

Article

Assessing the Pace of Decarbonization in EU Countries Using Multi-Criteria Decision Analysis

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Abstract

Greenhouse gas emissions from the energy sector are the main driver of global warming, which has led to an increase in the average surface temperature of the Earth by more than 1 °C above pre-industrial levels. Responding to the urgent need for energy transition, the countries of the European Union have set themselves the goal of achieving climate neutrality by 2050. The main objective of this article is to comprehensively assess the progress of decarbonization in the 27 European Union countries between 2004 and 2024, using an advanced multi-criteria model. The study used the quantitative Analytical Hierarchy Process (AHP) method to construct a multidimensional decision-making model. Eight energy technologies were evaluated through the prism of 13 criteria grouped into three pillars of sustainable development: economic (including technical), environmental, and social. Based on the weights of each criterion, estimated by a group of experts, a synthetic decarbonization index (DI) was calculated for each technology. In the next stage, a cumulative decarbonization index (CDI) was formulated for each country, reflecting the structure of its energy mix. The analysis revealed a fundamental divergence between conventional and zero-emission technologies. Renewable sources and nuclear energy have the highest positive impact on decarbonization (highest DI): hydropower (27.5), nuclear (20.7), wind (20.3). The lowest, unfavorable values of the index are characteristic of fossil fuels: oil (3.6), coal (3.9), and gas (4.8). The average cumulative decarbonization index (CDI) for the EU-27 rose from 14.0 in 2004 to 26.4 in 2024, demonstrating the effectiveness of the EU's common policy. The leaders of the transition are countries with diversified, green mixes, such as Luxembourg (CDI = 40.4), Lithuania (CDI = 39.6), Portugal (38.5), Austria (36.9), and Spain (33.6). Despite starting from the lowest level in 2004 (CDI = 5.2), Poland recorded one of the most dynamic increases in 2024 (CDI = 17.7), mainly due to a reduction in the share of coal from 93% to 53.5%. The analysis confirms the effectiveness of the EU's common climate and energy policy and demonstrates the usefulness of the methodology presented for a comprehensive assessment of the decarbonization process. The results indicate the need to further increase the share of zero-emission energy sources in the energy mix in order to achieve the objectives of the European Green Deal. The varying pace of transformation among Member States requires an individualized approach and support for countries with a historical dependence on fossil fuels.



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1. Introduction

For decades, the production of electricity using fossil fuels has contributed to the technological and economic development of many countries, leading to an increase in living standards. However, for years there has been a shift away from fossil fuels due to progressive adverse climate change and negative environmental impacts. Scientific evidence directly links the use of fossil fuels to increased greenhouse gas emissions, which are rapidly and irreversibly changing the global climate and causing global warming. In the fight against climate change, pollution reduction, and the building of energy independence, the use of alternative sources of electricity is crucial.

Sustainable development is a fundamental goal of the economic policy of every society, at the national, regional, and local levels. Every developed country emphasizes economic growth, but it is important to remember that no economy can grow without energy. Unprecedented technological development is increasing the rate of energy demand. Energy production determines the status of modern societies.

Energy is fundamental to life at all levels, from basic biological processes to complex social and emotional functioning. Energy is closely linked to the three pillars of sustainable development: economic, environmental, and social. The use of renewable energy sources and the exploration of new clean energy systems are the foundation of the sustainable development model.

Legislative Measures for Climate Protection

One of the first steps taken towards sustainable economic development was the establishment of the World Commission on Environment and Development in 1983. It was chaired by Gro Brundtland, under the auspices of the Secretary-General of the United Nations (UN). The 1987 report “Our Common Future” [1] was the first to use the term “sustainable development,” which laid the foundation for further pro-environmental actions.

In 1988, in response to growing concerns about climate change, the Intergovernmental Panel on Climate Change (IPCC) was established. The IPCC organizes consultation meetings of experts to prepare reports, which are then published [2]. A milestone in climate protection was the Earth Summit in Rio de Janeiro in 1992 [3]. During the conference, the United Nations Framework Convention on Climate Change (UNFCCC) was adopted, setting out the principles of cooperation to reduce greenhouse gas emissions [4]. Another document was Agenda 21 (Action Programme–Agenda 21), a list of goals to be achieved in the 21st century. These goals included international cooperation to accelerate the sustainable development of developing countries, the fight against poverty, the protection of the atmosphere, and the protection of the Earth’s surface, including soils, forests, seas, and other ecosystems [5]. The Convention on Biological Diversity [6] and documents on the sustainable use of ecosystems were also developed in Rio.

In 1997, the famous Kyoto Protocol [7] was signed at a conference in Japan, specifying the amount of greenhouse gas emission reductions for developed countries. Overall, these targets meant a 5% reduction in emissions compared to 1990 levels over the five-year period 2008–2012, and for socialist countries, including Poland, a 6% reduction compared to 1988. For European Union countries, the target was set at 8% compared to 1990 emissions. The Kyoto Protocol also identified six substances responsible for climate change: carbon dioxide, nitrous oxide, methane, perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), and sulfur hexafluoride [8].

In 2015, the United Nations Climate Change Conference was held in Paris [9]. It was the 21st annual session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (1992) and the 11th session of the Meeting of the Parties to the Kyoto Protocol (1997). The aim of the symposium was to establish a significant

reduction in greenhouse gas emissions in order to keep global temperature rise well below 2 °C and to pursue efforts to limit it to 1.5 °C above pre-industrial levels [10]. To date, 28 COP (Conference of the Parties) climate symposia have been held, but not all of them have resulted in satisfactory declarations.

The European Union is a global leader in the implementation of environmentally friendly solutions. For many years, it has been implementing directives and regulations limiting the use of fossil fuels and promoting the development of renewable energy sources. The European Commission has developed an action plan for Europe, the European Green Deal. The most important goals of the Green Deal are: achieving climate neutrality by 2050, decoupling economic growth from resource consumption, and applying regional justice [11].

A package of legislative proposals was also adopted to align EU climate, energy, transport, and tax policies with the main objective of reducing net greenhouse gas emissions by 55% by 2030 compared to 1990 levels [12]. In 2021, the Fit for 55 package was adopted, consisting of climate and energy legislation. The following legislation was approved:

- revision of the emissions trading system to include polluting sectors such as buildings and road transport from 2027 in ETS II (Emission Trading System) and maritime transport [13],
- review of the market stability reserve to address the structural imbalance between supply and demand for allowances in the EU ETS [14],
- implementation of a carbon leakage instrument that sets a greenhouse gas emission charge for imported goods [15],
- a joint effort to reduce emissions among EU countries in transport, agriculture, construction, and waste management—from 29% to 40% by 2030 [16],
- strengthening regulations to increase carbon dioxide absorption in the LULUCF (land use, land use change, and forestry) sector [17],
- revising the transport proposal (net-zero emission passenger cars and vans by 2035 [18],
- changes to aviation emission allowances [19],
- increasing the number of charging and refueling stations for passenger cars and trucks powered by alternative fuels [20],
- requirement to gradually transition to sustainable aviation fuels [19],
- new targets for reducing energy consumption at EU level by 2030 [21],
- increased share of renewable energy in EU energy consumption by 2030-42.5% [19,22].

All measures are aimed at protecting the climate by reducing to the lowest possible level: the use of natural resources, harmful gas emissions, and the use of waste-producing methods of electricity generation.

2. Purpose of the Analysis and Research Methodology

The aim of this article is to assess the progress of decarbonization in the 27 countries of the European Union between 2004 and 2024. The study analyzed the best technologies for electricity production and supply in the energy mix of individual countries and then compared them in terms of selected parameters.

