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Models and Indices of Sustainability Assessment in the Energy Context

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Abstract: Today, the energy sector is characterized by a high degree of unsustainability in terms of sources and supply systems, infrastructure, and policies, including climate policy. Therefore, it is necessary to strengthen the functions of planning and to implement new energy strategies, which should lead to the sector's sustainability in the environmental, social, and economic dimensions. In this context, the aim of the article is to develop a model for the sustainability assessment process and to use it as a benchmarking framework for sustainability assessment indices used in energy problems. The study included 14 indices to assess various aspects of sustainable development. The indices were tested in terms of their sustainability dimensions, data sources, data normalization methods, index aggregation methods, and other elements of the sustainability assessment process. As a result of the research, it was found that none of the analyzed indices meet all the requirements for indices that are to be used for the assessment of sustainability. Therefore, the use of these indices in research problems related to energy sustainability requires a conscious analysis of their features and adaptation to specific research problems related to energy sustainability.

Keywords: sustainability indices; energy sustainability; sustainability assessment; sustainable development

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1. Introduction

In a broad context, the idea of sustainable development was discussed in the 1987 report of the United Nations Brundtland Commission [1]. According to the Commission, sustainable development should be understood as: "meeting the needs of the present without compromising the ability of future generations to meet their own needs". The cited definition should be analyzed in connection with various sectors of the economy and the environment and taking into account social well-being. It should be mentioned that the very concept of sustainable development is commonly understood as a calm and composed development that can lead to balance and equilibrium. In the literature, one can find a number of other terms related to sustainable development because over several decades, as noted by Johnston et al. [2], about three hundred alternative and variously modified definitions of sustainable development have been created, which exist mainly in the field of environmental management and related disciplines. An interesting work on the concept of sustainable development and the criticism of definitions found in the literature was published by Ramsey [3]. The author drew attention to the role of the social context, which is required when identifying the components of the conditions for sustainable development, and to the dispute that is taking place in connection with the development of a unified definition.

Sustainable development, or sustainability for short, according to Johnston et al. [2], means that the activity or action can be sustained (i.e., continued indefinitely). Similarly, Pearce [4] believes that sustainable development should be understood as permanent or everlasting development. However, getting closer to truly sustainable development requires introducing elements of a timescale, so in the case of the natural environment, attention is paid to, among other things, the use of resources so that they are not exhausted. In contrast, a holistic approach focuses on ways of living, working, and being that enable all people in the world to lead a healthy, fulfilling, and economically safe life without damaging the environment and without jeopardizing the future well-being of people and the planet [2].

Roostaie et al. [5] pointed out that although sustainable development is a well-established term, there are some related terms that are considered indefinite, most often in areas where the environmental origin of sustainable development is of secondary importance. This includes maintaining the status quo, i.e., the tendency to mitigate or avoid changes, and the long-term maintenance of this state, which will make the system even more sustainable. On the other hand, Lew et al. [6] drew attention to the use of the sustainable development concept in order to achieve various political beliefs, which do not always reflect the essence of this definition. At the same time, according to the authors, the main task of sustainable development is to protect and preserve natural and cultural resources in order to mitigate the changes. At the same time, they mentioned actions in this direction, e.g., reducing the use of coal and other natural resources, increasing biodiversity, protecting the works of the human mind and human work, and revitalizing intangible cultural traditions.

In the review of the work on sustainability assessment, also known as an integrated assessment, sustainability impact assessment, Bond et al. [7] defined the cited concept as any process that directs decision-making toward sustainable development. Among the examples of forms of decision-making, the authors mentioned: daily individual choices of individuals, as well as projects, plans, programs, or policies identified with the domains assessing the effects. The authors pointed out that the approach to evaluation is territorially differentiated and depends on the existing legal structures, management, and form of decision-making, as well as on the conceptualization of sustainable development. In their work, Bebbington et al. [8] stressed the need for individuals, organizations, and societies to find models, metrics, and tools to express to what extent and how current activities are unsustainable. In response, you can learn about tools and techniques designed to support sustainability assessment processes. These include, but are not limited to: Multiple Criteria Analysis (MCA), cost–benefit analysis (CBA) forms, inclusive, deliberative techniques, life cycle assessment, indicators, and scenario planning. Flour and Bokhoree [9] presented considerations comparing various tools for assessing sustainable development at the national level, taking into account the integration of the environmental, economic, and social dimensions. According to the authors, this assessment enables an overview of how sustainable development performance decisions are made, with the aim of delivering a net benefit that positively impacts sustainable development.

