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# RENEWABLE ENERGY AND ENERGY INNOVATIONS: EXAMINING RELATIONSHIPS USING MARKOV SWITCHING REGRESSION MODEL

**Abstract**. *Accelerating the development of new energy infrastructure in the EU based on renewable energy sources is necessary for the targeted reduction of greenhouse gas emissions and increase in energy production from renewable sources. This article reviews current renewable energy development issues and research on energy innovations within the European energy policy. The effectiveness of energy generation from renewable resources and adaptation of energy innovations may be limited to the challenges of ensuring the flexibility of the pan-European energy system, as the development of energy storage systems and technologies to respond to demand is much slower than the development of renewable energy. Therefore, the study's primary purpose was to explain by mathematical modelling the determinism of variation in electricity production in the EU27 due to predictors of net electricity generation from certain types of renewable resources for 2017-2020. To identify the effects of the deployment of renewable energy in the EU27, a regression model of Markov switching for three regimes was chosen, consisting of selected predictors of clean energy generation from renewable sources (hydro, geothermal, wind, and solar). The statsmodels v0.13.2 toolkit in Python 3.10.5 was used to conduct this study. The variation between total electricity production and net electricity generation in the EU27 is not constant and depends on the mode of electricity production. That is, there is an asymmetry in the relationship between these parameters. The results also show that when the electricity generation rate in the EU27 is moderate, the net wind energy generation rate is not significant. Furthermore, the negative link between clean solar energy generation and electricity production in the EU is significant for all three regimes.*

**Keywords**: European energy policy, sustainable development goals, green innovations, the efficiency of energy policy.

**Introduction.** Investment and innovation flows have accelerated significantly in the EU in recent years as part of the renewable energy deployment. The electricity generation increase was mainly due to wind and solar power, while the production of other renewable sources remained virtually unchanged (hydro, geothermal, or biofuels). According to Eurostat estimates, from 2000 to 2019, the power of wind energy generation increased fourteen times, and solar power generation 700 times over the same period. However, the capacity of renewable energy increase is not equivalent to the growth of electricity generation. Solar and wind energy production is variable and depends on weather conditions, seasons, and geographical location. The new plants do not operate at maximum capacity all the time. Still, the construction and expansion of the relevant energy infrastructure are needed to meet the EU's renewable

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energy targets (Eurostat, 2021).

The share of variable renewable energy sources is expected to increase further in the coming years. Due to large-scale investment in innovative wind energy technologies and the development of offshore wind farms, it is expected that wind energy will become the leading source of renewable energy in the EU. Such leadership in innovation for continuous transition meets the challenges of the flexibility ensuring of the pan-European energy system, the development of energy storage system, response technology on demand is much more accessible than the development of renewable energy (IEA, 2020). However, is wind energy the best option for investing in energy innovation compared to other renewable energy sources in terms of electricity generation in the EU? Furthermore, is wind energy generation better suited to the peak load conditions of the European energy system? Deepening the understanding and mathematical modelling of the renewable electricity generation components in the EU is needed. Therefore, this article aimed to explain the determinism of variation in electricity production in the EU27 due to predictors of clean electricity generation from certain renewable resources using mathematical modelling.

This study contains five sections. The second section reviews some of the issues surrounding the deployment of energy innovation and the transition to a carbon-neutral economy in Europe. In the third section, the authors described the data and research methods (regression model of Markov switching). The results of modelling electricity generation in the EU27 for the three modes of the Markov model are presented in the fourth section. Furthermore, the conclusions complete this study.

**Literature Review.** The innovative development issue is quite popular among scientists in various fields. Thus, Ayodele et al. (2019) investigated innovation as a driver in enhancing the interaction between internal and external factors of agricultural development. Introduction of innovative technologies into the educational process (Vorontsova et al., 2018) and changing of paradigm and requirements for skills and knowledge of graduates and employees, the transition to the concept of «lifelong learning» analyzed by (Tutar et al., 2019). Teletov et al. (2020) defined the role of innovative marketing tools in promoting industrial products. Syhyda et al. (2020) identified the relationship between innovation and Industry 4.0 as a basis for developing the Internet of Things and information transformation. The innovations in commercialization are well studied, particularly in terms of the innovative impact of intensive commercialization of the post-industrial economy on the country's competitive advantages in the global economic environment (Virchenko et al., 2021). Lyeonov et al. (2020), Chukwu and Kasztelnik (2021), and Didenko and Sidelnyk (2021) analyze the innovative technologies introduced in the financial sector, which is inextricably linked with the functioning of the other national economy sectors and interdependent with the business environment parameters. Samoilikova (2020) demonstrates the study results of the world and European innovation development rankings, determines the financial policy indicators with the most significant impact on the dynamics of innovation, substantiates the causes of inadequate financial innovation security, formalizes functional relationships between competitiveness and innovation capacity, and between indicators of the country's innovation capacity and business and financial system development.