Economic (including technical), environmental, and social parameters of the energy production technologies used throughout the fuel life cycle were selected for a comprehensive assessment of sustainable energy development. This approach to analysis, which involves the interaction of various groups of factors, is seen as a multi-criteria decision-making problem. One of the multi-criteria decision-making methods, the Analytic Hierarchy Process (AHP) [23], was used to examine changes in the energy mix in countries implementing the EU's "Fit for 55" legislative package.

In terms of popularity and application in both theory and practice, the AHP method is the most commonly used multi-criteria method and is characterized by the greatest diversity of applications [24], including mining [25–30], marketing [31,32], medicine [33], environmental engineering [34,35], economics, and the financial sector [36]. The AHP method has also been applied in the energy sector [37–41]. The AHP procedure has been further developed into the Fuzzy AHP (FAHP) method, which enables the selection of the optimal solution based on expert assessments and their certainty through the use of fuzzy numbers. Promentilla [42] applied FAHP to compare electricity storage technologies in renewable energy systems. Siwiec [43], on the other hand, used this technique for a quantitative and qualitative analysis of pollutant emissions from the energy and industrial sector. Sobczyk et al. applied FAHP to analyze the impact of risk factors on the unit costs of hard coal exploitation [44].

In order to determine the level of emission neutrality of electricity generation technologies in the energy mix, a research methodology was developed that takes into account the share of energy generation technologies in selected countries. The research methodology comprises several key stages:

- I. Identification of criteria for the assessment of electricity generation technologies;
- II. Construction of a hierarchical model for achieving climate neutrality;
- III. Estimation and aggregation of weighting factors (expert assessments);
- IV. Construction of a decarbonization index;
- V. Construction of a cumulative decarbonization index.

2.1. Criteria for Assessing Electricity Generation Technologies

Key parameters related to electricity production, corresponding to general sustainability indicators and main and sub-objectives, were selected for analysis [45]. The implementation of these parameters ensures that the selected objectives are achieved.

Economic pillar (technical and economic aspects)

The classic model of sustainable development is based on three pillars (economic, environmental, and social), and in the context of energy, the technical pillar is often singled out as key to ensuring security, system reliability, and modern energy infrastructure. It is treated as an engine of economic development. It is the basis for the other pillars. The economic pillar focuses on the profitability, cost-effectiveness, and competitiveness of the energy sector.

Four criteria have been identified among *the technical aspects*:

- Efficiency factor [%] expresses the ratio of output energy to input energy. Efficiency refers to how much useful energy (in this case, electricity) can be obtained from a given energy source.
- Reliability factor [%] is the ability to generate electricity within a specified time. A power plant may experience downtime in energy production due to maintenance, servicing, or weather conditions such as lack of sunlight or wind. It shows the availability and efficiency of the power plant.
- Reserves to production ratio R/P [years]—the R/P ratio indicates the availability (in years) of a specific type of fuel based on current consumption and the annual rate of increase/decrease in consumption of each non-renewable energy source for electricity generation. When assessing fuel quantities, only well-known sources that can be practically exploited are taken into account.
- Capacity [%]—the actual amount of energy generated in a given period of time and the maximum energy that could be generated if the power plant were operating at full capacity during that time.

Three parameters were included in *the economic aspects*:

- Levelized cost of electricity (LCOE) [USD/MWh]—total cost of construction and operation of a power plant, including capital expenditure, operating expenditure, fuel, and disposal costs. This parameter is intended to contribute to the achievement of target 12.c: Rationalize inefficient fossil fuel subsidies that encourage wasteful consumption.
- Sensitivity to fuel price changes—the criterion used here is the share of fuel costs in the unit cost of electricity generation.
- External costs—costs incurred in relation to health and the environment. These costs can be measured but are not built into the cost of electricity. External costs are funds paid to restore people's health and ensure the efficient functioning of ecosystems. They compensate for the side effects of power plant operations.

The parameters described above represent the technical and economic aspects of economic governance. They are crucial for achieving sustainable development goals, which include:

- Implementing national social protection systems and measures for all (goal 1.3),
- ensuring access to affordable, reliable, sustainable, and modern energy for all by 2030 (goal 7),
- Increasing the share of renewable energy in the national energy mix by 2030 (goal 7),
- Doubling the national rate of improvement in energy efficiency by 2030 (goal 7),
- Promoting sustainable, inclusive, sustainable, and innovative economic growth, full and productive employment, and decent work for all (goals 8 and 9),
- Ensuring sustainable consumption and production patterns, achieving sustainable management of natural resources and their efficient use, ensuring awareness of sustainable development and a lifestyle in harmony with nature (goal 12).

The environmental pillar of sustainable development in the context of energy focuses on minimizing the negative impact of energy production, transmission, and consumption on the natural environment. Its goal is to transition to an energy system that operates within the framework of climate change mitigation.

Environmental aspects represent three parameters:

- Gas waste generation—this parameter takes into account greenhouse gas (GHG) emissions as CO₂ equivalents. It determines the concentration of carbon dioxide whose emission into the atmosphere would have the same effect as a given concentration of a comparable greenhouse gas.
- Particulate matter emissions—this is the emission of fine particulate matter (e.g., PM_{2.5} and PM₁₀) expressed as the number of particles per unit of energy in the life cycle of a power plant.
- Land management—the impact of power plants on the environment, social structure, and land use. This refers to the land area occupied by energy infrastructure.

These parameters ensure the partial achievement of the following goals:

- ensuring healthy lives (goal 3),
- by 2030, increase sustainable urbanization and sustainable human settlements management (goal 11),
- by 2030, achieve sustainable management of natural resources and their efficient use (goal 12),
- taking action to combat climate change and its impacts; strengthening human resilience to climate-related hazards; improving education, awareness-raising and human capacity on climate change mitigation (goal 13).

Sustainable development indicators relating to *the social pillar* focus on the impact of the energy system on people and society. The aim is to ensure that energy is not only clean and cost-effective, but also fair, accessible and beneficial to communities.

Social aspects are assessed using three parameters:

- Job creation—a parameter ensuring the achievement of the goal: To end poverty in all its forms.
- Compensation—compensation for the local community directly affected by the installation and operation of the power plant. Compensation for the deterioration of quality of life due to harmful emissions, landscape destruction, and noise.
- Social acceptance—consent of local residents to the operation of the power plant. Unmeasurable parameter. High acceptance is crucial for the pace of energy transition.

The parameters reflect the achievement of the following goals:

- ending poverty and hunger, creating food security and better nutrition, and promoting sustainable agriculture (goal 2),
- ensuring healthy lives and promoting well-being (goal 3),
- ensuring access to affordable, reliable, sustainable, and modern energy for all; percentage of population using clean fuels and clean energy technologies (goal 7),
- increasing the share of renewable energy in the national energy mix by 2030 (goal 7),
- promoting sustainable, inclusive, and sustainable economic growth, full and productive employment, and decent work for all (goal 8),
- making cities and human settlements safe and sustainable. By 2030, reduce the negative environmental impact of cities, paying attention to air quality and municipal waste management. Support positive economic, social, and environmental links between urban, suburban, and rural areas by strengthening national and regional development planning (goal 11),
- ensure sustainable consumption and production patterns; achieve sustainable management and efficient use of natural resources by 2030 (goal 12),
- take urgent action to slow down climate change (goal 13),
- protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, halt and reverse land degradation, and halt biodiversity loss (goal 15).