Energy is one of the important issues that should be raised in relation to sustainable development. Energy is essential in various areas of socio-economic life. However, today the energy sector in the world is experiencing a crisis manifested by a significant energy deficit and is characterized by a high degree of unsustainability, especially in terms of sources, supply system, infrastructure, and policy. Meanwhile, there is a growing expectation that energy will be safe, environmentally friendly, and efficiently produced and used properly. In many countries, overcoming the crisis will require consensus and the strengthening of the planning functions and implementation of new energy strategies that should lead to the environmental, social, and economic sustainability of the sector. The related process of measuring and assessing sustainability should have solid methodological foundations that will allow for the implementation of the postulate of multidimensionality (selection of indicators and components consistent with the assumed goal of the assessment) and the complexity of this process (e.g., taking into account: ranks of indicators, their normalization, aggregation and analysis of their sensitivity).

In this context, the article is a review and generalization of experience in the field of index engineering used for sustainability assessment in various dimensions and areas of socio-economic life. The aim of the article is to develop a generalized model of the sustainability assessment process and use it as a framework for comparative analysis of the measurement methodology and assessment of sustainability using indices for various purposes. The index analysis included: the number of dimensions of the sustainability assessment, their decomposition (components, indicators), the origin of the source data, methods of: normalization, ranking and aggregation of indicators, and the interpretation of the index values.

The literature on the subject recognizes a wide spectrum of applications of various sustainability indices in the energy context. Measures that allow tracking energy sustainability are described [10], attempts are made to improve these types of measures [11], and technological solutions are analyzed and created, taking into account the criteria of sustainable development [12,13]; however, most often, the state of sustainability research is reviewed in the field of reducing CO_2 emissions and exploiting renewable energy sources, e.g., in [14–19].

Our publication makes a significant contribution to the literature and practice on energy sustainability in two respects. First, the presented study focuses on various models of the process of evaluating this phenomenon and integrates them into a generalized form. Secondly, which is the merit of the study, the substantive ranges of sustainability assessments are compared against the background of the generalized model, presented in the form of indices for various purposes.

An important argument in favor of conducting research on the sustainable development of the energy sector is the fact that the assessment of the progress of this phenomenon is most often based on sets of indicators that are very one-sided and limited. They do not allow systemic monitoring of the sustainable development of the energy sector but only of its selected elements. The results of the comparative analysis of the range of sustainability assessments used within indices for various purposes are, according to the authors, very important, because they constitute the basis (starting point) for developing an assessment methodology and a set of indicators that will comprehensively cover the development of the energy sector, which in turn should contribute to the determination of development in a more sustainable way. This is very important because, according to González-Eguino [20], in the near future, the energy sector will have to deal with three major changes related to climate change, security of supply, and energy poverty.

2. Literature Review

In the literature, there are many works devoted to sustainable development in combination with the subject of energy. According to González-Eguino [20], one of the important issues to be discussed is the concept of energy poverty, which has a large impact on health, economic activity, and the environment, reduces the current and future productivity, and limits development potential. Kaygusuz [21] discusses the energy situation of developing countries for sustainable development and highlights numerous energy challenges. It was noted that a high level of energy services requires that they are widely available, affordable, reliable, safe, and environmentally friendly. It involves making fundamental changes in technology, methodology, infrastructure, and people’s behavior.

According to Iddris and Bhattacharyy [10], energy plays a key role in the modern world, and understanding how sustainable a country’s energy system remains an important political issue. The authors reviewed the completeness of the existing measures for tracking energy sustainability. On the basis of the conducted analyses, they found that the existing multidimensional indicators do not adequately reflect the dimension of sustainability; therefore, they proposed the Sustainable Energy Development Index (SEDI). Wu et al. [22] compared the strengths and weaknesses of the existing income and wealth indicators and proposed a new inequality measure based on electricity consumption in households.

According to the authors, the new measure may complement existing solutions and provide a relatively complete and sustainable image of the overall inequality of welfare.