In their works, Zakharkin and Zakharkina (2014); Zakharkin (2019) research the industrial enterprises' innovative development, which is usually influential consumers of energy resources and is directly involved in the transition to a carbon-neutral economy. The authors analyze the impact of environmental factors on the enterprises' innovation activities; identify the structure-forming and priority sectoral vector of development; propose tools for stimulating and state support for innovation activities of industrial enterprises. Ojeda, F.A. analyzed the degree of innovation of countries using a strategic matrix that allows for assessing the behaviour of leading countries for each of the diamond points, identifying strengths and weaknesses of existing policies, tools to address them, priorities for each strategy to increase innovation. On this basis, the concept of «green innovation diamond» is defined.

Kolosok et al. (2021) conducted a comprehensive literature review of modern research in energy, sustainable development, and innovation. For a long time, renewable energy has played a significant role in the study of scientists. Many research results on renewable energy have been published in the scientific literature. However, the subject of research varies significantly from study to study. Wustenhagen et al. (2007) study the social preconditions necessary for developing alternative energy. Gielen et al. (2019) and Johnstone et al. (2010) reviewed the importance of renewable energy for forming an innovative energy system. Reducing the negative impact on the environment through introducing renewable energy technologies has been studied by Markewitz et al. (2012) and Horbach et al. (2012). Features of renewable energy generation and distribution, problems and prospects of development in the European Union, modelling the industry economic growth, etc. Apergis and Payne (2010, 2012), Dogan and Seker (2016), (Delucchi, 2007), (Demirbas, 2009), Haas et al. (2015), Hamilton (1989), Jacobsson and Bergek (2004), Jacobsson and Laube (2006), (Menegaki, 2011), Schiebahn et al. (2015), Suri et al. (2007) researched in his works.

The authors Vakulenko and Myroshnychenko (2015) identify two approaches to implementing energy efficiency policy and innovations in the economy's energy sector at the regional level. In their study, the authors evaluate each approach, identifying investment, environmental, social, and organizational aspects, and develop practical recommendations for improving the development and implementation of comprehensive programs in the energy-saving and energy efficiency field.

The study by Vakulenko and Myroshnychenko (2015) draws attention to the institutional environment's significant role in the energy sector's development. Pavlyk (2020a) agrees and examines the impact of institutional determinants on the energy efficiency gap in the economy and confirms this by analyzing statistics. The study by Newell et al. (1999), despite long-standing research, raises the still compelling question of the relationship between energy and the pace of innovation in the energy, national, and global economies.

Bhowmik (2019) will study how the current energy policy of rolling out environmentally friendly technologies affects CO2 emissions and GDP per capita in the Scandinavian region. Balsalobre-Lorente et al. (2018) conducted research in the same direction. Given the importance of the institutional component in the implementation of energy policy, El Amri et al. (2020) argue that the control of greenhouse gas emission limits in the industrial sector economy creates new opportunities for promising economic development. The authors consider the most effective means of energy management aimed at changing the paradigm of energy development. Pavlyk (2020b) published similar results of the study on the energy efficiency gap. Many scientists are studying mechanisms for stimulating green innovation in energy. At the same time, considerable attention is paid to pricing instruments. Ley et al. (2016) study the Impact of Energy Prices on Green Innovation in detail.

Deployment of innovative energy technologies is possible only in the presence of a reliable evaluation system of their efficiency. It helps implement the most effective innovative projects in the energy sector. Lyulyov et al. (2021) and Kwilinski et al. (2022) studied the evaluation of innovative energy technologies, including smart grids. A study by Kwillinski et al. (2022) investigated the possibility of applying a universal approach to evaluating different energy innovations.

