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Efficiency of Electricity Production Technology from Post-Process Gas Heat: Ecological, Economic and Social Benefits

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Abstract: The strengthening of ecological conflicts due to the increase of the destructive impact from industrial companies on the environment provokes the development and implementation of the eco-innovation technologies. Besides, such technologies should allow obtaining not only the ecological benefits (the decrease of the negative impact on the environment) but also the economic and social advantages which correspond to sustainable development principles. This paper aims to justify the social, ecological and economic effects from implementing a new electricity production technology from post-process gas heat at companies. The data for empirical justification were obtained from the experiment of applying the electricity production technology from post-process gas heat at Polish industrial companies. In the first stage, bibliometric analysis was used for highlighting the scientific background of economic evaluation of the innovative activity on energy technologies of industrial companies and its impact on the environment and public health. Secondly, the economic and ecological efficiency of electricity production technology for the selected company was estimated. The results of the analysis confirm that new technologies allowed increasing the energy efficiency of the company by decreasing energy consumption, increasing productivity, etc. The findings prove that one of the ecological effects was the decrease of CO_2 and SO_2 emissions in the air. In this case, the link between the volume of CO_2 emissions and the rate of morbidity if such innovative technologies were scaled was checked. The findings show that decreasing CO_2 emissions by 1% leads to a decline in the death rate by 0.5%. If the new technology were scaled and implemented among similar industrial companies, it could decrease the rate of morbidity by 0.01% The results obtained could be used by the companies' management and policymakers in the framework to achieve sustainable development goals.

Keywords: climate change; CO_2; morbidity; green technologies; emissions; sustainable development

1. Introduction

The snowball effect of environmental issues from global warming calls for finding new solutions to cut CO_2 emissions. Besides, many instruments and mechanisms have been developed by experts and scientists. However, most of them do not have any practical application. Globally, scientists argue that new green technologies have not only ecological effect (a decline in CO_2 emissions and water and land pollution) but also economic and social ones. One of the main benefits of green technologies is the reduction of CO_2 emissions, which indirectly leads to a decline in the morbidity rate.

The results of bibliometric analysis shows that scientific interest in the green electricity production technology has been increasing since 1996 (Figure 1). The peak of the papers in the Scopus was in 2019 (857 articles). At the end of 2019, the European Union declared the New Green Deal Policy, according to which the EU plans to achieve the carbon-free economy by decreasing CO_2 emissions.

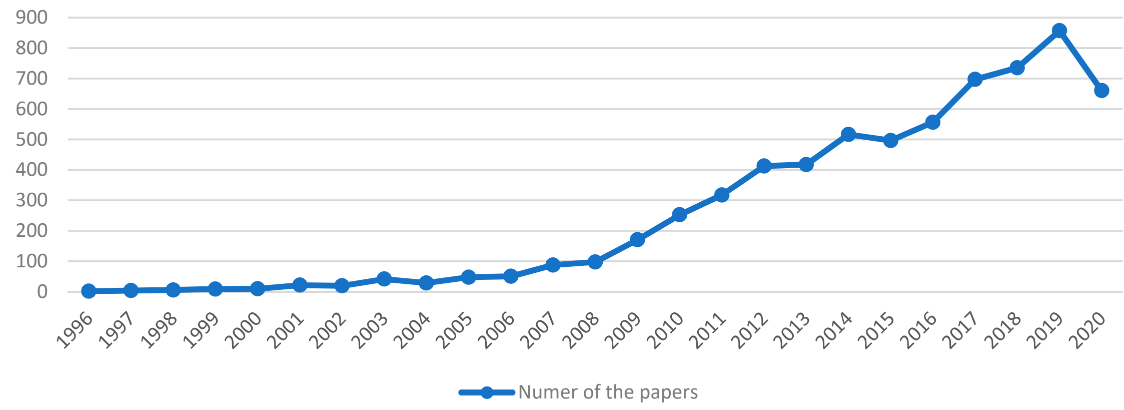

Figure 1. The publication activities in Scopus on green electricity production technology (source: developed by the author based on Scopus).

The most significant impact on the scientific research of this topic was made by Ansari Nirwan (New Jersey Institute of Technology). In [1,2], he and his colleagues proved that extension of green energy leads to technological and economic effects. Besides, Zhang X., Wang Y. and Wang S. confirmed that green electricity production has positive economic and ecological impacts [3,4] (Figure 2).

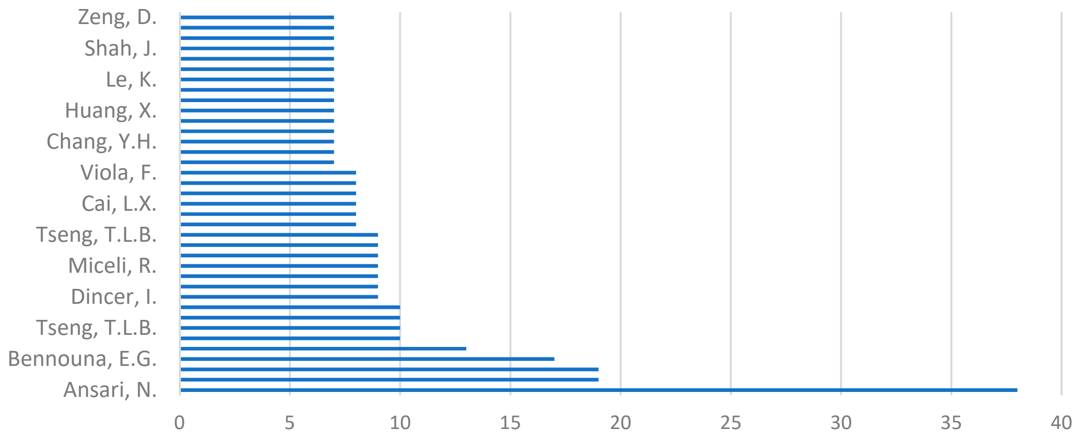

Figure 2. The Top 10 scientists who research the issues of green electricity production technology (source: developed by the author based on Scopus).

