PROBLEMY EKOROZWOJU/ PROBLEMS OF SUSTAINABLE DEVELOPMENT
SUBMITTED: 25.05.2024, ACCEPTED: 20.06.2024, PUBLISHED ON-LINE: 10.01.2025
2025, 20(1): 207-220
DOI: 10.35784/preko.6255

A Framework for Modeling the Decarbonization of the Economy Based on Energy Innovations in the Context of Industry 5.0 and Sustainable Development: International Perspective

Ramy modelowania dekarbonizacji gospodarki w oparciu o innowacje energetyczne w kontekście Przemysłu 5.0 i zrównoważonego rozwoju: perspektywa międzynarodowa

Maryna Kravchenko[1], Kateryna Kopishynska[2], Olena Trofymenko[3], Ivan Pyshnograiev[4], Kateryna Boiarynova[5]

National Technical University of Ukraine, Igor Sikorsky Kyiv Polytechnic Institute, Kyiv, Ukraine
[1]E-mail: marina.kravchenko.kpi@gmail.com, ORCID: 0000-0001-5405-0159
[2]E-mail: kopishynska@ukr.net, ORCID: 0000-0002-1609-2902
[3]E-mail: o.o.trofymenko@gmail.com, ORCID: 0000-0002-2339-0377
[4]E-mail: pyshnograiev@gmail.com, ORCID: 0000-0002-3346-8318
[5]E-mail: boyarinovaea@ukr.net, ORCID: 0000-0001-5879-2213

Abstract
The concept of Industry 5.0 emerges as a catalyst for accelerating sustainable development across various economic sectors. This article is devoted to the development of a framework for modeling the decarbonization of the economy based on energy innovation in the context of Industry 5.0 and sustainable development. The purpose of the article is to identify the stimulating factors for increasing the level of decarbonization, which corresponds to the Global Sustainable Development Goals adopted by the UN in 2015, especially Goal 7 *Affordable and Clean Energy*, Goal 9 *Industry, Innovation, and Infrastructure*, Goal 13 *Climate Action* and Goal 17 *Partnerships for the Goals*. Approaches to the formation of Industry 5.0 indicators, taking into account indicators of sustainable development and decarbonization of the economy, in particular, the Energy Transition Index, Global Innovation Energy Index, Digital Economy and Society Index, World Energy Trilemma Index, are investigated. The choice of Industry 5.0 components with indicators for the assessment of decarbonization, taking into account the components of sustainability, resilience and human-centricity, is justified. These include Energy intensity level of primary energy; Fossil CO_2 Emissions in Power Sector; Patents in Climate change mitigation technology; Research and development expenditure; Industry (including construction), value added (% of GDP); Information and communication technologies (ICTs); Knowledge workers; Human capital and research. A cluster analysis of the level of decarbonization for the 26 countries selected for the study from Europe, Asia and North America is carried out. Taking into account the factors studied, the factors influencing the level of decarbonization are identified based on multivariate regression modelling. Recommendations on accelerating the decarbonization of the economy are provided, taking into account the experience of leading countries.

Key words: decarbonization, energy innovations, Industry 5.0, sustainable development, multivariate regression

Streszczenie
Koncepcja Przemysłu 5.0 jawi się jako katalizator przyspieszający zrównoważony rozwój w różnych sektorach gospodarki. Artykuł poświęcony jest opracowaniu ram modelowania dekarbonizacji gospodarki w oparciu o innowacje energetyczne w kontekście Przemysłu 5.0 i zrównoważonego rozwoju. Celem artykułu jest identyfikacja

czynników stymulujących wzrost poziomu dekarbonizacji, co wpisuje się w Globalne Cele Zrównoważonego Rozwoju przyjęte przez ONZ w 2015 roku, w szczególności Celowi 7 *Przystępna i czysta energia*, Celowi 9 *Przemysł, innowacje i infrastruktura*, Celowi 13 *Działania na rzecz klimatu* oraz Celowi 17 *Partnerstwa dla Celów*. Badane są podejścia do tworzenia wskaźników Przemysłu 5.0, uwzględniające wskaźniki zrównoważonego rozwoju i dekarbonizacji gospodarki, w szczególności Energy Transition Index, Global Innovation Energy Index, Digital Economy and Society Index i World Energy Trilemma Index. Wybór komponentów Przemysłu 5.0 wraz ze wskaźnikami oceny dekarbonizacji, uwzględniającymi komponenty zrównoważonego rozwoju, odporności i skupienia się na człowieku, jest uzasadniony. Należą do nich: poziom energochłonności energii pierwotnej; Emisje CO_2 ze źródeł kopalnych w sektorze energetycznym; Patenty w technologii łagodzenia zmian klimatycznych; Wydatki na badania i rozwój; Przemysł (w tym budownictwo), wartość dodana (% PKB); Technologie informacyjno-komunikacyjne (ICT); Pracownicy umysłowi; Kapitał ludzki i badania naukowe. Przeprowadzono analizę skupień poziomu dekarbonizacji dla 26 wybranych krajów z Europy, Azji i Ameryki Płn. Biorąc pod uwagę badane czynniki, na podstawie wieloczynnikowego modelowania regresji identyfikuje się czynniki wpływające na poziom dekarbonizacji. Wydano rekomendacje mające na celu przyspieszenie dekarbonizacji gospodarki, biorąc pod uwagę doświadczenia krajów wiodących.

Słowa kluczowe: dekarbonizacja, innowacje energetyczne, Przemysł 5.0, zrównoważony rozwój, regresja wielowymiarowa

1. Introduction

In the face of escalating climate change and the imperative to achieve sustainable development goals, the decarbonization of economies has emerged as a critical global challenge. Central to this endeavor is the integration of advanced energy innovations within the framework of Industry 5.0 – a paradigm that emphasizes the convergence of digitalization, automation, and sustainability in industrial processes. This defines the key difference between Industry 5.0 and Industry 4.0. The fourth industrial revolution is based on the integration of information and operational technologies with near-real-time connectivity in the factory to provide operational information to decision makers. However, Industry 4.0 relies heavily on automation, which can cause resistance from factory workers. The testing of these technologies showed positive results, but there was a need for their further intellectualization and individualization of production processes for specific client needs, so specialists are currently beginning to adapt to the model of the next industrial level - Industry 5.0. The importance of developing Industry 5.0 technologies and their significant contribution to sustainable development is confirmed by the European Commission's reports *Industry 5.0: Towards more sustainable, human-centric and resilient European Industry* (European Commission, 2021), Industry of the Future - A transformative vision for Europe: governing systemic transformations towards a sustainable industry (Report on the state of the Digital Decade, 2023). Sustainable development strategies encompass a broad range of approaches aimed at achieving economic prosperity, social inclusion, and environmental sustainability both globally and locally. These strategies are essential for addressing pressing challenges such as climate change, resource depletion, and social inequality. Taking into account the new opportunities of Industry 5.0, the decarbonization of the global economy is expected to accelerate, which is a goal set by leading countries. The EU's decarbonization strategy is presented in the European Green Deal (European Commission. 2020), the US - in the National Blueprint for Transportation Decarbonization (U.S. Department of Transportation, 2023), the UK - Net Zero Strategy: Build Back Greener (HM Government, 2021) and others. This confirms the importance and timeliness of forming decarbonization directions, taking into account the conditions of Industry 5.0, which determines the relevance of this study.

2. Literature review

Research by modern scientists emphasizes the importance of the role of Industry 5.0 in ensuring sustainable development, which is closely linked to decarbonization. One of the first to publicly present their vision of a model of Industry 5.0 was the American business consulting firm Frost & Sullivan (Frost & Sullivan, 2019), which believed that new business scenarios complemented by cutting-edge technology themes and focused on providing a customized customer experience underpin Industry 5.0. It is also characterized by the return of labour to factories, distributed manufacturing, intelligent supply chains and hyper-customization, all aimed at delivering a personalized customer experience time after time. After that, the concept of Industry 5.0 was discussed by participants from research and technology organizations as well as funding agencies across Europe. The study (Asif M. et al., 2023) states that the distinguishing aspect of Industry 5.0, compared to its predecessors, is its commitment to recalibrating economic and social equilibrium through responsible governance, it emphasizes enhancing sustainability and advancing towards a digital society.