**Methodology and research methods.** Eurostat's monthly data cover the period from January 2017 to December 2020. The dependent variable - electricity generation in the EU27 - is determined by the electricity generation index, and, as shown in Table 1, four independent indices are included in the analysis. To obtain explicit data attributes, the authors decided to standardize them. All model parameters were standardized to facilitate their proportional contribution to the model optimization result. Z-score scaling (1) was used to equalize the mean values and the standard deviation for all variables in the data set:

$$x'_t = \frac{x_t - \mu}{\sigma} \quad (1)$$

where $x_t$ – original vector of time variables $t$, $\mu$ – the average value of this variables vector, $\sigma$ – its standard deviation.

After standardizing the data, graphs were constructed to select the best model for the parameters estimated by implementing multiple event modes (Figure 1). Let's consider the results of data standardization. We can see for the EU27 different seasonal peaks and troughs for the index of total electricity production and indices of clean energy generation from certain renewable resources (hydro, geothermal, wind, and solar).

**Table 1. The input variables of the model**

| Indicator | Indicator description | Unit of measure |
|---|---|---|
| $ei_m$ | The EU27 production of electricity | Gigawatt-hour (GWh) |
| $nrg_h$ | The EU27 net electricity generation by hydropower | Gigawatt-hour (GWh) |
| $nrg_g$ | The EU27 net electricity generation by geothermal power | Gigawatt-hour (GWh) |
| $nrg_w$ | The EU27 net electricity generation by wind power | Gigawatt-hour (GWh) |
| $nrg_s$ | The EU27 net electricity generation by solar power | Gigawatt-hour (GWh) |

Sources: developed by the authors.

Given the frequent changes in the EU renewable energy deployment and hence the random nature of green energy driving innovations, the Markov-switching dynamic regression model was chosen to assess the effects of EU energy policy. The Markov-switching mechanism was first considered by Goldfeld and Quandt (1973). And then, Hamilton (1989) proposed a method for estimating this mechanism and presented a detailed analysis of the Markov-switching model. The model is widely used to evaluate different states of dynamic data and can be found in the works of Maneejuk et al. (2021), Temkeng and Fofack (2021), and Moutinho et al. (2022). In general, the Markov-switching model has the form as the follows (2):

$$y_t = c_s + x_t\alpha_s + z_t\beta_s + \varepsilon_s \quad (2)$$

where $y_t$ – dependent variable that describes the dynamic behaviour of a data series in the time $t$; $c_s$ – free member regression for the regime $s$ = {1,..,S}; $x_t$ – vector of exogenous invariant variables in the time $t$; $\alpha_s$ – invariant coefficients for the regime s = {1,..,S}; $z_t$ – exogenous dependent variables vector for the regime $s$ = {1,..,S}; $\beta_s$ – dependent coefficients for the regime $s$ = {1,..,S}; $\varepsilon_s$ – is an i.i.d. normal error, taking into account the random nature of innovations in the energy sector for the regime $s$ = {1,..,S}.

Also, the Markov-switching model can be written taking into account the dynamic nature of the modes s in the form below (3):

$$y_t \sim \begin{cases} f_1(y_t; x_t, \theta_1), s = 1 \\ \quad \vdots \qquad , \quad \vdots \\ f_S(y_t; x_t, \theta_S), s = S \end{cases} \quad (3)$$

where $f_i$ – sub model of the $i$-th regime $s$ = {1,..,S}; $\theta_i$ – a set of dynamic model parameters that consider the random nature of innovations in the energy sector for the regime $s$ = {1,..,S}.

According to the proposed model, the authors tested the determinism of variation in electricity production by predictors of the electricity net generation from certain types of renewable resources (hydro, geothermal, wind, and solar) in the EU27 by substantiating hypotheses (4):

$$H_0 : \beta_1 = \beta_2 = .. = \beta_N = 0;$$
$$H_a : \exists\ \beta_i \neq 0,\ i = 2,..,N. \qquad (4)$$

To conduct this study, we used the statsmodels v0.13.2 toolkit in Python 3.10.5. Markov switching dynamic regression simulation for three modes was performed using this toolkit.