Besides, in [3,4], the authors confirmed the hypothesis that developing green energy leads to achieving sustainable development goals. Figure 3 presents the visualisation of bibliometrics analysis according to the leading scientists and their co-citations.

It should be noted that a vast range of scholars confirmed that spreading green electricity production among householders and industrial companies allows minimising the CO_2 emissions, decreasing the rate of morbidity and obtaining additional economic benefits in the long run. In this case, it is possible to conclude that developing green electricity production is a multidisciplinary theme which contributes to knowledge and expertise. The findings show that this theme has often been analysed by scientists from the engineering and energy fields, accounting for 23% and 18% or research, respectively. Only 2–5% of the papers study these issues from the economic points of view (Figure 4).

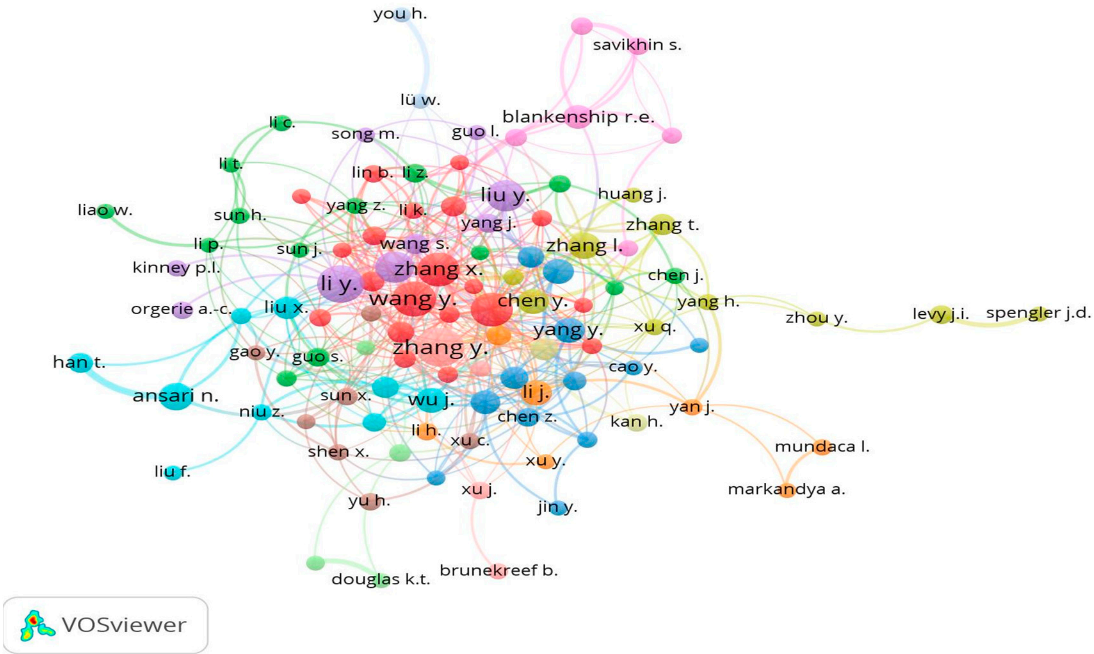

Figure 3. Visualisation of the bibliometric analysis of the papers on green electricity production technology according to the co-citation filter (source: developed by the author based on Scopus and VOSviewer).

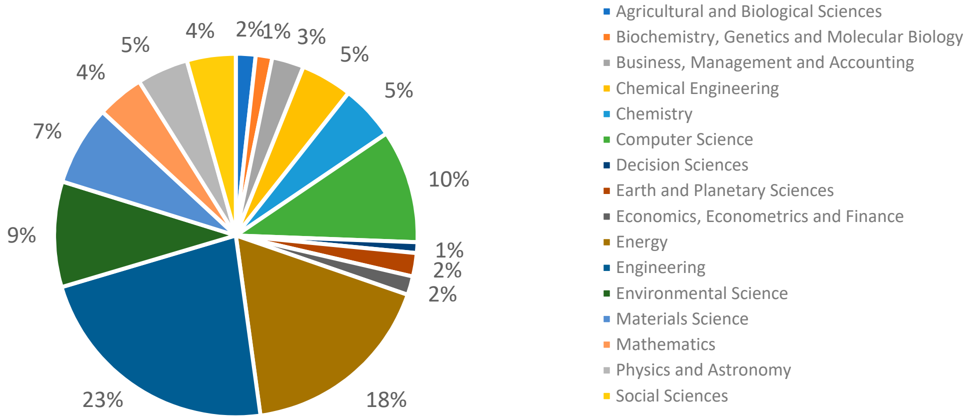

Figure 4. The main subject areas studying green electricity production technology (source: developed by the author based on Scopus and VOSviewer).

