make its economy more efficient and sustainable, following the guidelines of European policies regarding the energy performance of residential housing. Among the measures are (i) to support and promote policies to encourage energy efficiency and the rehabilitation of energy-efficient residential buildings; (ii) encourage the promotion of smart technologies; (iii) decrease energy consumption; (iv) reduce the emissions of greenhouse gas; (v) increase energy efficiency with the use of renewable energy sources; (vi) reduce energy consumption needs and energy dependence; and (vii) promote financial mechanisms and incentives to encourage the construction of energy-efficient real estate parks.

Energy efficiency policies for residential properties in Portugal contribute to sustainable growth and an efficient economy in terms of resources and reducing greenhouse gas emissions. In addition, the public sector can create new markets for energy-efficient technologies, services, and business models. On the economic front, it is necessary to optimise investments in promoting energy efficiency in the housing sector. Increased public sector credit and subsidy policies reduce the financing costs, encouraging development and investment in renewable energy technologies and energy efficiency. In addition, it is necessary to develop strategic planning to direct resources and investments, thereby establishing policies and goals to promote energy efficiency. On the social front, it is essential to learn to use energy responsibly and raise awareness among users to improve the present and ensure a better future for future generations.

Furthermore, it is crucial to adopt the best practices and small actions to save energy. On the environmental front, it is recommended to apply renewable energy to construct and improve residential properties, such as photovoltaic solar panels. Therefore, it is crucial to supply the maximum energy from renewable energies to prevent and mitigate environmental impacts from energy production. The application of renewable energies is essential for increasing energy efficiency and ensuring sustainability.

Finally, the finds of this investigation may lead us to develop future investigations, such as the effect of energy efficiency certificates on transaction prices and rents. As we already know, the environmental and energy labelling schemes make visible in the market a dimension of a product that is not easily visible, in this case, energy performance. Therefore, in the absence of information from sellers regarding the energy performance of a property, the added value of a well-insulated building would not be reflected in the transaction price or rent. It may, in turn, dissuade owners from making energy-saving improvements—especially if they are planning to rent their property or sell it in the short term. Therefore, it is essential to understand how these energy certificates affect the transaction prices and rents in Portugal to develop public policies that mitigate possible imbalances in the housing market and increase the access to residential properties with high energy efficiency by low-income families.

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