Book Chapter

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 the industrial companies on the environment provokes the developing 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. The paper aims to justify the social, ecological and economic effects from implementing a new electricity production technology from post-process gas heat at the companies. The data for empirical justification was obtained from the experiment of applying the electricity production technology from post-process gas heat at Polish industrial companies. At the first stage, the author used the bibliometric analysis for highlighting the scientific background of economic evaluation of the innovations activity on energy technologies of industrial companies and its impact on the environment and public health. Secondly, the author estimated the economic and ecological efficiency of electricity production technology for the selected company. The results of the analysis confirmed that new technologies allowed increasing the energy efficiency of the company by decreasing energy consumption, increasing productivity etc. The findings proved that one of the ecological effects was the decrease of \( CO_2 \) and \( SO_2 \) emissions in the air. In this case, the author checked the link between the volume of \( CO_2 \) emissions and the rate of morbidity if such innovative technologies are scaled. The findings proved that decreasing \( CO_2 \) emissions by 1% leads to a decline in the death rate by 0.5%. The author approximated if the new technology was
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

Introduction

The snowball effect of environmental issues from the global warming calls for finding new solutions to cut the $CO_2$ emissions in the atmosphere. Besides, the massive range of instruments and mechanisms have been developed by experts and scientists. However, most of them do not have any practical application. Worldwide scientists justified that new green technologies have not only ecological effect (a decline in $CO_2$ emissions, 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 lead to a decline in the morbidity rate.

Thus, the results of bibliometric analysis proved that the scientists’ interest to 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). Noting this at the end of 2019, the European Union declared the New Green Deal Policy, according to which the EU is going to achieve the carbon-free economy by decreasing $CO_2$ emissions.
The most significant impact on the scientific research of this topic was made by Ansari Nirwan (New Jersey Institute of Technology). In the papers [1-2], he and his colleagues proved that extension of green energy leads to technological and economic effects. Besides, the scientists Zhang X., Wang Y., Wang S. confirmed that green electricity production has a positive economic and ecological impact [3-4] (Figure 2).

Besides, in the papers [3-4], the scientists 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.
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)

It should be noted that a vast range of scholars confirmed that spreading green electricity production among householders and industrial companies allows minimising the \( \text{CO}_2 \) emissions, decreasing the rate of morbidity and obtaining the additional economic benefits in the long-time period. In this case, it is possible to make conclusions that developing green electricity production is the multidisciplinary theme which contributes to the combination of knowledge and expertise. The findings show that this theme has often been analysed by scientists from the engineering and energy fields: the relevance makes up 23% and 18%. Only 2-5% of the papers studied these issues from the economic points of view (Figure 4).
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 first most significant cluster (blue) focuses on energy transfer technologies. Besides, this cluster is penetrating to all other clusters. The second cluster (green) focuses on energy conservation and green buildings. The yellow clusters merge 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 allows lowering the rate of morbidity. The red cluster is located close to the energy conservation and energy transfer clusters.

Findings of the bibliometric analysis showed that the theme of green electricity production technology is multidisciplinary. Besides, the green energy development allows achieving economic, social and ecological effects.

Thus, in the papers [6-10], the scientists confirm that distributing renewable energy among households allows achieving ecological and social effects. The authors of the article [8] maintain 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, in the papers [6,10] the scholars justify that biogas technologies for industrial companies are profitable and
has an indirect ecological and social effect. Besides, the authors [11-13] maintain 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 scientists in the papers [14-19] identify the instruments for stimulating green energy (feed-in tariff, taxes, green certificates, green investments and bonds) development and prove that efficiency of electricity production technology depends on the country. Lyulyov O. and his co-authors [20] maintain that green technologies lower the environmental damage. The group of the scientists in the articles [20-23] empirically prove that green energy enhances the energy security, the GDP and decreases the $CO_2$ emissions.

The analysis confirms that developing green technologies depends on the countries’ economic, social, innovation and ecological capabilities. Thus, the scientists in the papers [24-27] prove that the shadow economy and efficiency of public governance have a statistical impact on spreading the renewable energy. The authors [28-31] conclude that convergence of

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**Figure 4:** A visualisation map of the co-occurrence analysis **(Source: developed by the author based on Scopus and VOSviewer)**.
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 [32-34] confirm 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 scholars [35-44] analyse the options of the industrial companies to implement the green technologies. They prove 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 the companies which are not using green technologies and try to reduce the harmful damage to the environment.