The paper (Ling et al., 2024) defines the principles for decarbonizing the transport sector through the introduction of innovations and the development of electric vehicles, emphasizing the need to comply with sustainability criteria. The topic of transforming innovations for decarbonization development is considered in the study (Labanca et al., 2020), which notes the importance of social development for the purpose of decarbonization.

The study (Verdolini, 2023) provides an overview of decarbonization options for six key industrial sectors and examines the strengths and weaknesses of various approaches to modelling industrial emissions reductions. It also highlights the cross-cutting issues of decarbonization. All this proves the diversity of research on decarbonization and forms the prerequisites for an integrated approach to modelling the decarbonization of the economy based on energy innovations in the context of Industry 5.0 (Miralles-Quirós, 2022). The study (Kravchenko et al., 2023) proved the positive impact of energy innovations on sustainable development on the example of a sample of countries.

This demonstrates the wide array of studies regarding decarbonization and lays the groundwork for a comprehensive approach to modeling the decarbonization of the economy through energy innovations within the framework of Industry 5.0.

3. Methodology

The study was conducted in the following stages:

1) the peculiarities of development and formation of indicators for measuring the development of Industry 5.0, taking into account the needs of ensuring sustainable development, were identified;
2) a cluster analysis of the level of decarbonization of selected countries in terms of Industry 5.0 components and sustainable development was carried out, which allowed us to identify four clusters of countries for further analysis;
3) based on multivariate regression modelling, the stimulating factors for reducing CO_2 emissions were identified and the identified factors were compared with the directions of their development in the cluster-leading countries. The choice of the following indicators for modelling was substantiated: Energy intensity level of primary energy (World Bank, 2024); Fossil CO_2 Emissions in Power Sector (EDGAR, 2024); Patents in Climate change mitigation technology (OECD, 2024); Research and development expenditure (Global Innovation Index, 2024); Industry (including construction), value added (% of GDP) (World Bank, 2024); Information and communication technologies (ICTs) (WIPO, 2024); Knowledge workers (WIPO, 2024); Human capital and research (WIPO, 2024).

4. Results and discussion

Today, the concept of Industry 5.0 allows to accelerate the implementation of sustainable development principles in various sectors of the economy. Experts defined technologies supporting the concept of Industry 5.0 and these include (Slavic et al., 2024):

- Human-centric solutions and human-machine-interaction technologies that interconnect and combine the strengths of humans and machines.
- Bio-inspired technologies and smart materials that allow materials with embedded sensors and enhanced features while being recyclable.
- Real time-based digital twins and simulation to model entire systems.
- Cyber safe data transmission, storage, and analysis technologies that are able to handle data and system interoperability.
- Artificial Intelligence, e.g. to detect causalities in complex, dynamic systems, leading to actionable intelligence.
- Technologies for energy efficiency and trustworthy autonomy as the above-named technologies will require large amounts of energy.

After the shocks of the COVID-19 pandemic, the EU seeks to review its approaches to industrialization, adapting them to new operating conditions and societal needs. In particular, it is assumed that a renewed European *Industry 5.0* can make industries more forward-looking, resilient, sustainable and human-oriented. To achieve true prosperity and sustainable development, industries must redefine their core purpose to encompass social well-being, environmental responsibility, and societal progress. This necessitates a shift towards responsible innovation that prioritizes not just cost-efficiency and profit maximization, but also the shared prosperity of all stakeholders. This includes investors, workers, consumers, communities, and the environment itself (European Commission, 2021). Therefore, the European Commission identified human-centricity, resilience and sustainability as the key pillars of the concept of Industry 5.0. (fig.1).

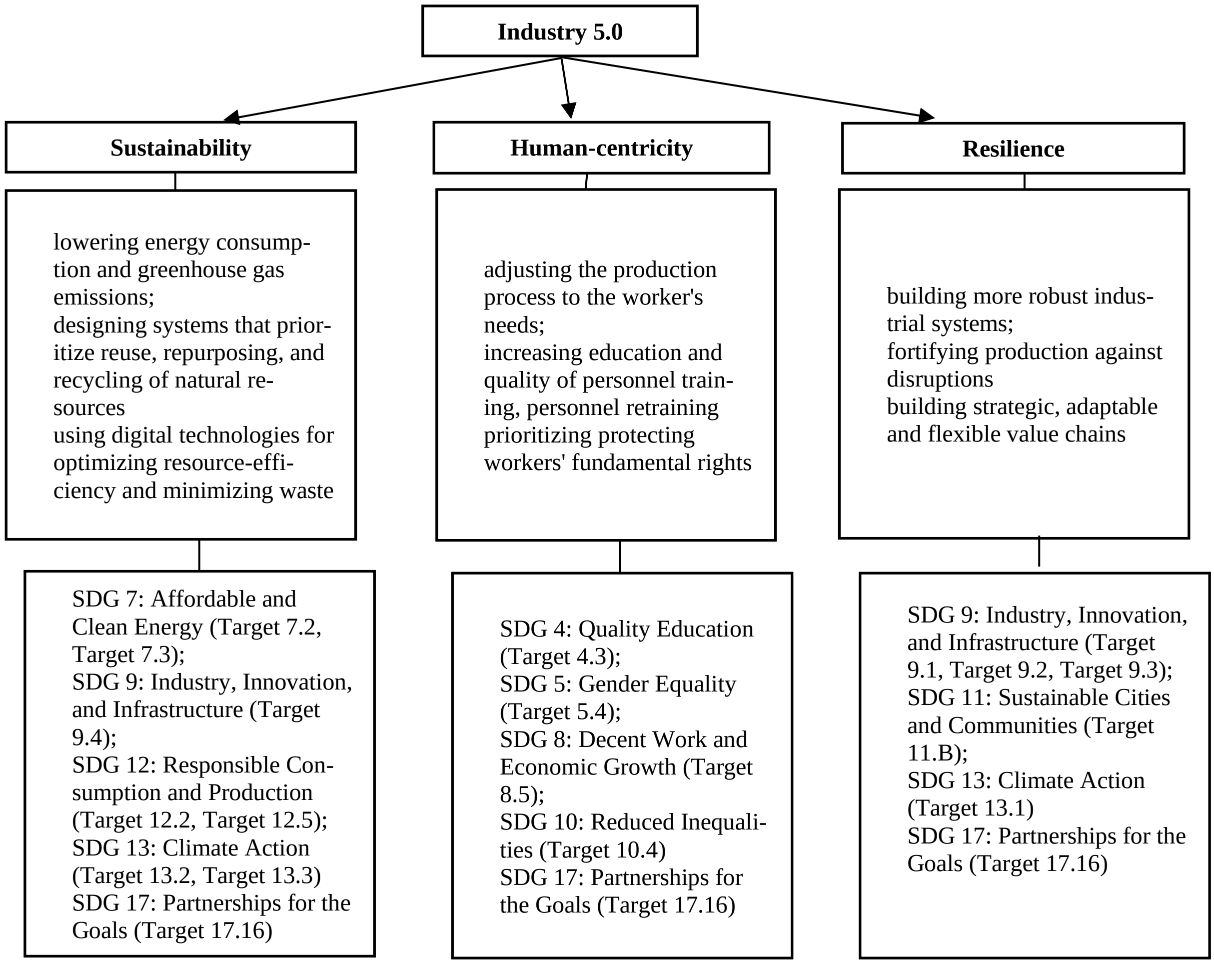

Figure1. The characteristics of the key pillars of Industry 5.0. with corresponding SDGs, source: compiled by the authors on the basis of (European Commission, 2021)

Sustainable production and energy consumption remains one of the key issues of ensuring modern industrial production in the context of the transition to Industry 5.0. The introduction of innovative technologies into the energy sector acts as a catalyst for such a transition and can be included in the characteristics of each pillar.