Thus, the results of the co-occurrence analysis allow allocating the six main clusters of the scientific schools which analysed the issues of green energy. The most significant cluster (blue) focuses on energy transfer technologies. Besides, this cluster penetrates all other clusters. The second cluster (green) focuses on energy conservation and green buildings. The yellow cluster merges the smart technologies in green energy policy. The red cluster focuses on health, pollution and morbidity. It should be noted that scientists [5] proved that decreasing CO_2 emission lowers the rate of morbidity. The red cluster is located close to the energy conservation and energy transfer clusters. (Figure 5).

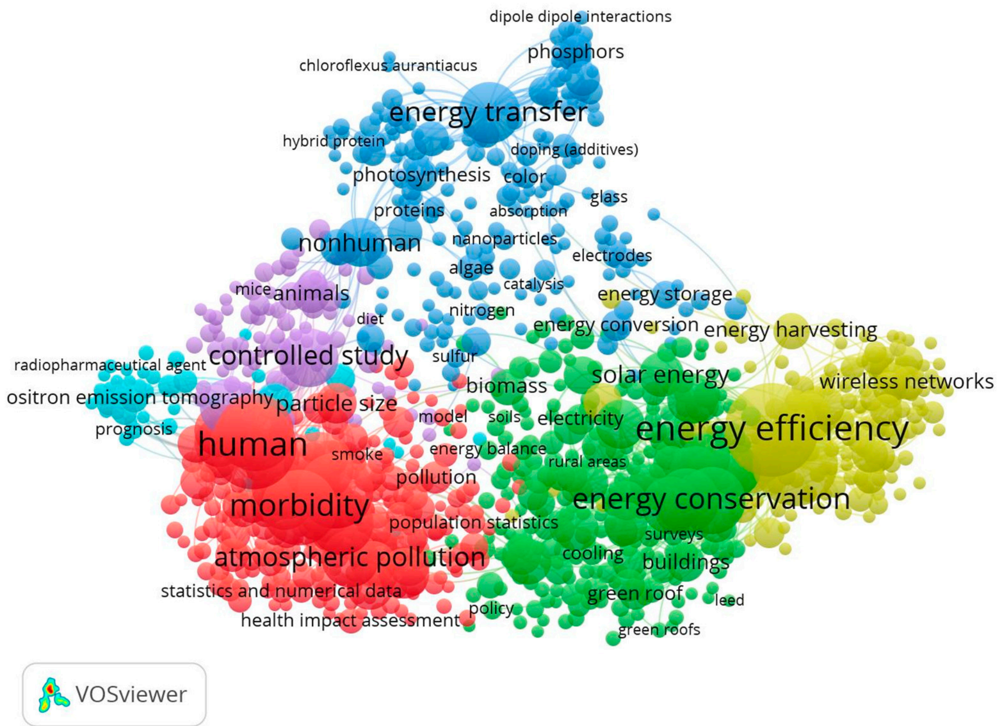

Figure 5. A visualisation map of the co-occurrence analysis (source: developed by the author based on Scopus and VOSviewer).

Findings of the bibliometric analysis show that the theme of green electricity production technology is multidisciplinary. The cluster of energy efficiency has a mediator role among morbidity and air pollutions (red), energy transfer (navy blue) and energy conservation (green) clusters. Besides, green energy development allows achieving economic, social and ecological effects.

Thus, in [6–10], the authors confirmed that distributing renewable energy among households allows achieving ecological and social effects. The authors of [8] maintained that the economic efficiency of renewable energy for Ukraine is low and spreading green technologies is related to the currency exchange rate and utility bills in the country. They concluded that, for Ukraine, the green technologies for households are not profitable. However, the authors of [6,10] argued that biogas technologies for industrial companies are profitable and have indirect ecological and social effects. The authors of [11–13] maintained that the agricultural sector has a considerable potential to produce green energy and implement innovative technologies for that purpose. Based on the comparison and empirical analysis, the authors of [14–20] identified the instruments for stimulating green energy (feed-in tariff, taxes, green certificates and green investments and bonds) development and proved that efficiency of electricity production technology depends on the country. Lyulyov O. and co-authors [21] maintained that green technologies lower the environmental damage. The authors of [21–26] empirically proved that green energy enhances energy security and GDP and decreases CO_2 emissions.

The analysis confirms that developing green technologies depends on the countries' economic, social, innovation and ecological capabilities. Thus, the authors of [27–35] proved that the shadow economy and efficiency of public governance have a statistical impact on spreading the renewable energy. The authors of [36–39] concluded that convergence of institutional, economic and ecological development of the country allows increasing the share of renewable energy in the total energy consumption and decreasing the CO_2 emissions. The authors of [40–42] confirmed the efficiency of green technologies and resources saving at the company is related to innovations development in the country and the company's capabilities to implement the IT in the technological process.

The authors of [43–55] analysed the options of the industrial companies to implement green technologies. They proved the hypothesis that green technology of electricity production allows reducing the cost and increasing the company's profitability. Besides, the green standards of EU countries limit cooperation with companies which are not using green technologies and try to reduce the harmful damage to the environment.

Despite of the powerful scientific background on analysis of the energy efficiency, the findings allow identifying the following research gap: the linking of social, ecological and economic effects as a result from implementing innovative technology for electricity production.

This paper aims to show the social, ecological and economic effects of implementing new green technology for electricity production from post-process gas heat at companies.