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

**Materials and Methods**

Megacities comprise the most significant share of industries. 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 the atmosphere polluted with the nitrogen oxide, sulphur dioxide, carbon oxide, etc. The huge average concentration of those pollutants leads to increasing morbidity and mortality. Thus, the pollution from the big industrial companies has become the source of 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) and reducing a negative impact on the environment, and as a consequence, improving the public health.
The main hypotheses of the research are:

H1: the energy innovations at the industrial companies lead not only to economic but also to ecological and social benefits;

H2: the scaling of the innovation activities among the industrial companies on implementing energy efficiency technologies is the primary driver of social and economic development of the territory, the energy innovations contribute to the increase of the company’s productivity, reduction of the anthropogenic damage for the environment and improvement of the public health quality.

At the first stage of the research, with the purpose to check the H1, the author estimated the efficiency of the energy recovery system as an example of energy innovations at the Polish company. The installation allows using the heat from the combustion of post-reaction gases to heat compressed air to supply it 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 reaction 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 and a pressure of 6,000 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.

With the purpose to identify the impact of the implemented energy innovations at the industrial companies on the environment and public health as in the paper [45-46], the authors used the model of the production function of the public health

\[
H = F(E, CO_2, P, SE)
\]

where \( H \) is 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; \( SE \) 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, in the paper [47], the authors analysed the impact of Fossil Fuel Energy Consumption on the environment on the example of the EU countries. They highlighted that the energy dependence of a country influenced 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.

The global rating agencies estimate the innovation activities of the country using the integrated evaluation of the innovation development of the system [52; 53]: Global Innovation Index, Bloomberg Innovation Index, Global Competitiveness Index, Innovation Union Scoreboard, the quantity of the patents. In the paper, 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 the atmosphere pollutions, involving a decrease of carbon dioxide (\( CO_2 \)) emissions. Besides, it allows solving
issues with the safety of the atmosphere, which is the basis of public health [5].

The social and economic indicators involve the following: the openness of the economy, the level of urbanisation. The openness of the economy (Trade) allows estimating the options of innovation diffusion for increasing the country’s energy efficiency.

Cole M. A. in the paper [48] analyses how the openness of economy impacts the energy consumption in 32 developed countries in 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, the social wellbeing of the country, which could improve energy efficiency. In the paper [48,49] the scientists prove the statistical impact of the urbanisation on energy efficiency. The model (1) could be presented as an equation:

\[ H_t = \phi + \alpha E_t + \beta CO_2_t + \gamma \ln GII_t + \delta_1 Trade_t + \delta_2 U_t + \mu_t \quad (2) \]

where \( \phi, \alpha, \beta, \gamma, \delta_1, \delta_2 \) are regression parameters which are evaluated and explain the impact of \( E \) (net imports divided by the gross available energy, %), \( CO_2 \) (in a 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), \( U \) (Urban population, % of the total population) on \( H \) (death rate, crude, per 1,000 people); \( \mu \) is the error term; \( t=1,\ldots,T \).

At the first stage, for the purpose of the further analysis of the 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. The model (2) does not allow identifying the long-term impact of the determinants and eliminates the lags in the estimation. At the next stage, using the autoregressive
distributed lag (ARDL) method, the cointegration among the considered variables was done:

$$\Delta \ln H_t = \phi + \sum_{j=1}^{k_1} \alpha_0 \Delta \ln H_{t-j} + \sum_{j=1}^{k_1} \alpha_1 \Delta \ln E_{t-j}$$
$$+ \sum_{j=1}^{k_2} \beta \Delta \ln CO_{2t-j} + \sum_{j=1}^{k_3} \gamma \Delta \ln GII_{t-j} + \sum_{j=1}^{k_4} \delta 1 Trade_{t-j} + \sum_{j=1}^{k_5} \delta 2 U_t + \alpha_3 H_{t-1} + \alpha_4 E_{t-1} + \beta_1 CO_{2t-1} + \gamma_1 \ln GII_t + \delta_4 Trade_t + \delta_5 U_t + \mu_t$$ \hspace{1cm} (3)

where $\Delta$ is the first difference; $\phi$, $\alpha_0$, $\alpha_1$, $\beta$, $\gamma$, $\delta 1$, $\delta 2$, are the estimated coefficient of the lagged level of each variable; $\alpha_3$, $\alpha_4$, $\beta_1$, $\gamma_1$, $\delta 4$, $\delta 5$ are the lagged length of each variable chosen by the Schwarz data criteria; $\mu$ is the error term; $t=1,\ldots,T$.