At the moment, there is no integrated indicator that would allow us to quantitatively measure the level and speed of the transition to Industry 5.0. And in various sources, scientists, depending on the research tasks, offer their own approaches to the assessment for each pillar. For example, the authors of the work (Slavic et. al, 2024) proposed the key indicators for measuring the levels of implementation of Industry 5.0 approaches in the manufacturing sector of the Republic of Serbia. For instance, 9-10 indicators were selected for each pillar, according to which 146 enterprises of various industries were evaluated. In another work, the researchers (Masoomi, 2023) used expert assessments of 23 sustainable development challenges and 19 Industry 5.0 advantages to determine the impact of Industry 5.0 on the energy supply chain. The authors (Masoomi B. et al., 2023) identified 11 actions and approaches that serve as enablers of Industry 5.0.

At the macro level, the efficiency of energy use and consumption, the active implementation of innovations in the energy sector, the level of digitalization of various industries in the context of Industry 5.0 can be measured by separate indicators that take into account a large number of components.

The world's energy landscape is undergoing a dramatic transformation. Energy and climate change policies are now top priorities for governments around the globe. To determine the effectiveness of the implementation of such policies by various countries, the Energy Transition Index (ETI) was presented at the World Economic Forum; the index balances three imperatives of the energy triangle – equity, security and sustainability and evaluates *Energy access for all, Building a secure energy system* and *Balancing energy needs with a sustainable future* accordingly. That is, according to its meaningful components, the Energy Transition Index could characterize the achievements of the energy sector of countries in the conditions of Industry 5.0 based on the *Sustainability* pillar.

According to the results of the calculation of the index for 120 countries, it can be observed that European countries are in the top ten of the ranking (fig.2). These countries make significant efforts to comply with the recommendations of the European Green Course, in particular, this is reflected in the indicators of the index components such as *System performance* and *Transition readiness*. The top 10 countries account for only 2% of global CO_2 emissions from fuel combustion and 4% of total energy supply (World Economic Forum, 2023).

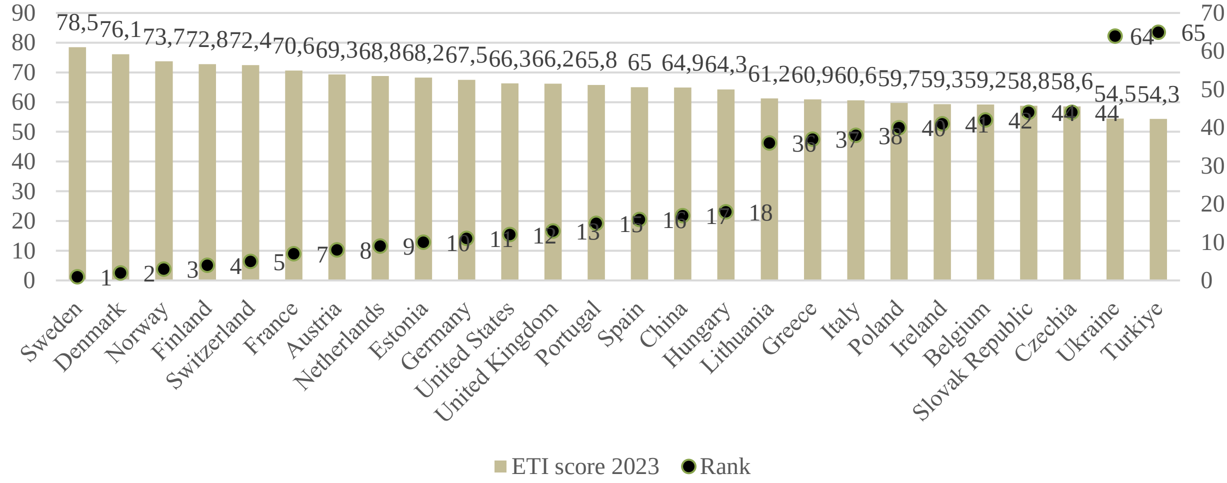

Figure 2. ETI score and 2023 ranking for chosen countries, source: compiled by the authors on the basis of (Buuren, 2018)

The Global Innovation Energy Index could be used to characterize the achievements of the countries' energy sector in the context of Industry 5.0 under the *Resilience* pillar. It consists of three composite indices, each of which measures one of the functions of the innovation system, namely: generation of options, expansion of innovations (distribution) and development of mass use, social legitimation.

The development, implementation and support of energy innovations can reflect the resilience of the energy system in the face of external disturbances (for example, the increase in prices for energy resources, which provokes the mobilization of the potential for the search for alternative resources, the use of renewable resources for energy generation; the shortage of energy resources, which requires the optimization of the use of existing capacities and infrastructure, the introduction of digital technologies, etc.).

The Global Innovation Energy Index (Smith, 2021) is calculated for 34 countries. According to the results of the GEII ranking of countries for 2021, the leaders in the first ten are also mostly European countries (fig.3). However, the latest available estimated data for 2021 do not provide an opportunity to fully assess the resilience of countries to supply chain disruptions caused by the war in Ukraine since 2022 and sanctions for Russian oil and gas supply.

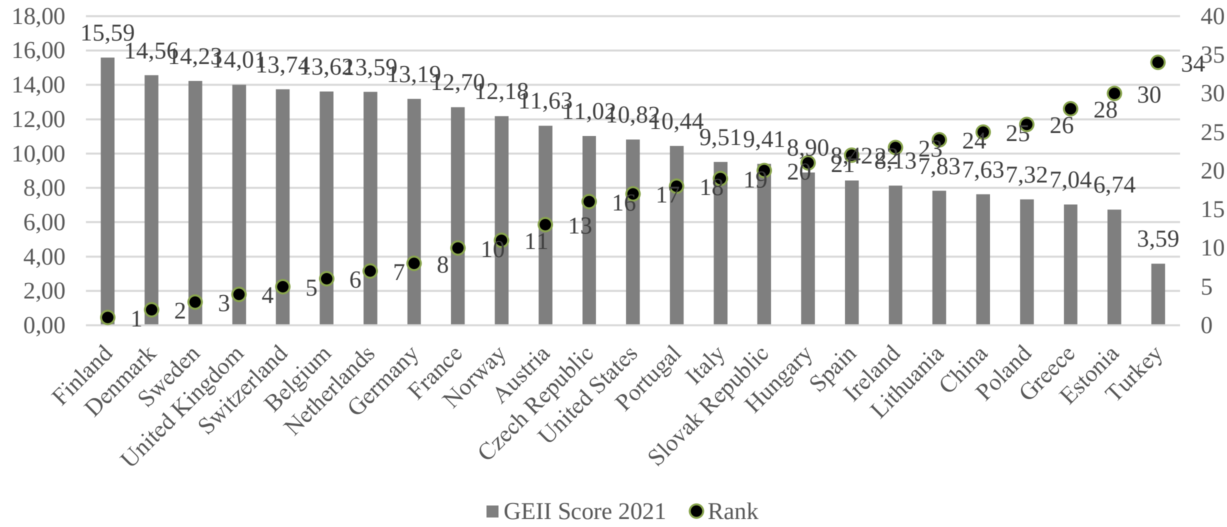

Figure 3. GEII score and 2021 ranking for chosen countries, source: compiled by the authors on the basis of (Smith, 2021)