2. Materials and Methods

Megacities have the most significant share of industry. On the one hand, this leads to overconsumption of primary energy resources. On the other hand, this provokes the increase of harmful damage to the environment. The main negative consequence is air pollution from nitrogen oxide, sulphur dioxide, carbon oxide, etc. The high average concentration of those pollutants leads to increasing morbidity and mortality. Thus, the pollution from big industrial companies has a negative impact on health. At the same time, the distribution of energy efficiency technologies among industrial companies allows enhancing the social and economic development of the country (city, region, etc.) and reducing a negative impact on the environment and, as a consequence, improving the public health.

The main hypothesises of the research are:

Hypothesis 1 (H1). *The energy innovations at industrial companies lead not only to economic but also ecological and social benefits.*

Hypothesis 2 (H2). *The scaling of the innovation activities among industrial companies for implementing energy efficiency technologies is the primary driver of social and economic development of a territory. Energy innovations contribute to the increase of a company's productivity, reduction of the anthropogenic damage to the environment and improvement of the public health quality.*

In the first stage of the research, with the purpose to check H1, the efficiency of the energy recovery system as an example of energy innovations at a Polish company was estimated. The installation allows using the heat from the combustion of post-reaction gases to heat compressed air to supply to a gas turbine for electricity production. The core elements of the energy recovery system are as follows as:

- An exhaust for suction of a 12 MVA furnace, adapted for controlled combustion after gases react with control of excess combustion air and regulation of the gas temperature at the outlet of the air funnel in the range from 750 to 950 °C
- Regulation of flue gas temperature in this range carried out by the flow of air supplied from the nozzles located in the vault of the exhaust and the electrode coolers
- Nozzles in the vault of the exhaust, providing 53% of the air for combustion, which penetrates the space of the exhaust to a depth of approximately 1.8 m, thereby obtaining adequate mixing with process gases
- Air nozzles in electrode coolers, providing 36% of combustion air
- Combustion air to get an excess factor $\lambda = 1.1$, supplied by a fan with a capacity of 12,000 m_n^3/h and a pressure of 6000 PA
- A flue gas collector connecting the outlet nozzle from the exhaust to the installation connecting the furnace to the dust filter.
- Dome recuperator installed at the beginning of the hot gas pipeline, which removes hot gases to the dust collection unit, where the exhaust heat is extracted by compressed air supplied from the turbocharger compressor.

To identify the impact of the implemented energy innovations at the industrial companies on the environment and public health as in [54,55], the following model of the production function of public health was used:

$$H = F\,(E, CO_2, P, SE) \tag{1}$$

where H represents indicators of public health; E is the level of the energy consumption in the country; CO_2 is an indicator of atmosphere pollution; P is energy innovation technologies and their transfer in the country; and SE is a vector of social and economic indicators.

The indicators of energy dependence (E) are used for estimating the energy efficiency of the production from an economic point of view. Thus, the authors of [56], analysed the impact of fossil fuel energy consumption on the environment in EU countries. They highlighted that the energy dependence of a country influences the economic development of a country. Thus, the decline in the fossil fuel energy consumption could be the core driver of the country's energy dependence.

Global rating agencies estimate the innovation activities of a country using the integrated evaluation of the innovation development of the system [57,58]: Global Innovation Index, Bloomberg Innovation Index, Global Competitiveness Index, Innovation Union Scoreboard and the quantity of the patents. Here, the Global Innovation Index is used as an indicator of the country's innovation development. The key benefit of spreading the green technology of electricity production in all sectors is the decline in air pollution, including a decrease of carbon dioxide (CO_2) emissions. It also allows solving issues with the safety of the atmosphere, which is the basis of public health [5].

The social and economic indicators include the following: the openness of the economy and the level of urbanisation. The openness of the economy (Trade) allows estimating the options of innovation diffusion to increase the country's energy efficiency.

Cole M. A. [59] analysed how the openness of an economy impacts the energy consumption in 32 developed countries during 1975–1995. The empirical findings confirm that trade liberalisation allows increasing energy use per capita for all selected countries. The urbanisation level (U) of the country has a significant impact on the economic growth and the social wellbeing of the country, which could improve energy efficiency. The authors of [59–65] proved the statistical impact of urbanisation on energy efficiency. Model (1) can be presented as follows:

$$H_t = \phi + \alpha\, E_t + \beta CO_{2t} + \gamma \ln GII_t + \delta_1 Trade_t + \delta_2 U_t + \mu_{it} \tag{2}$$

where ϕ, α, β, γ, δ_1 and δ_2 are regression parameters which are evaluated and explain the impact of E (net imports divided by the gross available energy, %), CO_2 (in million metric tons of CO_2), GII (number of patents in energy innovation technologies), Trade (the sum of exports and imports of goods and services measured as a share of gross domestic product, % of GDP) and U (Urban population, % of the total population) on H (death rate, crude, per 1000 people); μ is the error term; and t = 1, . . . ,T.

In the first stage, to further analyse Model (2), the statistical analysis of model's parameters and the check of variables' stationarity were done by using the augmented Dickey–Fuller test, Phillips–Perron test and Dickey–Fuller–GLS test. Model (2) does not allow identifying the long-term impact of the determinants and eliminates the lags in the estimation. In the next stage, using the autoregressive distributed lag (ARDL) method, the cointegration among the considered variables was done:

$$\begin{gathered}\Delta \ln H_t = \phi + \sum_{j=1}^{k_1} \alpha_0 \Delta \ln H_{t-j} + \sum_{j=1}^{k_1} \alpha_1 \Delta \ln E_{t-j} + \sum_{j=1}^{k_2} \beta \Delta \ln CO_{2t-j} + \sum_{j=1}^{k_3} \gamma \Delta \ln GII_{t-j} + \\ \sum_{j=1}^{k_4} \delta 1 Trade_{t-j} + \sum_{j=1}^{k_5} \delta 2 U_t + \alpha_3\, H_{t-1} + \alpha_4\, E_{t-1} + \beta_1 CO_{2t-1} + \gamma_1 \ln GII_t + \delta_4 Trade_t + \\ \delta_5 U_t + \mu_{it}\end{gathered} \tag{3}$$

where Δ is the first difference; ϕ, α_0, α_1, β, γ, δ_1 and δ_2, are the estimated coefficients of the lagged level of the variables; α_3, α_4, β_1, γ_1, δ_4 and δ_5 are the lag lengths of the variables chosen by the Schwarz data criteria; μ is the error term; and t = 1, . . . ,T.