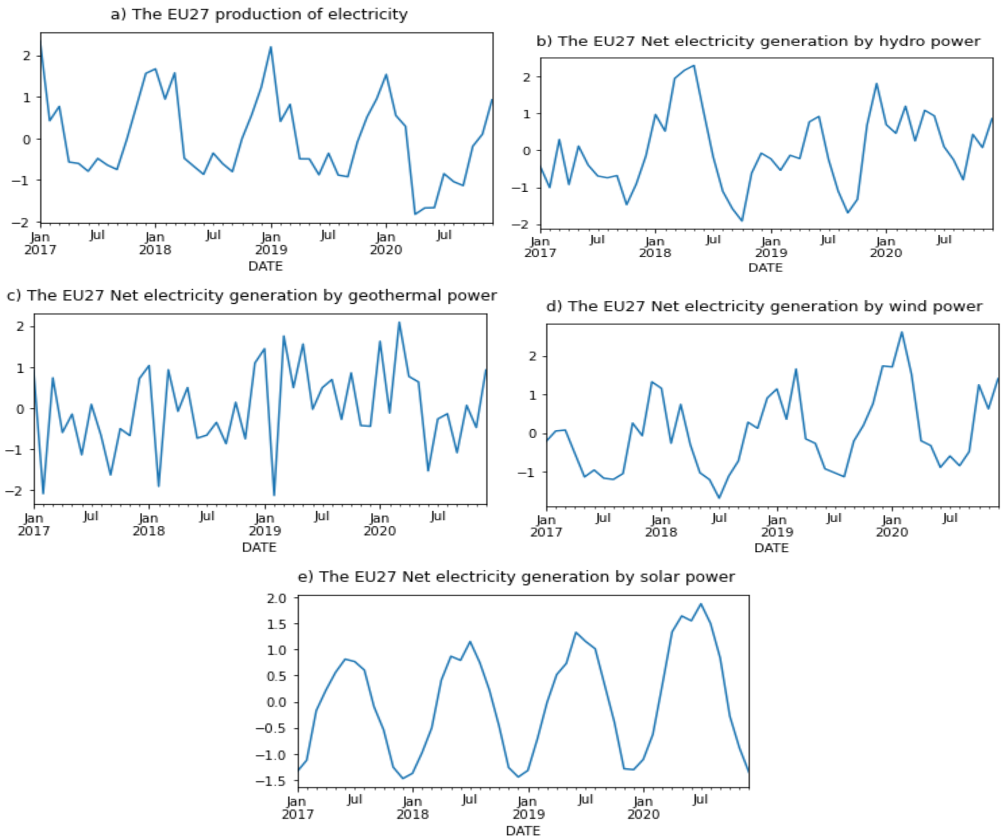


**Figure 1. Comparing the input variables of the model**

Sources: developed by the authors based on (Eurostat, 2022a, 2022b).

**Results**. Modelling was performed based on three modes to identify the effects of invariant and dependent characteristics of the innovative deployment of renewable energy in the EU27. Table 2 presents the Markov-switching dynamic regression modelling of electricity generation and selected predictors of energy generation from renewable energy sources (hydro, geothermal, wind, and solar) in the EU27. In this case, these three regimes can be considered to have low, moderate, and high levels of electricity production in the EU27. Fig. 2 shows the smoothed probabilities of each of the three modes.

**Table 2. The results of Markov-switching dynamic regression modelling**

Regime 0 parameters

| | coef | std err | z | P>\|z\| | [0.025 | 0.975] |
|---|---|---|---|---|---|---|
| const | -0.1370 | 0.017 | -7.939 | 0.000 | -0.171 | -0.103 |
| x1 | 0.0141 | 0.022 | 0.637 | 0.524 | -0.029 | 0.057 |
| x2 | 0.0050 | 0.029 | 0.169 | 0.866 | -0.053 | 0.062 |
| x3 | -0.1004 | 0.039 | -2.600 | 0.009 | -0.176 | -0.025 |
| x4 | -0.3115 | 0.048 | -6.489 | 0.000 | -0.406 | -0.217 |
| sigma2 | 0.0009 | 0.001 | 1.796 | 0.073 | -8.36e-05 | 0.002 |

Regime 1 parameters

| | coef | std err | z | P>\|z\| | [0.025 | 0.975] |
|---|---|---|---|---|---|---|
| const | 0.0056 | 0.040 | 0.138 | 0.890 | -0.074 | 0.085 |
| x1 | -0.0889 | 0.053 | -1.678 | 0.093 | -0.193 | 0.015 |
| x2 | 0.0687 | 0.051 | 1.356 | 0.175 | -0.031 | 0.168 |
| x3 | 0.3284 | 0.081 | 4.053 | 0.000 | 0.170 | 0.487 |
| x4 | -0.4399 | 0.060 | -7.349 | 0.000 | -0.557 | -0.323 |
| sigma2 | 0.0203 | 0.008 | 2.424 | 0.015 | 0.004 | 0.037 |