From the point of view of measuring the achievements of the energy sector of individual countries in the conditions of Industry 5.0, the evaluation of the results according to the *Human-centricity* pillar is the most difficult task. On the one hand, such achievements should reflect the integration of digital technologies into business processes, automation and robotization of factories to simplify human labor, and on the other hand, they should concern the

adaptation of these technological changes to the needs of employees, as well as the development of additional skills and talents of employees.
To evaluate the results of digitalization at the national level, the European Commission uses DESI - Digital Economy and Society Index (DESI, 2022). It is a key tool for understanding how European countries are performing in the digital age. It measures progress across various digital aspects, helping EU member states identify areas for improvement and track their overall digital competitiveness. DESI 2022 includes eleven indicators to assess progress according to four dimensions: *Human capital* (At least basic digital skills; ICT specialists; Female ICT specialists), *Connectivity* (Gigabit for everyone (Fixed very high-capacity network coverage); 5G coverage), *Integration of digital technology* (technology SMEs with a basic level of digital intensity; AI; Cloud; Big data), *Digital public services* (Digital public services for citizens; Digital public services for businesses).
According to the results of the calculation of the index in 2022, Finland, Denmark, the Netherlands, Sweden and Norway are among the top five countries in terms of digitalization. It is worth noting that such locomotive countries of the EU economy as Germany and France are not even included in the top ten of the ranking (Fig. 4). One of the problematic aspects in Germany is the level of basic digital skills and basic digital content creation skills, which is slightly below the EU average.
In general, the EU faces a significant challenge due to its overdependence on foreign sources (over 80%) for digital products, services, infrastructure, and intellectual property. This is particularly noticeable in areas like semiconductors, where both the EU and the US rely heavily (75-90%) on Asian production.

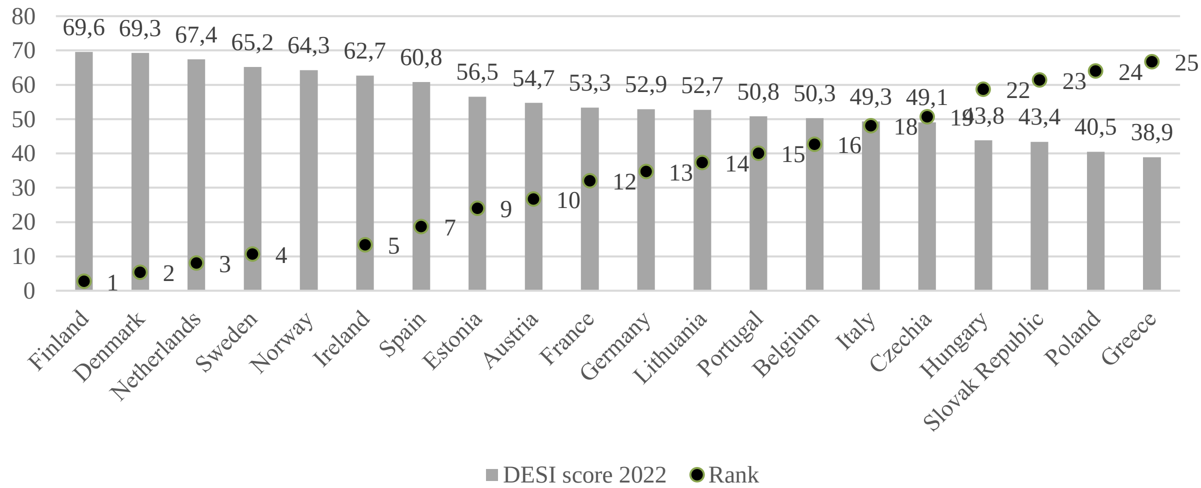

Figure 4. DESI score and 2022 ranking for chosen countries, source: compiled by the authors on the basis of (DESI, 2022)

However, DESI is calculated only for European countries, which, for example, complicates the process of comparison with other countries when it comes to measuring the achievements of the energy sector in the context of Industry 5.0. in particular, comparison with the USA and China, whose energy transition results are important components of achieving the decarbonization of the world economy (the long-term goal of zero CO_2 emissions by 2050).
Another general indicator in the energy sector is the World Energy Trilemma Index (World Energy Trilemma Index, 2022) - an annual measurement of national energy system performances across each of the three trilemma dimensions: Energy Security, Energy Equity, Environmental Sustainability. The World Energy Trilemma Report and Index has been produced annually since 2010 by the World Energy Council in partnership with global consulting firm Oliver Wyman, as well as Marsh & McLennan Advantage, part of its parent company Marsh & McLennan.
Within this index, Energy Security measures a country's ability to reliably meet current and future energy demand, withstand systemic shocks, and quickly recover from them with minimal supply disruptions. This dimension covers the efficiency of management of internal and external energy sources, as well as the reliability and sustainability of the energy infrastructure. Energy Equity assesses a country's ability to provide universal access to reliable, affordable and surplus energy for domestic and commercial use. The dimension covers basic access to electricity and clean fuels and technologies for cooking, access to prosperity-promoting levels of energy consumption, and the availability of electricity, gas and fuel. Environmental sustainability of energy systems means transitioning a country's energy system to mitigate and avoid potential environmental harm and the effects of climate change. The measure focuses on productivity and efficiency in generation, transmission and distribution, decarbonization and air quality.

Fig. 5 shows the distribution of EU countries by the dimensions of the Energy Trilemma Index. The value of Energy security and Energy equity closer to 1 indicates a high level of countries according to this indicator and means a place in the ranking according to the corresponding dimension, while the countries closer to the origin of the coordinates have stronger positions. The larger radius of the circle, the higher the ranking of the country in the Environmental sustainability dimension.

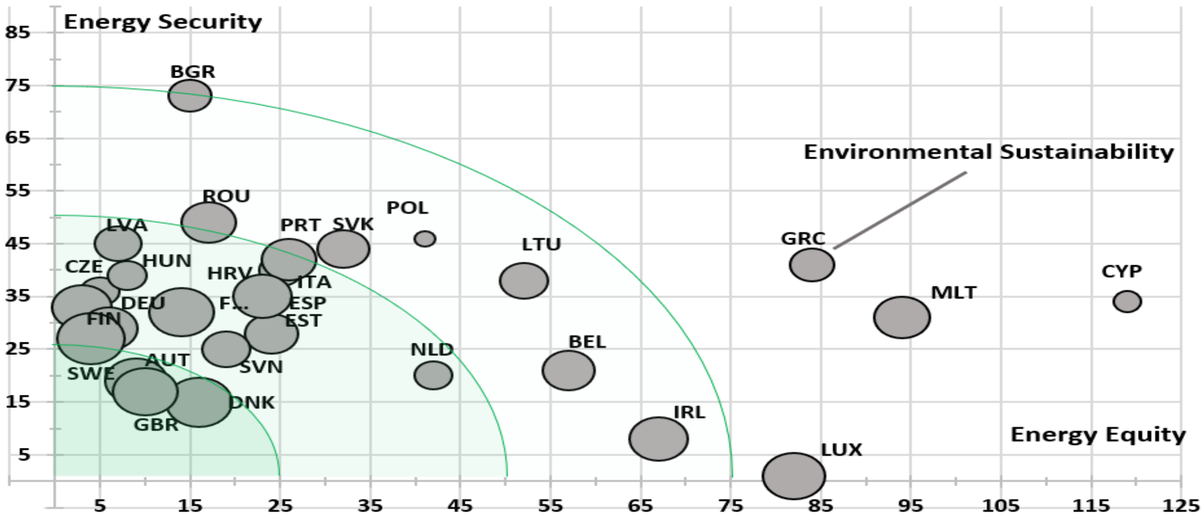

Figure 5. Graphic visualization of the studied countries by the energy equity (X-axis) and the energy security (Y-axis), the radius of the circle determines the value of environmental sustainability, 2022, source: compiled by the authors based on the data (World Energy Trilemma Index, 2022)

Among the studied countries, Sweden, Denmark, France, the United Kingdom, Luxembourg, Austria, Ireland, Spain, and Germany are in the list of Top-10 leaders in terms of Environmental sustainability in the order of the places taken by the countries. According to the other two indicators, 4 clusters can be conventionally distinguished. Such countries as Austria, Sweden, the United Kingdom and Denmark occupy the highest places, which indicates a higher level of Energy security and Energy equity. For instance, in terms of Energy security and Energy equity, Sweden took 4th and 27th place.
As we can see, the use of certain indices to measure the achievements of carbon neutrality by individual countries in the context of Industry 5.0 and sustainable development can be very complicated due to certain limitations regarding their calculation (limitations regarding the index calculation period, the number of countries that are studied in the ranking process, etc.). Therefore, we consider it expedient to use the following indicators for modeling the level of decarbonization of countries in the conditions of Industry 5.0 (fig. 6)

Sustainability	Human-centricity	Resilience
• Energy intensity level of primary energy; • Fossil CO_2 Emissions in Power Sector.	• Information and communication technologies (ICTs); • Knowledge workers; • Human capital and research.	• Patents in Climate change mitigation technology; • Research and development expenditure; • Industry (including construction), value added (% of GDP).