2.2. Model Structure for Achieving Climate Neutrality

The hierarchical model consists of three levels. The first level contains the main objective of the task—achieving climate neutrality. The second level of the model is represented by four groups of aspects used to evaluate electricity generation technologies: technical aspects, economic aspects, environmental aspects, and social aspects. The structure of the hierarchical model is shown in Figure 1. At the lower, third level of the hierarchical model, sub-parameters were introduced, which are a detailed elaboration of the group of criteria at level II. The sub-parameters correlate with the indicators of the pillars of sustainable energy development. In the group of technical aspects, four sub-parameters were taken into account: efficiency factor [%], availability factor [%], R/P factor [years], capacity/power of the power plant [%]. In the group of economic aspects, three parameters were distinguished: the cost of electricity production (LCOE) [USD/MWh], sensitivity to fuel price changes, and external costs [Euro cents/kWh]. In the environmental category, the following were introduced: waste generation (greenhouse gas (GHG) emissions) [kg CO₂/MWh], PM particulate emissions [mg/kWh], and land requirements [km²/1000 MW]. In the social aspects group, three sub-parameters were taken into account: job creation (new employees/500 MW), compensation [euro cents/kWh], and social acceptance.

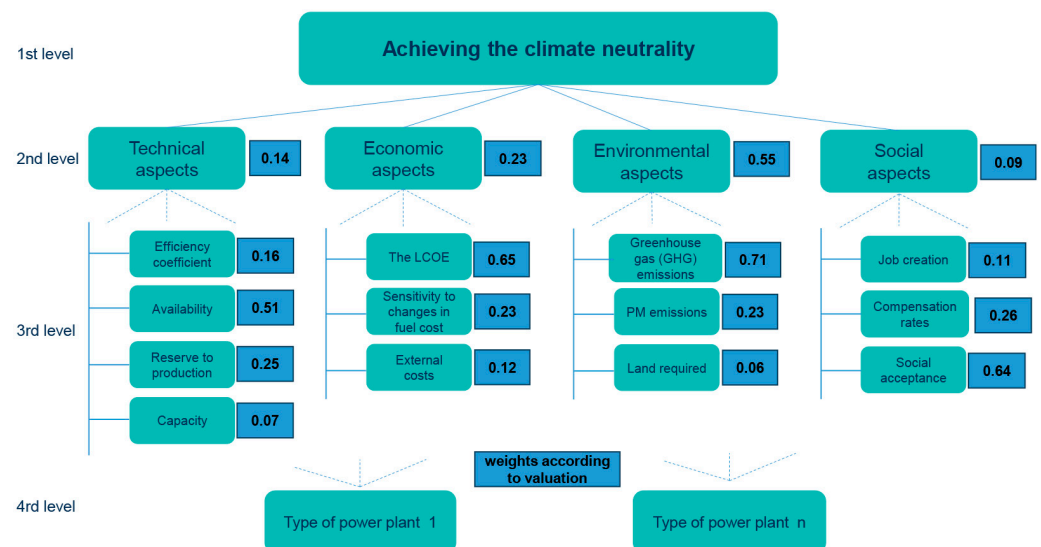


Figure 1. Model for assessing the achievement of climate neutrality in EU countries.

2.3. Assessment of the Priorities of Individual Criteria Forming the Model

Expert assessments were used to quantitatively determine individual criteria in relation to the objective. The assessments presented in the analysis (pairwise comparisons of criteria and subcriteria, based on Saaty's 9-point scale [23]) were carried out as part of a group decision-making process, known as brainstorming. The experts were selected from among research scientists representing various fields of science, including energy, economics, social sciences, and environmental engineering. The literature on expert surveys does not provide clear guidelines on the number of experts who should participate in an AHP study. It should be noted that 'more is not necessarily better' and that small expert samples are not uncommon in studies based on expert surveys [46]. In total, 12 experts participated in the model valuation. Based on prepared interactive surveys, the experts performed pairwise comparisons of all elements within each level relative to every element of the higher level, and the resulting scores were recorded in a square $N \times N$ matrix. An example of the interactive survey is shown in Figure 2. The analysis utilized the BPMMSG AHP Excel template version 12.08.2013 [47] as well as custom-author worksheets.

AHP Analytic Hierarchy Process (EVM multiple inputs)
 K. D. Goepel Version 12.08.2013 <http://bpmmsg.com>
 Only input data in the light green fields and worksheets!

n= 4 Number of criteria (3 to 10) Scale: 1 Linear
 N= 12 Number of Participants (1 to 20) α: 0.1 Consensus: 96.8%
 p= 0 selected Participant (0=consol.) 2 7 Consolidated

Objective: [Green bar]
 Author: [Green bar]
 Date: [Green bar] EVM check: 2,214E-07

Table	Criterion	Comment	Weights	Rk
1	technical aspects		13.8%	3
2	economic aspects		22.9%	2
3	environmental aspects		54.6%	1
4	social aspects		8.7%	4
5				
6				
7				
8				
9				
10		For 96.10 unprotect the input sheets and expand the question section ("x" in row 66)		

Result: Eigenvalue: 4.002
 Consistency Ratio: 0.37 GC: 0.00 lambda: 4.002 CR: 4.5%

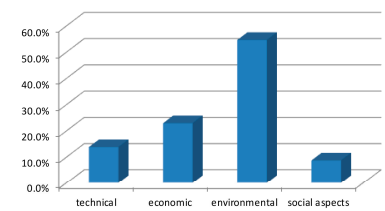


Figure 2. Survey on pairwise comparison of variables of the first level of the model for assessing progress toward climate neutrality in EU countries. Source: own study.

Hierarchical models developed using the AHP method can be sensitive to even small changes in the values of the comparison matrix, which translates into variability of the final result. Therefore, a sensitivity analysis was conducted, providing important information

about the ranking of energy generation technologies in the context of the decarbonization process. This analysis aimed to assess the stability of the AHP model and determine which criterion and which performance indicator could cause a change in the ranking between a pair of alternatives (rank reversal), even when relatively small changes occur in the statements of preferences. The primary data for the analysis are the weights of individual criteria. If small changes in the model's evaluations can significantly modify the result, the ranking is unstable and thus unreliable (we cannot be sure that the final effect is not incidental). Conversely, if reasonably small changes in the weights of the criteria do not produce noticeable modifications to the result, we can assume that the obtained result is a consequence of proper expert assessments during the model valuation. Sensitivity analysis can be used to assess the quality of the valuation procedure.

The conducted sensitivity analysis answered the question of how results would change if the structure of preferences of the experts valuing the model were slightly different. The presented analysis results depend on the criteria included in the structure and their valuations.

The sensitivity analysis covered four groups of factors. When valuing the hierarchical model, experts assessing the goal of achieving climate neutrality by 2050 considered environmental factors to be the most important group, accounting for 55% of the entire phenomenon. In performing the sensitivity analysis, the weight of this criterion group was varied in steps of 10 percentage points. The weights of the other criterion groups changed proportionally to each other (Figure 3).