In the last stage, the causality among all parameters was checked using the vector error correction model (VECM):

$$\Delta ln\mathrm{H_t} = \pi_0 + \sum_{j=1}^{k_1} \pi_1 \Delta \ln H_{t-j} + \sum_{j=1}^{k_1} \pi_2 \Delta \ln E_{t-j} + \sum_{j=1}^{k_2} \pi_3 \Delta \ln CO_{2t-j} + \sum_{j=1}^{k_3} \pi_4 \Delta \ln GII_{t-j} + \sum_{j=1}^{k_4} \pi_5 Trade_{t-j} + \sum_{j=1}^{k_5} \pi_6 2U_t + \omega 1ECT_{t-1} + \varepsilon_{it} \quad (4)$$

$$\Delta lnE_t = \chi_0 + \sum_{j=1}^{k_1} \chi_1 \Delta \ln H_{t-j} + \sum_{j=1}^{k_1} \chi_2 \Delta \ln E_{t-j} + \sum_{j=1}^{k_2} \chi_3 \Delta \ln CO_{2t-j} + \sum_{j=1}^{k_3} \chi_4 \Delta \ln GII_{t-j} + \sum_{j=1}^{k_4} \chi_5 Trade_{t-j} + \sum_{j=1}^{k_5} \chi_6 2U_t + \omega 2ECT_{t-1} + \varepsilon_{it} \quad (5)$$

$$\Delta lnCO_{2t} = \rho_0 + \sum_{j=1}^{k_1} \rho_1 \Delta \ln H_{t-j} + \sum_{j=1}^{k_1} \rho_2 \Delta \ln E_{t-j} + \sum_{j=1}^{k_2} \rho_3 \Delta \ln CO_{2t-j} + \sum_{j=1}^{k_3} \rho_4 \Delta \ln GII_{t-j} + \sum_{j=1}^{k_4} \rho_5 Trade_{t-j} + \sum_{j=1}^{k_5} \rho_6 2U_t + \omega 3ECT_{t-1} + \varepsilon_{it} \quad (6)$$

$$\Delta lnGII_t = \zeta_0 + \sum_{j=1}^{k_1} \zeta_1 \Delta \ln H_{t-j} + \sum_{j=1}^{k_1} \zeta_2 \Delta \ln E_{t-j} + \sum_{j=1}^{k_2} \zeta_3 \Delta \ln CO_{2t-j} + \sum_{j=1}^{k_3} \zeta_4 \Delta \ln GII_{t-j} + \sum_{j=1}^{k_4} \zeta_5 Trade_{t-j+} \sum_{j=1}^{k_5} \zeta_6 2U_t + \omega 4ECT_{t-1} \varepsilon_{it} \quad (7)$$

$$\Delta ln\mathrm{Trade}_t = \theta_0 + \sum_{j=1}^{k_1} \theta_1 \Delta \ln H_{t-j} + \sum_{j=1}^{k_1} \theta_2 \Delta \ln E_{t-j} + \sum_{j=1}^{k_2} \theta_3 \Delta \ln CO_{2t-j} + \sum_{j=1}^{k_3} \theta_4 \Delta \ln GII_{t-j} + \sum_{j=1}^{k_4} \theta_5 Trade_{t-j} + \sum_{j=1}^{k_5} \theta_6 2U_t + \omega 5ECT_{t-1} + \varepsilon_{it} \quad (8)$$

$$\Delta ln\mathrm{U_t} = \phi_0 + \sum_{j=1}^{k_1} \phi_1 \Delta \ln H_{t-j} + \sum_{j=1}^{k_1} \phi_2 \Delta \ln E_{t-j} + \sum_{j=1}^{k_2} \phi_3 \Delta \ln CO_{2t-j} + \sum_{j=1}^{k_3} \phi_4 \Delta \ln GII_{t-j} + \sum_{j=1}^{k_4} \phi_5 Trade_{t-j} + \sum_{j=1}^{k_5} \phi_6 2U_t + \omega 7ECT_{t-1} + \varepsilon_{it} \quad (9)$$

where ECTt − 1 are the lagged error correction terms; Δ is the first difference operator; π, χ, ρ, ζ, θ, ϕ are estimated indicators; ε_{it} is the error term; and k is the lagged length of the variables chosen by the Schwarz data criteria (SIC).

3. Results

The empirical findings from the approbation of the developed patent for the energy recovery system confirm that this innovation allows obtaining economic, social and ecological benefits.

To estimate the economic efficiency, the traditional approach of investment efficiency estimation was used. The Net Present Value (NPV) and Internal Rate of Return (IRR) with a rate of 8.49% were calculated (Table 1). During the research, two options were calculated: with and without subsidies. If the company does not receive subsidies from the government on the energy recovery system, the investment will be profitable for the company. Of course, if the company receives subsidies, the economic efficiency of the investment will be higher. Thus, the IRR is 17.07% without subsides and 29.05% with subsides.