Figure 6. Industry 5.0 components with indicators for the assessment of decarbonization

According to the results of K-means clustering by the CO_2 emissions indicator (kg per 2017 PPP $ of GDP) (World Resources Institute, 2020), four clusters were obtained in the countries selected for the study (Table 1). The lowest rate of CO_2 emissions - ranging from 0.059 (Switzerland) to 0.093 (France) is observed in such countries as Switzerland, Sweden, Ireland, Denmark and France, which are grouped into Cluster 1. The highest rate of emissions is observed in Ukraine (0.319) and China (0.476), which are combined in Cluster 2. The largest number of the studied countries is combined in Cluster 4 with the value of CO_2 emissions (kg per 2017 PPP $ of GDP) ranging from 0.105 to 0.151, namely: Norway, the United Kingdom, Lithuania, Portugal, Spain, Italy, Austria, the Netherlands, Finland, Germany, Hungary, Estonia, Belgium. Cluster 3 is characterized by the level of CO_2 emissions ranging from 0.171 to 0.226 and unites such countries as Turkey, the Slovak Republic, Greece, the Czech Republic, the United States, Poland.

Table 1. The results of clustering the studied countries by the CO_2 emissions indicator (kg per 2017 PPP $ of GDP), 2020

Country	Par	Year	Val	cluster
Switzerland	CO_2	2020	0.05950509	1
Sweden	CO_2	2020	0.06317764	1
Ireland	CO_2	2020	0.07373484	1
Denmark	CO_2	2020	0.08487077	1
France	CO_2	2020	0.09336846	1
Norway	CO_2	2020	0.10544818	4
United Kingdom	CO_2	2020	0.10982341	4
Lithuania	CO_2	2020	0.11253434	4
Portugal	CO_2	2020	0.11823652	4
Spain	CO_2	2020	0.11870808	4
Italy	CO_2	2020	0.12105260	4
Austria	CO_2	2020	0.12790816	4
Netherlands	CO_2	2020	0.13766104	4
Finland	CO_2	2020	0.13869488	4
Germany	CO_2	2020	0.14011621	4
Hungary	CO_2	2020	0.14701710	4
Estonia	CO_2	2020	0.14877129	4
Belgium	CO_2	2020	0.15088683	4
Turkey	CO_2	2020	0.17008394	3
Slovak Republic	CO_2	2020	0.17179877	3
Greece	CO_2	2020	0.17650222	3
Czech Republic	CO_2	2020	0.21490740	3
United States	CO_2	2020	0.21664003	3
Poland	CO_2	2020	0.22636811	3
Ukraine	CO_2	2020	0.31983368	2
China	CO_2	2020	0.47593568	2

Let's apply the multivariate regression modeling to outline the influence of the proposed indicators (Fig. 6) for 2013-2020 (corresponding to the available data) on the decarbonization processes. For this purpose, the data imputation methods need to be used since official statistics has some gaps for Sweden, Norway, Switzerland, United States and Finland. Predictive mean matching algorithm, which was implemented in R (Buuren, 2018), allowed us to fill in all necessary data.

The general model and separate model for each cluster from Table 1 are constructed. Let's consider the first one in detail. At the first step all selected indicators are imputed into model (Fig.7). The determination coefficient is 0.8466 and model is significant (p-value < 2.2e-16), but some variables have p-value > 0.1.

```
Residuals:
     Min       1Q   Median       3Q      Max
-0.07866 -0.03260  0.00334  0.02278  0.21031

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)  1.463e-01  3.724e-02   3.930 0.000118 ***
Energy       4.053e-02  2.547e-03  15.914  < 2e-16 ***
Fossil       5.910e-05  5.345e-06  11.057  < 2e-16 ***
GHG         -1.010e-02  4.037e-03  -2.502 0.013157 *
Hcapital    -9.554e-05  7.363e-04  -0.130 0.896890
Industry    -1.351e-04  6.526e-04  -0.207 0.836185
ICT         -6.293e-04  2.659e-04  -2.367 0.018906 *
Knowledge_w -7.372e-04  4.613e-04  -1.598 0.111590
Patents      2.231e-03  1.163e-03   1.919 0.056417 .
Rd_exp      -1.850e-02  7.433e-03  -2.488 0.013654 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.04228 on 198 degrees of freedom
Multiple R-squared:  0.8514,    Adjusted R-squared:  0.8446
F-statistic:   126 on 9 and 198 DF,  p-value: < 2.2e-16
```

Figure 7. The results of the multivariate regression modeling with all selected indicators

After removing insignificant parameters, the next version of the model is obtained (Fig. 8). As can be seen the distribution of the residuals is not symmetric. The Q–Q plot (Fig. 9) confirms the difference between the distribution of residuals and the normal one. Thus, the model requires improvement.

```
Residuals:
      Min        1Q    Median        3Q       Max
-0.080281 -0.035469 -0.000888  0.027132  0.213450

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)  1.474e-01  2.347e-02   6.280 2.05e-09 ***
Energy       4.086e-02  2.514e-03  16.251  < 2e-16 ***
Fossil       5.126e-05  3.758e-06  13.640  < 2e-16 ***
ICT         -7.877e-04  2.516e-04  -3.131  0.00200 **
Knowledge_w -8.245e-04  4.038e-04  -2.042  0.04249 *
Patents      2.046e-03  1.162e-03   1.761  0.07980 .
Rd_exp      -1.632e-02  6.051e-03  -2.696  0.00761 **
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.04267 on 201 degrees of freedom
Multiple R-squared:  0.8464,	Adjusted R-squared:  0.8418
F-statistic: 184.5 on 6 and 201 DF,  p-value: < 2.2e-16
```

Figure 8. The results of the multivariate regression modeling with significant parameters

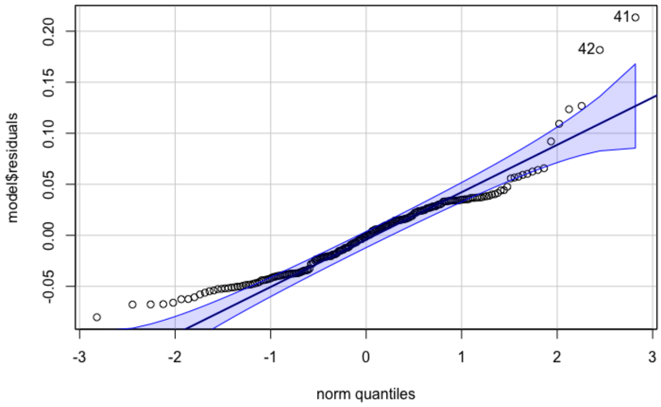

Figure 9. The testing the hypothesis of normal distribution of residuals for model with significant parameters