Regime 2 parameters

| | coef | std err | z | P>\|z\| | [0.025 | 0.975] |
|---|---|---|---|---|---|---|
| const | 0.0380 | 0.070 | 0.541 | 0.588 | -0.100 | 0.176 |
| x1 | 0.2238 | 0.105 | 2.139 | 0.032 | 0.019 | 0.429 |
| x2 | 0.2827 | 0.080 | 3.526 | 0.000 | 0.126 | 0.440 |
| x3 | -0.1789 | 0.112 | -1.596 | 0.110 | -0.399 | 0.041 |
| x4 | -1.2486 | 0.100 | -12.504 | 0.000 | -1.444 | -1.053 |
| sigma2 | 0.0910 | 0.031 | 2.890 | 0.004 | 0.029 | 0.153 |

Sources: developed by the authors based on (Eurostat, 2022a, 2022b).

Looking at the values of the selected coefficients in the results, we can write the model equation for a particular mode as follows:

– for mode 0 model parameters (5):

$$ei_m = -0.1370 + 0.0141 \cdot \mathrm{nrg}_h + 0.005 \cdot \mathrm{nrg}_g - 0.1004 \cdot \mathrm{nrg}_w - 0.3115 \cdot \mathrm{nrg}_s + \varepsilon_t \quad (5)$$

where $\varepsilon_t$~ N(0, 0.0009).

- for mode 1 model parameters (6):

$$ei_m = 0.0056 - 0.0889 \cdot \mathrm{nrg}_h + 0.0687 \cdot \mathrm{nrg}_g + 0.3284 \cdot \mathrm{nrg}_w - 0.4399 \cdot \mathrm{nrg}_s + \varepsilon_t \quad (6)$$

where $\varepsilon_t$~ N(0, 0.0203).

- for mode 2 model parameters (7):

$$ei_m = 0.0380 + 0.2238 \cdot \mathrm{nrg}_h + 0.2827 \cdot \mathrm{nrg}_g - 0.1789 \cdot \mathrm{nrg}_w - 1.2486 \cdot \mathrm{nrg}_s + \varepsilon_t \quad (7)$$

where $\varepsilon_t$~ N(0, 0.091).

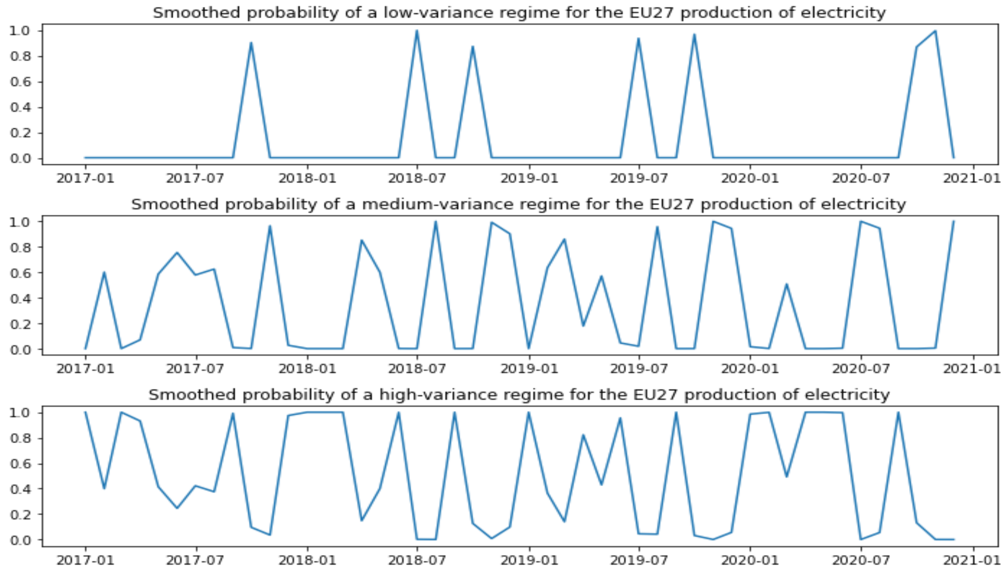


**Figure 2. The smoothed probabilities of regimes**

Sources: developed by the authors on the basis of (Eurostat, 2022a, 2022b).