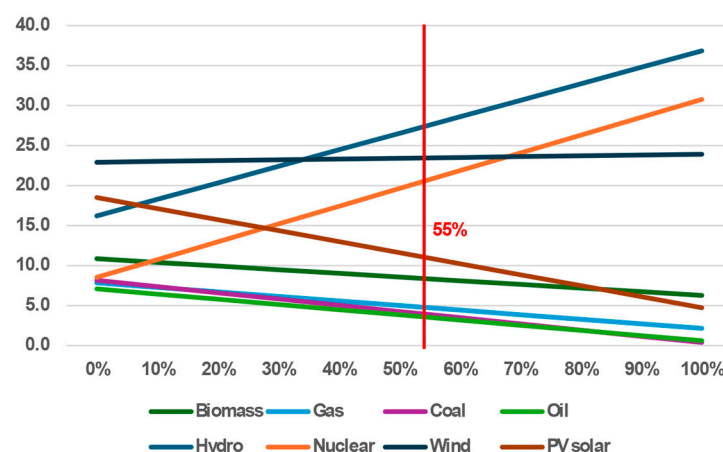


Figure 3. Sensitivity analysis for the DI as a function of the weight of environmental aspects. Source: own study.

The results of the average DI values for the analyzed energy technologies are shown on the vertical axis of the chart, while the weights from 0 to 100% are on the horizontal axis (Figure 3). The red vertical line represents the reference weight of 55% for environmental factors. In the expert valuations, the highest DI value was recorded for hydro, wind, and nuclear power plants.

It should be noted that increasing the influence of environmental factors by increasing the weight of this group substantially raises the DI for nuclear and hydro plants, while for wind plants the increase is minor. For the remaining types of plants, reducing the weight of environmental factors results in an increase in the DI value. This indicates that in these technologies, the DI is more strongly influenced by criteria arising from technical, economic, and social factors.

The sensitivity analysis showed that changing the impact of environmental factors by adjusting weights does not substantially alter the ranking of energy technologies. This

means that the developed hierarchical decarbonization assessment model is robust to changes in the weight values of the analyzed factor groups.

The results of the priority vector calculations are presented in Figure 1 next to the individual criteria. The weights of the four groups are: 0.14 for technical aspects, 0.23 for economic aspects, 0.55 for environmental aspects, and 0.09 for social aspects.

For the partial parameters of technical aspects, the following weights were obtained: 0.16 for efficiency, 0.51 for availability, 0.25 for resource sufficiency (production resources), and 0.07 for power plant capacity.

The priority vectors for the partial criteria of economic aspects are: 0.65 for Lazard's Levelized Cost of Energy (LCOE), 0.23 for the sensitivity of energy production costs to fuel price changes, and 0.12 for external costs.

The priority vector values for the sub-criteria for environmental aspects are: 0.71 for greenhouse gas (GHG) emissions, 0.23 for PM particulate matter emissions, and 0.06 for land requirements.

For the sub-criteria of social aspects, the estimated weights are 0.11 for job creation, 0.26 for compensation, and 0.64 for social acceptance.

2.4. Construction of the DI Decarbonization Index

All criteria used to construct the hierarchical structure for assessing climate neutrality were used to construct the DI decarbonization index. The DI is the sum of the product of the weights of individual criteria and the normalized values of these criteria in different types of power plants that make up the energy mix in the analyzed EU countries:

$$DI = \sum_{i=1}^n N_i \cdot z_i \quad (1)$$

where

DI —value of the power plant decarbonization index,

i —number of statistical features (criteria),

n —number of statistical features,

N_i —weight of the i -th statistical feature,

z_i —value of the normalized feature of the i -th power plant.

The statistical features used in the construction of the index are named, therefore they had to be standardized and made comparable through normalization.

In the presented analysis, the global unitarization method was chosen, enabling the comparison of indices over time.

Two unitarization formulas were used for the transformations:

– for stimulants:

$$z_{ij} = \frac{x_{ij} - \min\{x_{ij}\}}{\max\{x_{ij}\} - \min\{x_{ij}\}} \quad (2)$$

– for destimulants:

$$z_{ij} = \frac{\max\{x_{ij}\} - x_{ij}}{\max\{x_{ij}\} - \min\{x_{ij}\}} \quad (3)$$

where

i —power plant type;

j —statistical feature number (criterion);

x_{ij} —value of the j -th feature in the i -th power plant;

$\min\{x_{ij}\}$ —minimum value (lower reference point);

$\max\{x_{ij}\}$ —maximum value (upper reference point);

z_{ij} —transformed values.

The quantitative values for each of the 13 criteria across the eight energy technologies (Table 1) were sourced from internationally recognized and peer-reviewed references, statistical yearbooks, and industry reports to ensure reliability and comparability. Key sources include: the International Energy Agency (IEA) and BP Statistical Review for fuel-specific data and emission factors [48,49]; Lazard’s Levelized Cost of Energy Analysis for LCOE [50]; the OECD-NEA for nuclear energy parameters [50]; and studies by Afgan & Carvalho [38] and Shaaban et al. [40] for comprehensive multi-criteria assessments providing data on land use, employment, and externalities. In the case of qualitative criteria, such as social acceptance or sensitivity to fuel price changes, assessments made by experts using the AHP methodology were used, ensuring their consistent integration with quantitative criteria. The normalized values for each of the 13 criteria are presented in Table 2.

The DI decarbonization index provides information on the scale of the impact of a selected energy source on reducing the greenhouse effect (i.e., reducing greenhouse gas emissions). The interpretation of the DI value is as follows: the higher the index value, the greater the impact of the power plant on achieving climate neutrality (Figure 4).

The DI decarbonization index values obtained using the AHP method were calculated for 27 EU countries for the period from 2004, when Poland and nine other Central and Eastern European countries joined the EU, to 2024. The index consists of thirteen criteria grouped into four groups of aspects representing the pillars of sustainable development: economic (including technical), environmental, and social.

The analysis shows that increasing the share of renewable energy sources in the energy mix is of utmost importance for the EU’s energy and climate transition. This applies in particular to hydroelectric power plants (DI = 27.5), nuclear power plants (DI = 20.7), wind power plants (DI = 20.3), and energy obtained from photovoltaics (DI = 10.9). The least desirable energy sources are fossil fuels such as coal, oil, and gas, the combustion of which generates greenhouse gas emissions, including carbon dioxide (CO₂), but also nitrogen oxides (NO_x), sulfur dioxide (SO₂), and particulate matter. This is confirmed by the lowest decarbonization index values (Oil 3.6, Coal 3.9, and Gas 4.8).

Table 1. Values for each criterion in individual types of power plants.

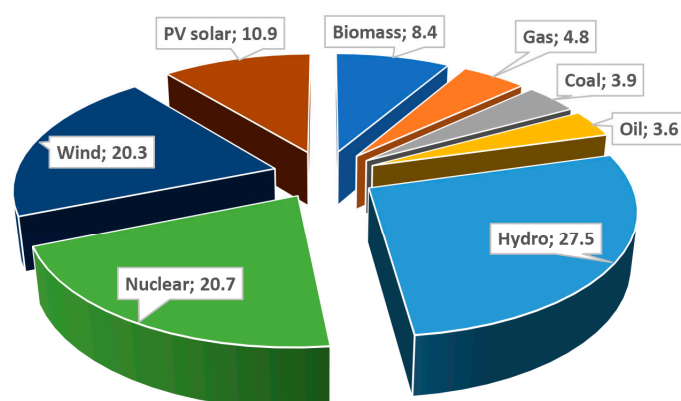
	Technical Aspects				Economic Aspects			Environmental Aspects			Social Aspects		
	Efficiency Coefficient	Availability	Reserve to Production	Capacity	The LCOE	Changes in Fuel Cost	External Costs	Greenhouse Gas (GHG) Emissions	PM Emissions	Land Required	Job Creation	Compensation Rates	Social Acceptance
	[%]	[%]	[Years]	[%]	USD/MWh	AHP Estimate	Eurocents/kWh	kg CO ₂ /MWh	mgCO ₂ eq/kWh	km ² /kW	Employees/500 MW	EUROcents/kWh	AHP Estimate
Biomass	28	80	∞	59	61	0.34	2.65	30	269	5.2	36	2.65	10.9
Gas	39	91	47	14.7	92	0.43	2.00	640	34	0.04	2460	2.00	7.0
Coal	39.4	85.4	131	42.6	74	0.34	8.40	960	347	0.4	2500	8.40	4.4
Oil	37.5	92	55	8.5	95	0.43	6.75	690	128	0.4	2500	6.75	4.4
Hydro	80	50	∞	34.5	61	0	0.56	6	5	0.13	2500	0.56	14.6
Nuclear	33.5	96	70	92.3	110	0.23	0.49	15	2	0.01	2500	0.49	2.4
Wind	35	38	∞	34.3	42	0	0.16	11	20	0.79	5635	0.16	32.1
PV solar	17	20	∞	23.4	49	0	0.24	45	101	0.12	5370	0.24	24.1