As a result of the experiments, it was decided to process the CO_2 parameter and take the square root of it. Obtained model and the Q–Q plot for its residuals are presented on Fig. 10 and Fig 11. All necessary characteristics are within suitable limits.

```
Residuals:
      Min        1Q    Median        3Q       Max
-0.109001 -0.031936 -0.004427  0.029489  0.193090

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)  4.040e-01  2.555e-02  15.811  < 2e-16 ***
Energy       4.351e-02  2.766e-03  15.729  < 2e-16 ***
Fossil       4.653e-05  4.132e-06  11.260  < 2e-16 ***
ICT         -6.211e-04  2.771e-04  -2.241 0.026115 *
Knowledge_w -1.546e-03  4.445e-04  -3.479 0.000616 ***
Rd_exp      -1.376e-02  6.657e-03  -2.067 0.039967 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.04701 on 202 degrees of freedom
Multiple R-squared:  0.8191,	Adjusted R-squared:  0.8146
F-statistic:   183 on 5 and 202 DF,  p-value: < 2.2e-16
```

Figure 10. The results of the multivariate regression modeling with the processed CO_2 parameter

Thus, the general model obtains the following form:

$$CO2 = (0{,}404 + 0{,}0435 \cdot Energy + 0{,}0000465 \cdot Fossil + 0 \cdot Hcapital + 0 \cdot Industry - 0{,}000621 \cdot ICT - 0{,}00154 \cdot Knowledge_w + 0 \cdot Patenrs - 0{,}0138 \cdot Rd_{exp})^2 \quad (1)$$

Adjusted R-squared: 0.8418, p-value: < 2.2e-16,

where *CO2* - the CO_2 emissions per GDP, *Energy* - Energy intensity level of primary energy, *Fossil* - Fossil CO_2 Emissions in Power Sector, *Hcapital* - Human capital and research, *Industry* - Industry (including construction), value added (% of GDP), *ICT* - Information and communication technologies, *Knowledge_w* - Knowledge workers, *Patents* - Patents in Climate change mitigation technology, *Rdexp* - Research and development expenditure.

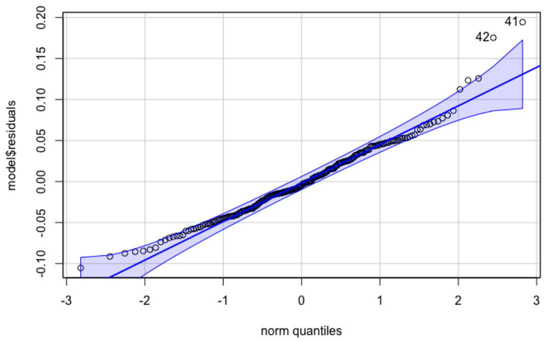

Figure 11. The testing the hypothesis of normal distribution of residuals for model with the processed CO_2 parameter

According to the general model (1), the level of CO_2 emissions depends most on the growth of the Energy intensity level of primary energy (directly proportional dependence). While the model shows that with the growth of Research and development expenditure and Knowledge workers, the increase in the ICT index, the level of CO_2 decreases.

It is interesting to note that in the greatest number of obtained models there is a direct relationship between the number of Patents in Climate change mitigation technologies and the level of CO_2, which may indicate the ineffective use of these patents or the formal registration of patents without further implementation in production processes.

Let's analyze the regression models for the clusters in brief.

The model for Cluster 1 obtains the following form:

$$CO2 = 0{,}2387 + 0 \cdot Energy + 0{,}00228 \cdot Fossil + 0 \cdot Hcapital - 0{,}00262 \cdot Industry - 0{,}000608 \cdot ICT + 0 \cdot Knowledge_w + 0{,}000916 \cdot Patents - 0{,}0222 \cdot Rd\_exp, \quad (2)$$

Adjusted R-squared: 0.8508, p-value: 4.227e-14.

The features typical of the model for Cluster 1 are the direct dependence of the CO_2 level of the countries of Cluster 1 on Fossil CO_2 Emissions in Power Sector, Knowledge workers, Patents in Climate change mitigation technologies and the inversely proportional dependence on Industry (including construction), value added (% of GDP), Information and communication technologies (ICTs), GHG Emissions from waste and Research and development expenditure. That is, to reduce CO_2 in the countries of this cluster, together with the growth of industrial production, it is advisable to develop innovative research and implement digital technologies for the development of energy innovations, while it is important to introduce innovations initiated in *Patents in Climate change mitigation technologies* into industry, that is, to increase patent efficiency. In accordance with the goals of sustainable development, the countries of this cluster should take such measures: transitioning towards renewable energy sources and enhancing energy efficiency (SDG 7); promoting innovation and infrastructure development, particularly in research and development (SDG 9); integrating climate change measures into policies and enhancing capacity for mitigation and adaptation (SDG 13); strengthening global partnerships to support sustainable development goals (SDG 17). Switzerland is the leader in this cluster in terms of CO_2. It is worth noting that Switzerland is exceptionally highly industrialized. The proportion of GDP stemming from manufacturing industry is among the highest in the industrialized world, which is characterized by a powerful manufacturing cluster and strong engineering expertise. According to the study (Switzerland Global Enterprise, 2021), the country is most effective worldwide in transforming innovation investment into results. A stimulating factor for the development of energy innovations in Switzerland under the conditions of Industry 5.0 is the formation of a modern legislative framework for their development. The following strategies can be identified in Switzerland for the development of energy innovation:

1) Energy Strategy 2050 focuses on the transition to energy based on renewable energy and energy efficiency, as well as on the abandonment of the use of nuclear energy;
2) Swiss Innovation Park is an initiative aimed at supporting innovation in all areas, including energy.

It provides resources and an environment for the development and commercialization of new technologies in the field of energy. That is why the country is highly prepared for the development of Industry 5.0, along with other countries of the cluster. This cluster also includes Sweden, which is a leader among EU countries in the field of renewable energy - more than 55% of electricity in the national system comes from renewable sources and the EU's lowest energy costs and 99.9 per cent grid stability (Hemstrom, 2022), Sweden's Smart Energy ecosystem enables the integration of renewables into energy systems by implementing best practices in digitalization, multi-directional energy flows, energy storage and smart flexible grids.

The model for Cluster 2 obtains the following form:

$$CO2 = 0{,}5544 + 0 \cdot Energy + 0 \cdot Fossil + 0 \cdot GHG - 0{,}00331 \cdot Hcapital + 0{,}00425 \cdot Industry - 0{,}00345 \cdot ICT + 0 \cdot Knowledge_w - 0{,}00552 \cdot Patents + 0{,}0862 \cdot Rd\_exp \quad (3)$$

Adjusted R-squared: 0.9947, p-value: 6.535e-12.

According to the results of Cluster 2 modeling, a fall in the level of CO_2 emissions correlates with the growth of the indicators of Human capital and research and Patents in Climate change mitigation technologies, while a rise of the indicators of Industry (including construction), value added (% of GDP) increases the level of CO_2 emissions, and a rise in Research and development expenditure does not lead to a fall in the level of CO_2 emissions. This can be explained by the fact that Research and development expenditure was to a greater extent aimed specifically at the real sector of the economy, because high research expenditures in successful industries and business areas, as a rule, have a hard component in their business portfolios (on which they both grew and worked), that is, taking into account the experience of growth on previous technological modes, without considering the environmental component. Therefore, it is important for this cluster to increase the level of Patents in Climate change mitigation technologies, because they testify to the development of environmental technologies and, according to the model, their positive impact on ensuring the decarbonization of the economy is confirmed. Thus, to ensure sustainable development, countries of Cluster 2 should: enhance the skills and capabilities needed for innovation and sustainable development (SDG 4); promote technological advancements, including patents in climate change mitigation technologies, which are crucial for reducing CO_2 emissions (SDG 9); climate action through integrating environmental considerations into policies and fostering awareness and capacity-building efforts (SDG 13); mobilize resources and expertise needed to support sustainable development initiatives, including those related to climate change mitigation technologies (SDG 17). We should also note that due to the high level of CO_2 emissions, China has been increasingly focusing on sustainability and environmental conservation within Industry 5.0; green manufacturing practices, such as energy efficiency improvements and waste reduction, are becoming more prevalent in China. China was among the Top spenders globally in energy R&D in 2020 - the second place after the USA with research investments of more than 8 billion dollars (IEA, 2022). Key China's policy initiatives on the reduction of carbon dioxide emissions and in support of the development of innovations include: Updated Nationally Determined Contribution, 14th Five-year Plan for Energy, 14th Five-year Plan for Renewables, Made in China 2025, New Energy Vehicle Industry Development Plan, Carbon peaking and neutrality blueprint for urbanization and rural development.