Table 1. Findings of NPV and IRR of investment in energy recovery system with and without subsidies.

Indicators	Without Subsidies	With Subsidies
NPV, thousand PLN	16,041.1	28,578.8
IRR, %	17.07	29.05

Source: Developed by the author based on the company's corporate information.

The main economic risks for reducing the profitability of the energy recovery system depend on the fluctuation of the currency exchange rate of EUR and PLN, price of FeSi, the average price of energy and investment outlays. In this case, the sensitivity to the abovementioned factors was calculated.

The findings confirm that the economic efficiency of investing in energy recovery system achieves the critical level if the currency exchange rate and price for FeSi decline by more than 10% and the average price of energy increases by more than 10% (Table 2).

Table 2. NPV and IRR sensitivity to the currency exchange rate.

Indicators	Changes	EUR Exchange Rate	Price of FeSi (EU/t)	The Average Price of Energy (PLN/MWh)	Investment Outlays
NPV	+20	111,570.69	109,978.30	−20,495.44	8955.72
	+10	63,805.77	63,008.23	−2230.55	12,498.40
	0	16,041.05	16,041.05	16,041.05	16,041.05
	−10%	−31,723.71	−30,931.52	34,308.39	19,583.73
	−20%	−79,488.42	−77,904.48	52,584.37	23,126.38
IRR	+20	64.29%	63.43%	−4.47%	12.71%
	+10	40.47%	40.08%	7.23%	14.75%
	0	17.07%	17.07%	17.07%	17.07%
	−10%	−15.21%	−14.33%	26.30%	19.77%
	−20%	-	-	35.39%	22.96%

Source: Developed by the author based on the company's corporate information.

The main ecological effects are the reduction of CO_2, SO_2 and dust emissions. Thus, the new technologies allowed cutting the CO_2 and SO_2 emissions by 5.88% and 380%, correspondingly. The dust emissions declined by 33.3%. The efficiency of furnaces increased by 3.77%, and energy efficiency of FeSi production by 0.3%. At the same time, the company reduced the flue gas consumption from furnaces emitted into the atmosphere from 140,000 to 90,000 Nm^3/h (35.71%). The findings of the comparative analysis are presented in Table 3.

Table 3. A comparative analysis of the technological and ecological indicators of the company's performance with and without the energy recovery system (calculation for 2015).

Key Performance Indicators	Before	After	Changes, %
Efficiency furnaces Mg/24 h	22	22.83	3.77
Heat generation from recovery (GJ/h)	6.48	6.54	0.93
The energy efficiency of FeSi production by 75% (%)	50.5	50.65	0.30
Declining of CO_2 emissions (Mg/MWh)	0.85	0.9	5.88
Declining of SO_2 emissions (kg/MWh)	0.5	2.4	380.00
Declining of dust emissions (kg/MWh)	0.15	0.2	33.33
Flue gas consumption from furnaces emitted into the atmosphere (Nm^3/h)	140,000	90,000	−35.71
Electricity generation due to recovery (MWh)	2.19	2.27	3.65

Source: Developed by the author based on the company's corporate information.

It should be noted that, during 2015–2019, key performance indicators of the energy recovery system were approximately equal. Thus, each year the company reduced the CO_2 emission approximately by 5.88% as compared with 2014 (a year without an energy recovery system). Cumulatively, for five years, the company reduced the CO_2 emission by 0.35 Mg/MWh and SO_2 by 8.9 kg/MWh. The empirical data on the efficiency of the energy recovery system for 2015–2019 are shown in Table 4.

The empirical findings of key performance indicators of energy recovery system confirm that this energy innovation technology contributes not only to direct economic but also ecological benefits, namely the reduction of CO_2 and SO_2 emissions, which influenced the public health.

Thus, spreading such energy innovation technologies among industrial companies could lead to the social and economic growth of the territory, increasing the company's productivity, reducing the anthropogenic damage to the environment and improving the quality of public health.

In this case, in the next stage of the research, H2 was checked. Table 5 contains the findings of descriptive statistics of the indicators from Model (2) for Poland in the period of 1995–2018.

Table 4. Efficiency of the energy recovery system (calculation for 2015–2019).

Key Performance Indicators	2015	2016	2017	2018	2019
Efficiency furnaces Mg/24 h	22.83	22.27	22.34	22.78	22.32
Heat generation from recovery (GJ/h)	6.54	5.4	6.54	5	6.25
The energy efficiency of FeSi production by 75% (%)	50.65	50.65	50.6	50.56	50.5
Reduction of CO_2 emissions (Mg/MWh)	0.9	1	0.9	0.9	0.9
Reduction of SO_2 emissions (kg/MWh)	2.4	2.3	2.2	2.1	2.4
Reduction of dust emissions (kg/MWh)	0.2	0.18	0.21	0.2	0.2
Flue gas consumption from furnaces emitted into the atmosphere (Nm^3/h)	90,000	86,000	88,000	85,000	90,000
Electricity generation due to recovery (MWh)	2.27	2.27	2.2	2.21	2.19

Source: Developed by the author based on the company's corporate information.

Table 5. Descriptive statistics for E, CO_2, GII, Trade, U and H for Poland, 1995–2018.