Source: [38–41,48–54].

Table 2. Normalized results for each criterion and DI decarbonization index value for individual types of power plants.

	Technical Aspects				Economic Aspects			Environmental Aspects			Social Aspects			Decarbonization Index–DI
	Efficiency Coefficient	Availability	Reserve to Production	Capacity	The LCOE	Changes in Fuel Cost	External Costs	Greenhouse Gas (GHG) Emissions	PM Emissions	Land Required	Job Creation	Compensation Rates	Social Acceptance	
Weights														
Level 2		0.14				0.23			0.55			0.09		
Level 3	0.16	0.51	0.25	0.07	0.65	0.23	0.12	0.71	0.23	0.06	0.11	0.26	0.64	
Global weights	0.023	0.073	0.035	0.010	0.046	0.052	0.028	0.388	0.126	0.033	0.009	0.022	0.055	
Biomass	28	80	∞	59	61	0.34	2.65	30	269	5.2	36	2.65	10.9	8.4
Gas	39	91	47	14.7	92	0.43	2.00	640	34	0.04	2460	2.00	7.0	4.8
Coal	39.4	85.4	131	42.6	74	0.34	8.40	960	347	0.4	2500	8.40	4.4	3.9
Oil	37.5	92	55	8.5	95	0.43	6.75	690	128	0.4	2500	6.75	4.4	3.6
Hydro	80	50	∞	34.5	61	0	0.56	6	5	0.13	2500	0.56	14.6	27.5
Nuclear	33.5	96	70	92.3	110	0.23	0.49	15	2	0.01	2500	0.49	2.4	20.7
Wind	35	38	∞	34.3	42	0	0.16	11	20	0.79	5635	0.16	32.1	20.3
PV solar	17	20	∞	23.4	49	0	0.24	45	101	0.12	5370	0.24	24.1	10.9

Source: own study.

**Figure 4.** DI decarbonization index for the analyzed types of power plants. Source: own study.

2.5. Cumulative Decarbonization Index

The Cumulative Decarbonization Index (CDI) for individual EU countries in 2004–2024 takes into account the structure of energy sources used for energy production. The CDI is the sum of the products of the DI decarbonization indices for individual types of power plants and the normalized values of the share of power plants in the energy mix:

$$CDI = \sum_{i=1}^n DI_i \cdot e_i \quad (4)$$

where

CDI—cumulative decarbonization index value,

i —power plant type,

n —number of power plants,
 DI_i —power plant decarbonization index value,
 e_i —normalized value of the power plant's share in the energy mix.

3. Analysis of Results

The cumulative CDI decarbonization index values in EU countries for 2004–2024 are presented in Figure 5. The analysis of the energy mix structure in EU countries was prepared on the basis of data contained in the report on the EU energy sector of 23 January 2025 [55].

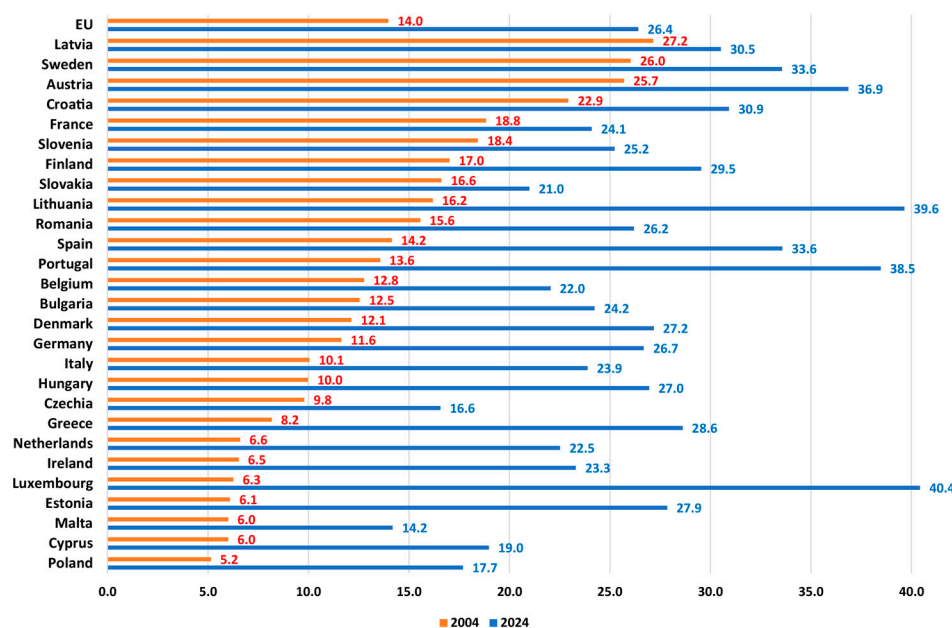


Figure 5. Value of the cumulative decarbonization index (CDI) in EU countries in 2004–2024. Source: own study.

A key methodological assumption in this study is the use of averaged, aggregated values of indicators (e.g., emissions intensity, efficiency) for each generating technology. The actual emissions intensity or efficiency of individual generating units depends on their age, the technology implemented, the technical condition, and the emission standards that applied at the time of construction. This approach enables a coherent comparison of decarbonization progress across countries; however, it may understate progress in countries that, in the short term, are unable to radically alter their energy mix but are actively investing in improving efficiency and reducing emissions from existing power plants.

Figure 6 shows the averaged plot of the cumulative decarbonization index (CDI) for the EU and for selected countries with the highest CDI values as well as countries exhibiting the greatest CDI growth dynamics.

In 2004, Poland had the lowest cumulative decarbonization index among the 27 EU countries (CDI = 5.2). This low value was influenced by the use of hard coal and lignite, which accounted for over 92% of energy production. The energy mix was supplemented to a small extent by hydroelectric and gas power plants and crude oil. Over the next twenty years, a dynamic increase in the CDI was observed, with a maximum value of 17.7 in 2024. This is due to the gradual reduction of the share of coal sources in the energy mix. In 2024, coal accounted for 53.5% of electricity production in total energy generation. We have observed an increase in the CDI since 2014 from 8.6 to 17.7 in 2024. During this period,

the importance of RES in the energy mix is growing rapidly: the total share of renewable energy increased by 20% and reached 29.8% in 2024.