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

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

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

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

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

\[ \Delta \ln \text{Trade}_t = \theta_0 + \sum_{j=1}^{k_1} \theta_1 \Delta \ln H_{t-j} + \sum_{j=1}^{k_2} \theta_2 \Delta \ln E_{t-j} + \sum_{j=1}^{k_3} \theta_3 \Delta \ln CO_{2t-j} + \sum_{j=1}^{k_4} \theta_4 \Delta \ln GII_{t-j} + \sum_{j=1}^{k_5} \theta_5 \text{Trade}_{t-j} + \sum_{j=1}^{k_5} \phi_6 2U_t + \omega 5ECT_{t-1} + \varepsilon_{it} \quad (8) \]

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

where \( ECT_{t-1} \) are the lagged error correction terms; \( \Delta \) is the first difference operator; \( \pi, \chi, \rho, \zeta, \theta, \phi \) are estimated indicators, \( \varepsilon_{it} \) is the error term; \( k \) is the lagged length of each variable chosen by the Schwarz data criteria (SIC).

**Results**

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

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

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

| Indicators | Changes | EUR exchange rate | Price of FeSi (EUR/t) | The average price of energy (PLN/MWh) | Investmen t outlays |
|------------|---------|-------------------|-----------------------|---------------------------------------|--------------------|
| NPV        | +20     | 111,570.69        | 109,978.30            | -20,495.44                            | 8,955.72           |
|            | +10     | 63,805.77         | 63,008.23             | -2,230.55                             | 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 findings confirm that the economic efficiency of investing in energy recovery system achieves the critical level if the currency exchange rate, price for FeSi decline by more than 10%, the average price of energy increases by more than 10% (Table 2).

The main ecological effects are the reduction of CO₂, SO₂ and dust emissions. Thus, the new technologies allowed cutting the CO₂ and SO₂ emissions by 5.88% and 380% correspondingly. The dust emissions declined by 33.3%. Besides, the efficiency of furnaces increased by 3.77%, 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 Nm³/h or by 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 the energy recovery system and without (calculation for 2015).

| Key Performance Indicators                          | Before | After  | Changes, % |
|-----------------------------------------------------|--------|--------|------------|
| Efficiency furnaces Mg / 24h                        | 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 (Nm³/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. So, each year the company reduces 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 reduces 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 showed in Table 4.

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

| Key Performance Indicators | 2015 | 2016 | 2017 | 2018 | 2019 |
|----------------------------|------|------|------|------|------|
| Efficiency furnaces Mg / 24h| 22.83| 22.27| 22.34| 22.78| 22.32|
| Heat generation from       | 6.54 | 5.4  | 6.54 | 5    | 6.25 |
recovery (GJ / h)

| Description | 50.65 | 50.65 | 50.6 | 50.56 | 50.5 |
|-------------|-------|-------|------|-------|------|
| The energy efficiency of FeSi production by 75% (%) |       |       |      |       |      |
| Reduction of $CO_2$ emissions (Mg / MWh) | 0.9   | 1     | 0.9  | 0.9   | 0.9  |
| Reduction of SO2 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 (Nm³/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.

The empirical finding of key performance indicators of energy recovery system confirmed that this energy innovation technologies contribute not only to direct economic but also ecological effects – reduction of $CO_2$ and SO2 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, at the next stage of the research, the H2 was checked. Table 5 contains the findings of descriptive statistics of the indicators from the model (2) for Poland in the period of 1995-2018.
Table 5: Descriptive statistics for E, CO₂, GII, Trade, U, H for Poland, 2010-2019.

| Descriptive statistics | E       | CO₂     | 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 CO₂ (0.042), H (0.036), 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 inefficient and ecological unsafety management of resource- and energy-intensive industries and technologies, raw material export orientation and over-concentration of production in industrial regions, as well as 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 model with Intercept and with Intercept and Trend confirmed that all indicators were at a level I (1) (Table 6). The findings allowed a further analysis of the long-term relations among the indicators of the model (2).