The model for Cluster 3 obtains the following form:

$$CO2 = -0{,}0875 + 0 \cdot Energy + 0 \cdot Fossil + 0{,}00353 \cdot Hcapital + 0{,}00265 \cdot Industry - 0 \cdot ICT + 0{,}00353 \cdot Knowledge_w + 0 \cdot Patents - 0{,}0518 \cdot Rd\_exp \quad (4)$$

Adjusted R-squared: 0.6765, p-value: 6.893e-11.

In Cluster 3, in contrast to Cluster 2, there is significant dependence of the level of CO_2 emissions on Research and development expenditure. At the same time, the growth of the indicators of Human capital and research, Industry (including construction), value added and Knowledge workers collectively have a negative effect on decarbonization, which indicates the concentration of knowledge technologies in the industrial sector with a focus on its growth without sufficient consideration of the environmental component. For the Cluster 3, the following SDGs are emphasized: (SDG 9) that consider environmental impacts and promote the adoption of clean technologies; (SDG 12) to ensure the efficient use of resources and minimize environmental impacts; (SDG 13) through integrating climate considerations into policies and strategies to mitigate greenhouse gas emissions; (SDG 17) to enhance collaboration and knowledge-sharing for sustainable development. Cluster 3's findings highlight the need to align research and industrial growth with sustainable practices and technologies, emphasizing the integration of environmental considerations into industrial processes and innovation strategies.

Although The United States has historically had relatively high levels of CO_2 emissions due to several factors such as industrial activity, high energy consumption, energy-intensive industries, reliance on fossil fuels, transportation as a source of emissions. In April 2024 the White House Office of Science and Technology Policy (OSTP), U.S. Department of Energy (DOE), and the U.S. Department of State released the National Innovation Pathway Report, highlighting the Biden-Harris Administration's all-hands-on-deck strategy for accelerating key clean energy technology innovations (United States Department of State, 2023). To support meeting the U.S. Nationally Determined Contribution and implementation of the Long-Term Strategy, the United States has a threefold net-zero technology action plan which will: Invest in R&D for a portfolio of game-changing innovations to ensure that there is an adequate suite of technologies to reliably, affordably, and equitably achieve net-zero emissions by 2050, demonstrate and support early deployment of emerging technologies, use regulations and financial incentives to accelerate manufacturing, deployment, and adoption of technologies that are available today. The U.S. national net-zero innovation pathway is informed by the National Long-Term Climate Strategy, which maps multiple pathways for achieving net-zero emissions no later than 2050. According to measures and the amount of investment in research to ensure energy innovation, the U.S. is the leader of this cluster.

The model for Cluster 4 obtains the following form:

$$CO2 = 0{,}1436 + 0{,}0608 \cdot Energy + 0{,}000238 \cdot Fossil - 0{,}00255 \cdot Hcapital - 0{,}00438 \cdot Industry + 0 \cdot ICT + 0 \cdot Knowledge_w + 0{,}00544 \cdot Patents + 0 \cdot Rd\_exp \quad (5)$$

Adjusted R-squared: 0.6313, p-value: < 2.2e-16.

In Cluster 4, the growth of the indicator of Energy intensity level of primary energy has the greatest impact on the growth of CO_2 emissions, which suggests that the energy balance of most countries of the cluster is dominated by fossil energy sources, and that is why the transition to sustainable energy technologies needs to be accelerated. Also, a directly proportional relationship is observed between CO2 emissions and such indicators as Fossil CO_2 Emissions in Power Sector and Patents in Climate change mitigation technologies, which indicates the insufficient efficiency of the introduction of patents into production. At the same time, the growth of the indicator of Human capital and research and Industry (including construction), value added (% of GDP) has a positive effect on the reduction of CO2 Emissions, indicating the use of modern innovative technologies to ensure the decarbonization of industry. According to SDGs, countries of Cluster 4 are advised: to reduce reliance on fossil fuels and enhance energy efficiency (SDG 7); to integrate clean technologies and practices to reduce CO_2 emissions (SDG 9); to climate action through policies and strategies that mitigate greenhouse gas emissions and enhance resilience to climate impacts (SDG 13); to support the adoption of sustainable technologies and practices globally (SDG 17). Cluster 4's findings underscore the importance of accelerating the transition to sustainable energy sources and improving the efficiency of climate change mitigation technologies. They also highlight the positive impact of human capital development, research, and innovation in reducing CO_2 emissions through the adoption of modern and innovative technologies in industry and construction sectors. This cluster contains the largest number of countries studied and the leader among them is Norway. Norway is a leader in CCS technology, which involves capturing CO_2 emissions from industrial processes or power plants and storing them underground to prevent their release into the atmosphere. The country's Sleipner and Snøhvit projects are among the world's first and largest CCS projects, respectively (Hauber G., 2023). Next to that, key areas where Norway focuses on energy innovation are renewable energy, hydropower, offshore wind, electric vehicles (EVs) and battery technology, smart grids and energy storage, energy efficiency, marine energy.

Therefore, the selection of clusters of the studied countries according to the level of CO_2 and the construction of a model for each cluster made it possible to determine the stimulating factors for reducing CO_2 emissions and to compare the identified factors with the directions of their development in the countries-leaders of the clusters.

In contrast to Industry 4.0, the development of Industry 5.0 is aimed at ensuring sustainable development, taking into account social, economic and environmental components. These components are fully disclosed in the Global Sustainable Development Goals. In turn, the decarbonisation of the economy based on energy innovations, although narrowly aimed at achieving Goal 7 *Affordable and Clean Energy*, Goal 9 *Industry, Innovation, and Infrastructure*, Goal 13 *Climate Action* and Goal 17 *Partnerships for the Goals*, but comprehensively covers the three basic components of sustainable development. The achievement of these goals is particularly urgent due to the global transformation of the energy market and the need to achieve climate neutrality by reducing CO_2 emissions. In developed countries, such as Germany, Sweden, France, and the UK, sustainable development strategies are aimed at increasing the share of renewable energy sources in the country's energy balance, achieving climate neutrality, improving energy efficiency, reducing greenhouse gas emissions, supporting the development of a green economy, protecting natural resources, and implementing a circular economy. These challenges correlate with the results of this study, which confirms the need to ensure decarbonization on the basis of sustainable development and Industry 5.0.

4. Conclusion

The assessment of countries' achievements in decarbonization within the context of Industry 5.0 and sustainable development is a multifaceted endeavor, requiring the utilization of various indices and modeling techniques. The Global Innovation Energy Index (GEII), alongside the World Energy Trilemma Index, offers valuable insights into national energy system performances and resilience. However, challenges such as limited coverage of countries and timeframes may impede comprehensive assessments. There was proposed a set of indicators for the assessment of decarbonization taking into account the main components of Industry 5.0: Sustainability, Resilience, Human-centricity.

To address these limitations, a multivariate regression model was applied, considering indicators ranging from energy intensity to research and development expenditure. The results revealed nuanced relationships between these factors and CO_2 emissions across different clusters of countries.

Cluster analysis identified distinct patterns among countries, shedding light on the diverse strategies and priorities for decarbonization. For instance, Cluster 1 countries, exemplified by Switzerland and Sweden, emphasize industrial innovation and renewable energy adoption. Meanwhile, Cluster 2, represented by China and Ukraine, showcases the importance of research investment and policy initiatives in addressing emissions.