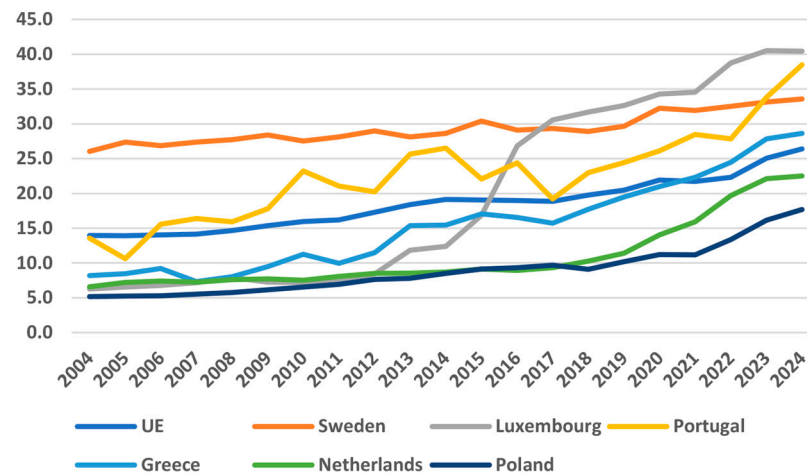


Figure 6. Cumulative decarbonisation indicator CDI values for the EU and selected EU countries in 2004–2024. Source: own study.

The highest cumulative decarbonization index value in 2004 was recorded in Sweden (CDI = 26.0). Sweden has a diversified energy mix, with hydropower (39.7%) and nuclear power (51.1%) accounting for the largest share. Depending on the season and hydrological conditions, these two sources account for a significant part of electricity production, often exceeding 90% in total. In recent years, Sweden has developed renewable energy on a large scale, primarily wind and biomass. In 2024, the CDI value rose to 33.6. This increase was mainly due to an increase in the share of wind energy in the energy mix to 23.3%, while the share of nuclear energy in energy production fell to 29%.

The highest cumulative decarbonization index values in 2024 were recorded in Luxembourg (CDI = 40.4) and Lithuania (CDI = 39.6). In Luxembourg, more than 90% of the energy mix comes from renewable energy sources. Biomass is the dominant renewable energy source, accounting for more than 30% of total energy production. Wind farms are also a significant renewable energy source in Luxembourg, accounting for 29% of energy production. In Lithuania, almost 70% of energy comes from renewable sources, including as much as 46% from wind energy and 19.3% from solar energy. However, it should be noted that a large amount of the energy consumed in the Lithuanian economy comes from imports, mainly from Sweden. In 2024, Lithuania imported 8.5 TWh of electricity, which accounts for more than half of the energy produced in the country [56].

Very high CDI values were also recorded in Portugal (38.5), Austria (36.9), and Spain (33.6). In 2024, as much as 88% of electricity in Portugal was generated from renewable energy sources. The largest share was achieved by the wind (34%) and solar (14.5%) energy sectors. In Austria, the main source of electricity is hydroelectric power plants, which account for 57% of the energy mix. In Spain, 49% of energy comes from renewable sources, mainly wind (26%) and solar (21%). Nuclear energy accounts for a significant share of the energy mix (19.6%).

All EU countries are implementing the principles of sustainable development in the energy transition, but the pace of change varies. The average CDI decarbonization index for the 27 EU countries increased from 14.0 in 2004 to 26.4 in 2024.

In all countries, the CDI has been on an upward trend since 2004. This is also reflected in the median value, which rose from Mdn = 12.7 in 2004 to Mdn = 26.6 in 2024.

The largest increase in the CDI among all EU countries was recorded in Luxembourg, Estonia, Greece, Ireland, the Netherlands, and Poland. In 2004, Estonia's energy mix was

still 95% based on oil shale, from which oil and gas were extracted. In 2024, as a result of the energy transition, as much as 57% of energy was obtained from renewable sources.

In 2004, Greece obtained as much as 76% of its energy from fossil fuels, including 61% from lignite-fired power plants and 15% from gas-fired power plants. Large investments in the development of renewable energy sources resulted in their share in the energy mix reaching 50% in 2024. This allowed for a reduction in greenhouse gas emissions and increased energy security.

A very similar energy transition can be observed in Ireland and the Netherlands. In 2004, both countries obtained their electricity mainly from gas (51% and 60%, respectively) and hard coal (25% and 25%, respectively). In 2024, the share of renewable energy in the energy mix increased to 46% in Ireland, mainly from wind energy (37%), and to 51% in the Netherlands, including 27% from wind energy and 18% from solar energy.

The energy transition that has taken place in Poland over the last two decades should also be highly valued. Decarbonizing the Polish economy is a particularly difficult undertaking due to its dependence on fossil fuels. In terms of the energy mix, coal is expected to continue to play a significant role, but due to the projected increase in energy demand, its share in electricity generation will gradually decline. At the same time, Poland will focus on diversifying its energy sources, gradually increasing the share of renewable energy sources: wind and photovoltaics, as well as introducing nuclear energy into the energy balance starting in 2033.

In Poland, the share of renewable energy sources reached 29.8% in 2024. It is also worth noting the very significant downward trend in the share of coal in the energy mix. The share of coal in 2004 was as high as 93%, and in 2024 it fell to 53.5% in domestic energy production. The scenarios for energy demand in the period 2040–2050 take into account the presence of hard coal in Poland's energy mix. The demand for raw materials for electricity and heat production in relation to hard coal is expected to reach 40 million tons in 2030 and 27 million tons in 2040 [57]. Hard coal will continue to play a key role in Poland's energy balance in the coming years [58].

4. Summary and Final Conclusions

In the face of anthropogenic climate change, which has already caused the average surface temperature of the Earth to rise by more than 1 °C above pre-industrial levels, the urgent decarbonization of the energy sector is a key challenge for the international community. At current rates, the average global temperature will rise by 1.5 °C as early as 2030 [59].

The presented research shows that the European Union, as a leader in climate action, is consistently implementing the assumptions of the energy transformation aimed at achieving climate neutrality by 2050. Over the last two decades, there has been a significant change in the structure of electricity generation, involving a gradual shift away from fossil fuels towards low-emission and zero-emission energy sources.

The presented study is a comprehensive, multi-faceted assessment of the progress of the decarbonization process in the 27 countries of the European Union in the years 2004–2024. The main achievement of the study is the development and application of an advanced decision-making model based on multi-criteria hierarchical analysis (AHP), which allowed for a quantitative assessment and comparison of the complexity of the energy transition.

A key element of the methodology was the construction of a decarbonization index (DI) for eight energy technologies, taking into account 13 criteria grouped into three pillars of sustainable development: economic (including technical), environmental, and social. The results clearly confirm the superiority of low- and zero-emission technologies. The

highest DI values were recorded for hydropower (27.5), nuclear power (20.7), and wind power (20.3). In contrast, fossil fuel-based technologies (oil, coal, gas) have radically lower scores (from 3.6 to 4.8), which objectively places them among the energy sources with a negative impact on climate goals.

At the macro level, the calculation of the cumulative decarbonization index (CDI) for each country, which is the result of the DI values of technologies and their share in the energy mix, revealed a clear positive trend for the European Union as a whole. The average CDI for the EU-27 rose from 14.0 in 2004 to 26.4 in 2024, demonstrating the effectiveness of the common climate and energy policy. However, a comparative analysis reveals significant differences in the pace of transformation between Member States. The leaders in terms of decarbonization in 2024 are countries with diversified energy mixes dominated by renewable energy sources and nuclear power, such as Luxembourg (CDI = 40.4), Lithuania (CDI = 39.6), Portugal (CDI = 38.5), Austria (CDI = 36.9), Sweden (CDI = 33.6), and Spain (CDI = 33.6).