Descriptive Statistics	E	CO_2	GII	Trade	U	H
Mean	21.44138	10.7875	72.875	75.27467	61.1015	9.933333
Median	22.9695	10.65	72.5	76.50917	61.285	9.9
Maximum	44.803	11.9	109	107.4782	61.787	10.9
Minimum	0.191	10.1	34	43.67839	60.058	9.4
Std. Dev.	12.07166	0.448488	21.60981	18.71732	0.589249	0.357122
Skewness	0.016655	0.949486	−0.007795	−0.01966	−0.51214	0.873502
Kurtosis	1.862156	3.461465	2.162855	1.951089	1.798414	3.694587
Jarque–Bera	1.295798	3.819046	0.701054	1.10176	2.492959	3.534472
Probability	0.523144	0.148151	0.704317	0.576442	0.287515	0.170804
Sum	514.593	258.9	1749	1806.592	1466.436	238.4
Sum Sq. Dev.	3351.673	4.62625	10740.63	8057.774	7.985944	2.933333

Source: Calculated by the author.

The highest level of the variation coefficient was on the indicators E (0.563), GII (0.296) and Trade (0.248) for the years analysed. It means that Poland has an unstable government policy in developing and supporting green innovation technologies among industrial companies. At the same time, the lowest level of the variation coefficient was on the indicators CO_2 (0.042), H (0.036) and U (0.009). This could be explained by the fact that Poland joined the EU in 2004 and has been implementing the policy of transition from the inefficient and ecologically unsafe management of resource- and energy-intensive industries and technologies, raw material export orientation and over-concentration of production in industrial regions, along with the introduction of innovative transformations, to sustainable development.

The empirical results of linear unit root tests (augmented Dickey–Fuller test, Phillips–Perron test and Dickey–Fuller–GLS test) in the model with intercept and with intercept and trend confirmed that all indicators were at a level I (1) (Table 6). Considering the empirical results, the indicators CO_2 and Human Development Index (H) with all tests (the model with intercept and with intercept and trend) were not statistically significant at their level. Besides, the augmented Dickey–Fuller test only in the model with intercept and trend showed that only E and Trade were stationary at their levels. Moreover, the indicators of the GII in the model with intercept and with intercept and trend for the Phillips–Perron test and Dickey–Fuller–GLS test, Trade in the model with intercept and trend for the Phillips–Perron test and Dickey–Fuller–GLS test, U in the model with intercept and with intercept and trend for the Dickey–Fuller–GLS test and E in the model with intercept and trend for the Dickey–Fuller–GLS test were stationary at their levels.

Table 6. The findings of linear unit root tests.

Variable	Augmented Dickey–Fuller		Phillips–Perron		Dickey–Fuller–GLS	
	Intercept	Intercept and Trend	Intercept	Intercept and Trend	Intercept	Intercept and Trend
E	−0.705	−3.454 ***	−0.393	−1.948	−0.327	−5.895 *
CO_2	−2.267	−1.845	−2.310	−1.841	−1.804	−1.880
GII	−2.362	−2.426	−3.683 **	−3.603 ***	−2.061 **	−3.571 **
Trade	−0.383	−3.854 **	0.087	−3.740 **	0.354	−3.995 *
U	−1.563	−3.195	1.168	−3.074	−2.165 **	−3.048 ***
H	−0.072	−1.687	−0.072	−1.319	−0.072	−1.319
ΔE	−3.991 *	−3.940 **	−3.024 **	−3.911 ***	−2.183 **	−3.802 *
ΔCO_2	−3.995 *	−4.470 *	−4.009 *	−4.470 *	−3.793 *	−4.371 *
Δ*GII*	−7.256 *	−7.389 *	−7.256 *	−7.389 *	−7.410 *	−7.737 *
ΔTrade	−5.275 *	−5.122 *	−13.096 *	−12.602 *	−5.377 *	−5.421 *
Δ*U*	−3.552 *	−5.664 *	−3.552 **	−3.907 **	−3.622 *	−4.117
Δ*H*	−5.805 *	−7.267 *	−5.801	−7.559	−5.801	−7.559

*, **, *** represent significance at the 1%, 5% and 10% levels. Source: Calculated by the author.

The findings allowed a further analysis of the long-term relations among the indicators of Model (2). In the next stage, the Johansen test for cointegration was done. The results of the Johansen test for cointegration are summarised in Table 7.

Table 7. The empirical results of the Johansen test for cointegration results.

Maximum Rank	Trace Statistic	5% Critical Value
r = 0	140.208	83.937 *
r = 1	70.460	60.061 *
r = 2	32.698	40.174
r = 3	18.345	24.275

* represent significance at the 1% level. Source: Calculated by the author.

The data in Table 7 allow concluding on the existing long-term relations among selected indicators. Nevertheless, considering the AIC criteria, 2 was the optimal lag for using the indicators in the model. The findings on Trace statistics (Table 7) allowed rejecting the null hypothesis on no cointegration among analysed indicators E, CO_2, GII, Trade, U and H.

Table 8 contains the findings on long- and short-run estimates of the ARDL model.

Table 8. The results of long and short-run estimates. Selected Model: ARDL (1, 1, 0, 0, 1, 0).