In Cluster 3, typified by the United States, emphasis on research and development expenditure underscores the need for a balanced approach integrating environmental considerations into industrial growth. Finally, Cluster 4, led by Norway, emphasizes the transition to sustainable energy sources and the efficient implementation of climate mitigation technologies.

These findings underscore the complex interplay between innovation, policy, and industrial practices in driving decarbonization efforts. Moreover, they highlight the importance of tailored approaches to address the specific challenges and opportunities within each cluster.
Moving forward, policymakers and stakeholders must leverage these insights to inform targeted strategies aimed at accelerating the transition to a low-carbon economy. By aligning innovation agendas with environmental objectives and fostering international collaboration, countries can pave the way for a sustainable and resilient future in the era of Industry 5.0 and sustainable development.

Acknowledgement

The authors gratefully acknowledge support from the Alliance of Guangzhou International Sister-City Universities (GISU), Ministry of Education and Science of Ukraine (project № 0124U000866) and Verkhovna Rada of Ukraine.

References

1. ASIF M., SEARCY C., CASTKA P., 2023, ESG and Industry 5.0: The role of technologies in enhancing ESG disclosure, *Technological Forecasting and Social Change* 195, https://doi.org/10.1016/j.techfore.2023.122806.
2. DESI, 2022, *Digital Economy and Society Index*, https://digital-strategy.ec.europa.eu/en/library/digital-economy-and-society-index-desi-2022 (2.03.2024).
3. EDGAR, 2024, *Emissions Database for Global Atmospheric Research*, https://edgar.jrc.ec.europa.eu/ *(*01.02.2024).
4. EUROPEAN COMMISSION, 2021, *Industry 5.0. Towards a sustainable, humancentric and resilient European industry*, https://research-and-innovation.ec.europa.eu/news/all-research-and-innovation-news/industry-50-towards-more-sustainable-resilient-and-human-centric-industry-2021-01-07_en (03.01.2024).
5. EUROPEAN COMMISSION, 2023, *Report on the state of the Digital Decade*, https://digital-strategy.ec.europa.eu/en/library/2023-report-state-digital-decade (04.01.2024).
6. EUROPEAN COMMISSION, 2020, *European Green Deal*, https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en (01.03.2024).
7. EURPEAN COMMISSION, 2023, *Report On The Stage Of The Digital Decade*, https://digital-decade-desi.digital-strategy.ec.europa.eu/datasets/desi/charts (01.03.2023).
8. FROST & SULLIVAN, 2019, *Industry 5.0 – Bringing Empowered Humans Back to the Shop Floor*, https://www.frost.com/frost-perspectives/industry-5-0-bringing-empowered-humans-back-to-the-shop-floor/ (02.02.2024).
9. HAUBER G., 2023, Norway's Sleipner and Snøhvit CCS: Industry models or cautionary tales?, https://ieefa.org/resources/norways-sleipner-and-snohvit-ccs-industry-models-or-cautionary-tales (05.03.2024).
10. HEMSTRÖM O., 2022, Sweden's Smart Energy Ecosystem, *Business Sweden*, https://www.business-sweden.com/insights/articles/swedens-smart-energy-ecosystem/ (01.03.2024).
11. HM GOVERNMENT, 2021, *Net Zero Strategy: Build Back Greener*, https://assets.publishing.service.gov.uk/media/6194dfa4d3bf7f0555071b1b/net-zero-strategy-beis.pdf (02.02.2024).
12. IEA, 2022, *Tracking clean energy innovation: Focus on China*, *https://iea.blob.core.windows.net/assets/6a6f3da9-d436-4b5b-ae3b-2622425d2ae4/TrackingCleanEnergyInnovation-FocusonChina_FINAL.pdf* (03.02.2024).
13. KRAVCHENKO M., TROFYMENKO O., KOPISHYNSKA K., PYSHNOGRAIEV I., 2023, Assessing the Development of Energy Innovations and Its Impact on the Sustainable Development of Countries, *System Analysis and Artificial Intelligence* 1170, https://doi.org/10.1007/978-3-031-37450-0_24.
14. LABANCA N., PEREIRA A. G., WATSON M., KRIEGER K., PADOVAN D., WATTS L., MOEZZI M., WALLENBORN G., WRIGHT R., LAES E., FATH B. D., RUZZENENTI F., MOOR T., BAUWENS T., MEHTA L., 2020, Transforming innovation for decarbonization? Insights from combining complex systems and social practice perspectives, *Energy Research & Social Science* 65, https://doi.org/10.1016/j.erss.2020.101452.
15. LING S., JIN S., WANG H., ZHANG Z., FENG Y., 2024, Transportation infrastructure upgrading and green development efficiency: *Empirical analysis with double machine learning method*, *Journal of Environmental Management* 358, https://doi.org/10.1016/j.jenvman.2024.120922.
16. MASOOMI B., GHASEMIAN SAHEBI I., GHOBAKHLOO M., MOSAYEBI A., 2023, Do industry 5.0 advantages address the sustainable development challenges of the renewable energy supply chain? *Sustainable Production and Consumption*, 43: 94-112, https://doi.org/10.1016/j.spc.2023.10.018.
17. MIRALLES-QUIRÓS M. M., MIRALLES-QUIRÓS J. L., 2022, Decarbonization and the Benefits of Tackling Climate Change, *Int J Environ Res Public Health* 19(13): 7776, https://doi.org/10.3390/ijerph19137776.
18. SLAVIC D., MARJANOVIC U., MEDIC N., SIMEUNOVIC N., RAKIC S., 2024, The Evaluation of Industry 5.0 Concepts: Social Network Analysis Approach, *Appl. Sci*. 14: 1291, https://doi.org/10.3390/ app14031291.
19. SMITH Ch., HART D., 2021, The 2021 Global Energy Innovation Index: National contributions to the global clean energy innovation system, *Information Technology and Innovation Foundation*, https://www2.itif.org/2021-global-energy-innovation-index.pdf (1.03.2024).
20. SWITZERLAND GLOBAL ENTERPRISE, 2021, *Advanced Manufacturing Switzerland*, https://www.greaterzuricharea.com/sites/default/files/2023-01/Factsheet%20Advanced%20Manufacturing%20Switzerland%20S-GE%202021%20%28EN%29_0.pdf (01.03.2024).

21. U.S. DEPARTMENT OF TRANSPORTATION, 2023, *National Blueprint for Transportation Decarbonization*, https://www.energy.gov/sites/default/files/2023-01/the-us-national-blueprint-for-transportation-decarbonization.pdf (01.03.2024).
22. UNITED STATES DEPARTMENT OF STATE, 2023, *National Innovation Pathway Of The United States*, https://www.whitehouse.gov/wp-content/uploads/2023/04/US-National-Innovation-Pathway.pdf (03.03.2024).
23. VAN BUUREN, S., 2018, *Flexible Imputation of Missing Data*, Second Edition (2nd ed.), Chapman and Hall/CRC, https://doi.org/10.1201/9780429492259.
24. VERDOLINI E., TORREGGIANI L., GIAROLA S., TAVONI M., HAFSTEAD M., ANDERSON L., 2023, *Industrial Deep Decarbonization: Modeling Approaches and Data Challenges*, Washington, USA.
25. WIPO, 2024, *Global Innovation Index*, https://www.wipo.int/global_innovation_index/en/ (01.02.2024).
26. WORLD BANK, 2024, *World Bank Open Data*, https://data.worldbank.org/ (01.03.2024).
27. WORLD ECONOMIC FORUM, 2023, *Fostering Effective Energy Transition 2023*, https://www.weforum.org/publications/fostering-effective-energy-transition-2023/ (05.01.2024).
28. WORLD ENERGY TRILEMMA INDEX, 2022, *World Energy Council in partnership with Oliver Wyman*, https://www.worldenergy.org/publications/entry/world-energy-trilemma-index-2022 (03.02.2024).
29. WORLD RESOURCES INSTITUTE, 2020, *Climate Watch, GHG Emissions*, https://climatewatchdata.org/ghg-emissions (03.03.2024).