The most dynamic progress has been observed in the group of countries undergoing a profound restructuring of their energy sector, which in 2004 was mainly based on fossil fuels. Poland, starting from the lowest level (CDI = 5.2), thanks to a reduction in the share of coal from 93% to 53.5% and the dynamic development of RES (to 29.8% in 2024), recorded one of the highest increases in the CDI (to 17.7), alongside Estonia, Greece, Ireland, and the Netherlands. Nevertheless, Poland's example clearly points to the challenges and the need for long-term planning for economies with an established coal position, where full transformation is a gradual process requiring significant investment and diversification of energy sources.

The sustainable development of the energy sector has become a fundamental and irreversible path for the European Union. The multi-criteria assessment method presented in the article is a valuable tool for decision-makers, enabling the objective comparison of technologies and tracking the progress of countries in this race against time, which is crucial for the future of the continent.

The research results unequivocally confirm that the foundation for achieving climate neutrality by the countries of the European Union is the continued transition to zero-emission energy sources. Further success will depend on the ability of all member states to maintain the pace of the transformation, while simultaneously ensuring social justice and the security of energy supply. Achieving the individual targets is a complex, long-term, and complicated undertaking. By fulfilling them, the pursuit should be directed towards the main goal, which is achieving climate neutrality. By strengthening the global partnership for sustainable development, supplemented by multilateral partnerships that mobilize and provide knowledge, experience, technology, and financial resources, this goal is achievable.

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the public domain: [<https://www.statista.com/>], [<https://www.bloomberg.com/>], [<https://www.iea.org/data-and-statistics/>], [<https://www.energyinst.org/statistical-review/>], [<https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2024.pdf>], [<https://www.oecd-neo.org/lcoe/>], [<https://ember-energy.org/>], [<https://enmin.lrv.lt/en/>].

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References

- Report of the World Commission on Environment and Development: Our Common Future. Available online: <https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf> (accessed on 26 June 2025).
- IPCC Intergovernmental Panel on Climate Change. Available online: <https://www.ipcc.ch/> (accessed on 27 June 2025).
- United Nations Conference on Environment and Development. Earth Summit 1992. Organizers: UNCED. Available online: <https://web.archive.org/web/20010405223601/http://www.un.org/geninfo/bp/enviro.html> (accessed on 27 June 2025).
- United Nations Framework Convention on Climate Change. Available online: https://treaties.un.org/Pages/ViewDetailsIII.aspx?src=IND&mtmsg_no=XXVII-7&chapter=27&Temp=mtmsg3&clang=_en (accessed on 27 June 2025).
- Agenda 21. Encyklopedia Zarządzania 2025. Available online: https://mfiles.pl/pl/index.php/Agenda_21 (accessed on 27 June 2025).
- Convention on Biological Diversity. Available online: https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtmsg_no=XXVII-8&chapter=27 (accessed on 27 June 2025).
- What Is the Kyoto Protocol? United Nations Climate Change. Available online: https://unfccc.int/kyoto_protocol (accessed on 27 June 2025).
- Corporate Finance Institute. Available online: <https://corporatefinanceinstitute.com/resources/esg/kyoto-protocol> (accessed on 27 June 2025).
- COP 21–UNFCCC. Framework Convention on Climate Change. Report of the Conference of the Parties on Its Twenty-First Session Held in Paris from 30 November to 13 December 2015. 2016. Available online: <https://unfccc.int/event/cop-21> (accessed on 27 June 2025).
- United Nations. The Paris Agreement. Available online: <https://www.un.org/en/climatechange/paris-agreement> (accessed on 27 June 2025).
- Zielony Ład: Klucz do Neutralnej Klimatycznie i Zrównoważonej UE. Available online: <https://www.europarl.europa.eu/topics/pl/article/20200618STO81513/zielony-lad-klucz-do-neutralnej-klimatycznie-i-zrownowazonej-ue> (accessed on 27 June 2025).
- Europejski Zielony Ład. Aspirowanie do Miana Pierwszego Kontynentu Neutralnego dla Klimatu. Komisja Europejska. Available online: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_pl (accessed on 7 July 2025).
- Parlament Europejski. Reforma Systemu Handlu Uprawnieniami do Emisji CO₂ w Pigułce. Available online: <https://www.europarl.europa.eu/topics/pl/article/20170213STO62208/reforma-systemu-handlu-uprawnieniami-do-emisji-co2-w-pigulce> (accessed on 27 June 2025).
- Climate Change: Parliament Extends the Market Stability Reserve to 2030. Available online: <https://www.europarl.europa.eu/news/pl/press-room/20230310IPR77241/climate-change-parliament-extends-the-market-stability-reserve-to-2030> (accessed on 7 June 2025).
- Walka z Ucieczką Emisji: Powstrzymanie Firm Przed Omijaniem Przepisów. Parlament Europejski. Available online: <https://www.europarl.europa.eu/topics/pl/article/20210303STO99110/walka-z-ucieczka-emisji-powstrzymanie-firm-przed-omijaniem-przepisow> (accessed on 27 June 2025).
- Ograniczanie Emisji Gazów Ciepłarnianych w UE: Krajowe Cele na 2030 r. Rozporządzenie ws. Rocznych Wiążących Ograniczeń Emisji Gazów Ciepłarnianych. Available online: <https://www.europarl.europa.eu/topics/pl/article/20180208STO97442/ograniczanie-emisji-gazow-cieplarnianych-w-ue-krajowe-cele-na-2030-r> (accessed on 7 July 2025).
- Walka ze Zmianą Klimatu: Lepsze Wykorzystanie Lasów UE do Pochłaniania Dwutlenku Węgla. Available online: <https://www.europarl.europa.eu/topics/pl/article/20170711STO79506/zmiana-klimatu-lepsze-wykorzystanie-lasow-ue-do-pochlaniania-dwutlenku-wegla> (accessed on 27 June 2025).
- Redukcja Emisji CO₂ z Samochodów Osobowych i Dostawczych: Wyjaśniamy Nowe Cele. Available online: <https://www.europarl.europa.eu/topics/pl/article/20180920STO14027/redukcja-emisji-co2-z-samochodow-osobowych-i-dostawczych-wyjasniamy-nowe-cele> (accessed on 27 June 2025).
- Redukcja Emisji z Samolotów i Statków: Działania UE. Available online: <https://www.europarl.europa.eu/topics/pl/article/2020610STO32720/redukcja-emisji-z-samolotow-i-statkow-dzialania-ue> (accessed on 27 June 2025).