Variable	Coefficient	Standard Error	*t*-Statistic	*p*-Values
		Long-run analysis		
E	0.051225	0.039727	1.28943	0.2181
CO_2	0.539355	0.172805	3.121167	0.0075
GII	−0.01305	0.021335	−0.6116	0.0506
Trade	0.20168	0.130767	1.54228	0.1453
U	3.17254	1.377576	−2.30299	0.0384
		Short-run analysis		
ΔE	−0.02641	0.00973	−2.71424	0.0168
ΔCO_2	0.426261	0.17644	2.415895	0.0311
Δ*GII*	0.000987	0.003504	0.281552	0.7827
ΔTrade	−0.04865	017407	−2.79456	0.0152
Δ*U*	2.937997	1.293584	2.271208	0.0408
R-squared	0.808716	Mean dependent var		10.75217
Adjusted R-squared	0.676288	SD dependent var		0.423051
SE of regression	0.240698	Akaike info criterion		0.288472
Sum squared resid	0.753161	Schwarz criterion		0.782165
Log-likelihood	6.682568	Hannan-Quinn criteria.		0.412635
F-statistic	6.10685	Durbin-Watson stat		2.093504
Prob(F-statistic)	0.0019			

Source: Calculated by the author.

The results allow concluding that the parameters of carbon dioxide emissions (CO_2), the number of patents in energy innovation technologies (GII) and urban population (U) had the statistically significant impact on the death rate, crude, per 1000 people (H). Thus, the reduction of carbon dioxide emissions (CO_2) by 1% leads to a decrease of the death rate (H) by 0.5%. Increasing the number of patents (GII) in energy innovation technologies leads to a decrease of the death rate (H) by 0.01%. This confirmed the positive impact of companies' innovation activities on the social development of the country. Besides, the findings confirm the positive impact of urban population (U) on the death rate (H), as found in [63]. Using the United Nations, the authors of [63] empirically found that the increase of urban population (U) leads to an increase in premature mortality by 39.6%. At the same time, in the short term, only indicators of carbon dioxide emissions (CO_2), urban population (U) and Trade had a statistically significant impact on the death rate (H).

Using the short- and long-run Granger causality tests for VECM, the causality between analysed indicators was checked (Table 9).

Table 9. The empirical results of Granger causality tests.

Dependent Variable	Short-Run						Long-Run
	Δ*H*	**ΔE**	**ΔCO_2**	**ΔGII**	**ΔTrade**	**Δ*U***	**ECT (−1)**
Δ*H*	0.390 *	−0.034 *	0.239 **	0.008	−0.003 ***	0.690	−0.407 *
ΔE	1.389	0.121 *	3.641 **	0.051	−0.096	26.24 **	−3.557
ΔCO_2	0.013	0.197	0.003 *	0.003	0.003	−2.77	0.311
ΔGII	65.6	−2.38	−20.37	−0.342 *	0.108 ***	68.75	−24.346
ΔTrade	0.800	−0.307 ***	5.27	0.004	−0.325 *	5.035	1.627
Δ*U*	0.020	0.001	0.002	0.004	−0.0007	0.928 *	−0.008 **

*, **, *** represent significance at the 1%, 5% and 10% levels. Source: Calculated by the author.

The findings allow concluding that for Poland bidirectional short-run causality between H and E exists at the 1% significance level. There is also a unidirectional short-run causality running from H and CO_2 at a 5% significance level and Trade at a 10% significance level. The ECT parameter comprises −1 and 0 and is significant in the case of Equations (4) and (9).

4. Conclusions

The implementation and extension of the energy recovery system among industrial companies allow obtaining direct and indirect effects. Thus, the findings prove that the energy recovery system leads to decreasing CO_2 emissions and increasing profit of the company by decreasing the energy costs. In this case, the government should develop incentive mechanisms for spreading such green technology in the industrial sector. Moreover, the energy recovery system is the most applicable for steel companies, which are the biggest polluters of the atmosphere. For this purpose, the most attractive instruments are tax exemptions and preferential loans on green innovation projects.

The findings show that the energy innovations at industrial companies lead not only to economic but also to ecological and social benefits. The same conclusion was obtained by the authors of [7,8,10,13]. At the same time, the efficiency of energy innovations is related to the currency rate, which is also confirmed by the authors of [6,8]. The implementation of the energy innovations at industrial companies leads to a reduction of the CO_2, SO_2 and dust emissions, which influences public health. Thus, the findings of short- and long-run Granger causality tests for VECM confirm the hypothesis that the distribution of the energy innovations among industrial companies allows reducing the CO_2 emissions and the death rate. The decline in carbon dioxide emissions by 1% allows decreasing the death rate by 0.5%, while increasing the number of patents in energy innovation technologies allows decreasing the death rate by 0.01%. Besides, the results of the ARDL model demonstrate the long- and short-run associations among carbon dioxide emissions, urban population and the death rate. However, the findings reject the existence of similar associations between the death rate and the number of patents in energy innovation technologies and net imports divided by the gross available energy. There are associations only in the long-run between the death rate and the number of patents in energy innovation technologies and in the short-run between the death rate and net imports divided by the gross available energy.

In this case, the Polish government should encourage and stimulate industrial companies and stakeholders to invest in energy innovation technologies. Considering the findings, the investment in energy innovations with government subsidies is more profitable than without. Besides, it is necessary to develop the appropriate condition for energy innovation sharing among industrial companies. It would allow obtaining the synergy effect which results in ecological, economic and social growth of the country.

Thus, the core drivers in the innovation policy of the country should be directed to using knowledge and scientific technologies, stimulating innovation activities, developing the attractive investment climate, modernising production assets, creating high-tech industries and sectors, increasing the energy efficiency of the industrial production and stimulating the sustainable development based on the attractive investment in green products and technologies. Consequently, the economic growth and social development of the country would be related not to the consumption of resources, but to the implementation of the green economy model.

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