The three-mode model analysis results show no relationship between all three modes of electricity generation and net hydropower generation. Net generation of geothermal energy does not affect the total electricity production in the EU27 in regimes 0 and 1, but it is related to electricity production in mode 2. The results also show that when the electricity generation factor in the EU27 is moderate in regime 1, the net wind energy generation factor is not significant. And for all three regimes, the negative link between clean solar energy generation and electricity production in the EU is substantial. That is, during the peaks of energy production (and hence - and its consumption), the generation of solar energy decreases, and during declines in energy production – it increases. This situation with unsustainable clean electricity generation in the EU27 still requires the deployment of additional balancing capacity to reduce generational fluctuations from renewable energy sources, usually covered by fossil energy sources, mainly natural gas and coal. Furthermore, the development of electricity storage systems to increase the energy systems' flexibility and reduce peak loads is still insufficient.

**Conclusions**. Expanding renewable energy sources in electricity generation is needed to achieve the EU's ambitious goals of building a climate-neutral economy. In recent decades, the capacity structure for electricity generation in the EU has changed dramatically through innovations in wind and solar energy. Due to this, the share of nuclear power in the EU electricity production has been reduced, while the capacity for generating energy from renewable sources has increased.

This paper examines the determinism of variation in electricity production in the EU27 due to predictors of net electricity generation from certain types of renewable resources from January 2017 to December 2020. The study assumed that there are three regimes for electricity generation in the EU27: low, moderate, and high. A regression model of Markov switching was used for empirical estimation. The empirical study's results allowed us to understand better the nature of variation in electricity production in the EU27. The level of variation between total electricity production and net electricity generation from certain types of renewable resources (hydro, geothermal, wind, and solar) in the EU27 is not constant. It depends on the mode of electricity production. That is, there is an asymmetry in the relationship between these parameters. The results also show that when the electricity generation rate in the EU27 is moderate, the net wind energy generation rate is not significant. And for all three regimes, the negative link between clean solar energy generation and electricity production in the EU is substantial. As the renewable energy introduction is well ahead of the energy storage systems deployment, there is an urgent need further to increase the flexibility of the EU energy system.

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**Відновлювана енергетика та енергетичні інновації: дослідження взаємозв'язків за допомогою регресійної моделі перемикання маркова**

Прискорення розбудови нової енергетичної інфраструктури в країнах ЄС на базі відновлюваних джерел енергії є необхідною умовою цільового скорочення викидів парникових газів та збільшення обсягу виробництва енергії з відновлюваних джерел. У цій статті виконано огляд актуальних питань розвитку сфери відновлюваної енергетики та дослідження енергетичних інновацій у межах європейської енергетичної політики. Результативність генерації енергії з відновлюваних ресурсів, адаптації енергетичних інновацій може обмежуватися викликами забезпечення гнучкості пан-європейської енергетичної системи, оскільки розвиток систем акумулювання енергії, технологій реагування на попит відбувається значно повільніше, ніж розвиток відновлюваної енергетики. Тому основною метою дослідження було пояснення засобами математичного моделювання детермінованості варіації виробництва електроенергії в ЄС27 за рахунок предикторів чистої генерації електроенергії з окремих видів відновлюваних ресурсів за 2017-2020 роки. Для виявлення ефектів розгортання інновацій у сфері відновлюваної енергетики в ЄС27 була обрана регресійна модель перемикання Маркова для трьох режимів, що складалася з обраних предикторів чистої генерації енергії з відновлюваних джерел (гідро, геотермальної, вітра та сонця). Для проведення даного дослідження застосовувався інструментарій statsmodels v0.13.2 у середовищі Python 3.10.5. Рівень варіації між загальним обсягом виробництвом електроенергії та обсягами чистої генерації електроенергії в ЄС27 не є постійними та залежать від режиму виробництва електроенергії. Тобто існує асиметрія взаємозв'язку між цими параметрами. Результати також свідчать про те, що коли коефіцієнт виробництва електроенергії в ЄС27 є помірний, коефіцієнт чистої генерації енергії вітру не є значущим. І для всіх трьох режимів є значущим негативний зв'язок між чистою генерацією енергії сонця та виробництвом електроенергії в ЄС.

**Ключові слова:** європейська енергетична політика, цілі сталого розвитку, зелені інновації, ефективності енергетичної політики.