20. Alternatywne Paliwa do Samochodów: Jak Zwiększyć Ich Wykorzystanie? Available online: <https://www.europarl.europa.eu/topics/pl/article/20221013STO43019/alternatywne-paliwa-do-samochodow-jak-zwiekszyt-ich-wykorzystanie> (accessed on 26 June 2025).
21. Oszczędzanie Energii: Działania UE dla Zmniejszenia Zużycia Energii. Available online: <https://www.europarl.europa.eu/topics/pl/article/20221128STO58002/oszczedzanie-energii-dzialania-ue-dla-zmniejszenia-zuzycia-energii> (accessed on 27 June 2025).
22. Jak UE Wspiera Energię Odnawialną? Available online: <https://www.europarl.europa.eu/topics/pl/article/20221128STO58001/jak-ue-wspiera-energie-odnawialna> (accessed on 27 June 2025).
23. Saaty, T.L. *Fundamentals of Decision Making and Priority Theory with the Analytic Hierarchy Process*, 2nd ed.; RWS Publications: Pittsburgh, PA, USA, 2000.
24. Prusak, A.; Stefanów, P. Badania nad właściwościami operacyjnymi metody AHP. *Folia Oeconomica Cracoviensia* **2011**, *52*, 87–104.
25. Bascetin, A. The study of decision making tools for equipment selection in mining engineering operations. *Gospod. Surowcami Miner.* **2009**, *25*, 37–56.
26. Sobczyk, E.J. Analytic Hierarchy Process (AHP) and Multivariate Statistical Analysis (MSA) in Evaluating Mining Difficulties in Coal Mines. New Challenges and Visions for Mining. In Proceedings of the 21st World Mining Congress and Expo, Cracow (Congress), Katowice, Poland, 7–11 September 2008; CRC Press: London, UK, 2008; p. 400.
27. Sobczyk, E.J.; Galica, D.; Kopacz, M.; Sobczyk, W. Selecting the optimal exploitation option using a digital deposit model and the AHP. *Resour. Policy* **2022**, *78*, 102952. [\[CrossRef\]](#)
28. Sobczyk, E.J.; Kaczmarek, J.; Fijorek, K.; Kopacz, M. Efficiency and financial standing of coal mining enterprises in Poland in terms of restructuring course and effects. *Gospod. Surowcami Miner.* **2020**, *40*, 127–152. [\[CrossRef\]](#)
29. Radwanek-Bąk, B.; Sobczyk, W.; Sobczyk, E.J. Support for Multiple Criteria Decisions for Mineral Deposits Valorization and Protection. *Resour. Policy* **2020**, *68*, 107795. [\[CrossRef\]](#)
30. Malanchuk, Y.; Moshynskyi, V.; Khrystyuk, A.; Malanchuk, Z.; Korniyenko, V.; Zhomyruk, R. Modelling mineral reserve assessment using discrete kriging methods. *Min. Miner. Depos.* **2024**, *18*, 89–98. [\[CrossRef\]](#)
31. Davies, M. Adaptive AHP: A review of marketing applications with extensions. *Eur. J. Mark.* **2001**, *35*, 872–894. [\[CrossRef\]](#)
32. Wind, Y.; Saaty, T.L. Marketing applications of the Analytic Hierarchy Process. *Manag. Sci.* **1980**, *26*, 641–658. [\[CrossRef\]](#)
33. Liberatore, M.J.; Nydick, R.L. The analytic hierarchy process in medical and health. *Eur. J. Oper. Res.* **2008**, *189*, 194–207. [\[CrossRef\]](#)
34. Biedrawa, A.; Sobczyk, W. AHP—Komputerowe wspomaganie podejmowania złożonych decyzji. *Rocz. Nauk. Eduk.-Tech. Inform.* **2010**, *1*, 285–291.
35. Sobczyk, W.; Kowalska, A.; Sobczyk, E.J. Wykorzystanie wielokryterialnej metody AHP i macierzy Leopolda do oceny wpływu eksploatacji złóż żwirowo-piaskowych na środowisko przyrodnicze doliny Jasiołki. *Miner. Resour. Manag.* **2014**, *30*, 157–172.
36. Adamus, W.; Łasak, P. Zastosowanie metody AHP do wyboru umiejscowienia nadzoru nad rynkiem finansowym. *Bank. Kredyt* **2010**, *41*, 73–100.
37. Pohekar, S.D.; Ramachandran, M. Application of multi-criteria decision making to sustainable energy planning—A review. *Renew. Sustain. Energy Rev.* **2004**, *8*, 365–381. [\[CrossRef\]](#)
38. Afgan, N.H.; Carvalho, M.G. Multi-criteria assessment of new and renewable Energy power plants. *Energy* **2002**, *27*, 739–755. [\[CrossRef\]](#)
39. Dipto, A.S.; Al Bari, M.A.; Nabil, S.T. Sustainability Analysis of Different Types of Power Plants Using Multi-Criteria Decision Analysis Methods. *J. Eng. Adv.* **2020**, *01*, 94–100. [\[CrossRef\]](#)
40. Shaaban, M.; Scheffran, J.; Böhrner, J.; Mohamed, S.; Elsobki, M.S. Sustainability Assessment of Electricity Generation Technologies in Egypt Using Multi-Criteria Decision Analysis. *Energies* **2018**, *11*, 1117. [\[CrossRef\]](#)
41. Chatzimouratidis, A.I.; Pilavachi, P.A. Multicriteria evaluation of power plants impact on the living standard using the analytic hierarchy process. *Energy Policy* **2008**, *36*, 1074–1089. [\[CrossRef\]](#)
42. Promentilla, M.A.B.; Aviso, K.B.; Tan, R.R. A fuzzy analytic hierarchy process (FAHP) approach for optimal selection of low-carbon energy technologies. *Chem. Eng. Trans.* **2015**, *45*, 1141–1146. [\[CrossRef\]](#)
43. Siwiec, D.; Pacana, A. Analiza emisji zanieczyszczeń sektora energetyczno-przemysłowego z wykorzystaniem rozmytego analitycznego procesu hierarchicznego i metody TOPSIS. *Stud. Mater.* **2020**, *2*, 32–45. [\[CrossRef\]](#)
44. Sobczyk, E.J.; Kulpa, J.; Kopacz, M.; Salamaga, M.; Sobczyk, W. Sustainable management of hard coal resources implemented by identifying risk factors in the mining process. *Gospod. Surowcami Miner.* **2024**, *40*, 23–48. [\[CrossRef\]](#)
45. United Nations. The 17 Goals. Available online: <https://sdgs.un.org/goals> (accessed on 25 August 2025).
46. Dua, R.; Almutairi, S.; Bansal, P. Emerging energy economics and policy research priorities for enabling the electric vehicle sector. *Energy Rep.* **2024**, *12*, 1836–1847. [\[CrossRef\]](#)
47. Goepel, K.D. Implementing the Analytic Hierarchy Process as a Standard Method for Multi-Criteria Decision Making in Corporate Enterprises—A New AHP Excel Template with Multiple Inputs. In Proceedings of the International Symposium on the Analytic Hierarchy Process, Kuala Lumpur, Malaysia, 23–26 June 2013. [\[CrossRef\]](#)
48. Available online: <https://www.iea.org/data-and-statistics/> (accessed on 22 June 2025).

49. Available online: <https://www.energyinst.org/statistical-review/> (accessed on 24 September 2025).
50. Available online: <https://www.oecd-neo.org/lcoe/> (accessed on 16 September 2025).
51. Available online: <https://www.statista.com> (accessed on 5 September 2025).
52. Available online: <https://www.bloomberg.com> (accessed on 2 June 2025).
53. Available online: <https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2024.pdf> (accessed on 24 June 2025).
54. European Electricity Review 2025. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_and_heat_statistics (accessed on 26 September 2025).
55. Available online: <https://ember-energy.org/> (accessed on 16 May 2025).
56. Available online: <https://enmin.lrv.lt/en/> (accessed on 16 September 2025).
57. Tokarski, S. Suwerenność energetyczna w polityce europejskiej i krajowej. *Energetyka Rozproszona* **2023**, *9*, 17–24. [CrossRef]
58. Polityka Energetyczna Polski (PEP). Available online: <https://www.gov.pl/web/klimat/polityka-energetyczna-polski> (accessed on 30 September 2025).
59. Available online: <https://naukaoklimacie.pl/> (accessed on 16 August 2025).

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