Table 6: The findings of linear unit root tests.

| Variable | Augmented Dickey-Fuller Intercept | Augmented Dickey-Fuller Intercept and trend | Phillips–Perron Intercept | Phillips–Perron Intercept and trend | Dickey-Fuller-GLS Intercept | Dickey-Fuller-GLS 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                                    | -3.074                    | -1.841                             | -1.804                      | -1.880                                |
| H        | -0.072                            | -1.687                                    | -0.072                    | -1.319                             | -0.072                      | -1.319                                |
| $\Delta E$ | -3.991*                         | -3.940**                                  | 3.024**                   | 3.911***                           | -2.183**                    | -3.802*                               |
| $\Delta CO_2$ | -4.470*                       | -4.099*                                   | -4.470*                   | -3.793*                            | -4.371*                     | -3.793*                               |
| $\Delta GII$ | -7.256*                        | -7.389*                                   | -7.389*                   | -7.410*                            | -7.737*                     | -7.737*                               |
| $\Delta Trade$ | -5.275*                      | -5.122*                                   | -12.062*                  | -5.377*                            | -5.421*                     | -5.421*                               |
| $\Delta U$ | -3.552*                        | -5.664*                                   | -3.907**                  | -3.622*                            | -4.117                       | -4.117                                |
| $\Delta H$ | -5.805*                        | -7.267*                                   | -5.801                    | -7.559                             | -5.801                      | -7.559                                |

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

At the next stage, the Johansen tests for cointegration was done. The results of Johansen tests for cointegration are summarized in Table 7.

Table 7: The empirical results of Johansen tests for cointegration results.

| Maximum rank | Trace statistic | 5% Critical value |
|--------------|----------------|-------------------|
| r=0          | 140.208        | 83.937*           |
| r=1          | 70.460         | 60.061*           |
The data in Table 7 allowed concluding on existing the long-term relations among selected indicators. Nevertheless, considering the AIC criteria, 2 was the optimal lag for involving the indicators in the model. The findings on Trace statistics (Table 7) allowed rejecting the null hypothesis on none cointegration among analysed indicators E, CO₂, GII, Trade, U τα Η.

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 |
| CO₂ | 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 |
| ΔCO₂ | 0.426261 | 0.17644 | 2.415895 | 0.0311 |
| ΔGII | 0.000987 | 0.003504 | 0.281552 | 0.7827 |
| ΔTrade | -0.04865 | 0.017407 | -2.79456 | 0.0152 |
| ΔU | 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 analysis results allowed concluding that the parameters of carbon dioxide emissions (CO₂), the number of patents in energy
innovation technologies (GII), urban population (U) had the statistically significant impact on the death rate, crude, per 1,000 people (H). So, the reduction of carbon dioxide emissions (CO₂) by 1% leads to a decrease of the death rate (H) by 0.5%. The increasing 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 confirmed the positive impact of urban population (U) on of the death rate (H) as in the paper [54]. On the example of the United Nations, the scientists in the paper [54] empirically justified that the increase of urban population (U) leads to premature mortality by 39.6%. At the same time, in the short-term period, only indicators of carbon dioxide emissions (CO₂), urban population (U) and Trade had a statistically significant impact on the death rate (H).

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

Table 9: The empirical results of Granger causality tests.

| Dependent variable | Short-run | Long-run | ECT (−1) |
|--------------------|-----------|----------|----------|
|                    | ΔH        | ΔE       | ΔCO₂     | ΔGII     | ΔTrade   | ΔU       |          |
| ΔH                 | 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   |
| ΔCO₂               | 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    |
| ΔU                 | 0.020     | 0.001    | 0.002    | 0.004    | -0.0007  | 0.928*   | -0.008** |

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

The findings allowed concluding that for Poland the 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 Eqs. (4) and (9).

**Conclusions**

The findings allowed maintaining that the energy innovations at the industrial companies lead not only to economic but also to ecological and social benefits. The same conclusion was obtained by the scientists in the papers [7,8,13,10]. At the same time, the efficiency of energy innovations is related to the currency rate, which is also confirmed by the scientists in the papers [6,8]. The implementation of the energy innovations at the industrial companies leads to a reduction of the \( CO_2 \), \( SO_2 \) and dust emissions which influenced the public health. So, the findings of short and the long-run Granger causality tests for VECM confirmed the hypothesis that the distribution of the energy innovations among the industrial companies allowed reducing the \( CO_2 \) emissions and the death rate. The decline in carbon dioxide emissions by 1% allowed decreasing the death rate by 0.5% and the increasing number of patents in energy innovation technologies allowed decreasing the death rate by 0.01%. Besides, the results of the ARDL model demonstrated the long and short-run associations among the carbon dioxide emissions, urban population and the death rate. However, the findings reject the existence the similar associations between the death rate and the number of patents in energy innovation technologies, net imports divided by the gross available energy, only in the long-run between the death rate and the number of patents in energy innovation technologies, 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 innovations sharing and transfers of
energy innovations among industrial companies. It allows obtaining the synergy effect which appears in ecological, economic and social growth of the country.

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

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