Humeres [12] drew attention to the combination of two themes in contemporary social sciences related to energy. He had in mind the technological transition to a more sustainable infrastructure and energy democracy. As a solution, he proposed a conceptual framework for a smart meter, which emphasized the importance of being transparent about technical functions and offering users the opportunity to participate in discussions, whereas Rogalev et al. [13] presented a comparative analysis of modern and future-proof manufacturing technologies in various economic conditions, taking into account the main criteria of sustainable development. The authors identified a production technology that, in their opinion, ensures the lowest costs of electricity supply and maximum economic efficiency of the investment with equally high environmental indicators. They also proposed a multi-factor economic and mathematical model that allows for the assessment of the efficiency indicators of any of the considered technologies in accordance with the criteria of sustainable development. Østergaard et al. [14] raised the subject of sustainable development with the use of renewable energy technologies. The authors presented an overview of the state of research in the field of the exploitation of renewable energy sources, with particular emphasis on the state of technologies using renewable energy sources, the state of the assessment of the availability of renewable energy sources, and the state of research on the type of systems that can integrate renewable energy sources.

The recently published literature includes the application of many sustainability indices to energy-related issues. The publication [15] presents research on the impact of the expansion of biofuel crops on the ecological Green Gross Domestic Product (GGDP). On the other hand, in [16], GGDP was included in the work on the regional model of bioenergy production, which can be produced from ethanol and/or agricultural waste. The study [17] was dedicated to long-term Genuine Savings (GS) estimates for Norway. It alluded to the oil and natural gas fields discovered in 1969, causing a significant depletion of natural resources and negative GS levels. They were used to build an integrated model of climate policy assessment. Therefore, work [18] focuses on activities that were aimed at reducing CO2 emissions in many strategic sectors of the economy. The article [23] analyses the relationship between energy consumption and the Index of Sustainable Economic Welfare (SEWI) in OPEC countries, in particular focusing on the relationship between energy, consumption, and sustainable economic welfare in these countries. The research results on the impact of the quality and volume of energy consumption by the population of selected countries in the world on the Human Development Index (HDI) are discussed in [24]. In contrast, the work [19] refers to the results of HDI in research on the relationship between green finance and climate change mitigation in N-11 countries (Bangladesh, Egypt, Indonesia, Iran, Mexico, Nigeria, Pakistan, Philippines, Turkey, South Korea, and Vietnam) and BRICS (Brazil, Russia, India, and China). Measuring the energy security and environmental sustainability of South Asian countries using the new ESESI index resulting from the combination of the Energy Security Index (EnSI) and the Environmental Sustainability Index (ESI) is included in [25]. On the other hand, publication [26] provides information on the Environmental Performance Index (EPI) in the context of developing possible strategies related to energy and environmental policy by examining the impact of patents on renewable energy. A similar approach was adopted in [27] on the relationship between energy policy and environmental performance in China, in particular, the role of green finance adopted by enterprises. The EIP was also used to estimate the connection between energy insecurity and energy poverty and the role of climate change and other environmental concerns, as presented in [28]. The publication [29] provides a comprehensive comparison of the Ecological Footprint (EF) and carbon dioxide emissions of ASEAN (Southeast Asian Associations) countries. On the other hand, the results of the analysis of the relationship between democracy, environmental regulation (including renewable energy consumption), economic growth, and EF in G7 countries (Germany, USA, Canada, Great Britain, France, Italy, and Japan) are discussed in [30]. In turn, the relationship between natural resources, renewable energy, human capital, and EF in the BRICS countries was assessed in [31]. The results of research on the City Development Index (CDI) and a policy proposal to improve urban land use efficiency, encourage a low-carbon energy structure to improve energy efficiency, improve carbon sequestration capacity in cities and implement water price differentials can be found in [11]. The publication [32] focuses on the considerations of the importance of the Dow Jones Sustainability Index (DJSI) in US and European Union enterprises. The paper highlights the significant negative impact of including the DJSI in the assessment of the market value of enterprises, among others, from the energy sector. In turn, [33] discusses the impact of the DJSI, exchange rate, and consumer sentiment index on carbon dioxide emissions.

Among the papers published recently on the measurement of sustainability in the energy context, the paper by Liu et al. [34] deserves attention, who proposed a novel production prediction model using an attention mechanism-based gated recurrent unit integrating the uniform manifold approximation and projection. According to the authors, the experiment results show that compared with other time series data prediction models, the proposed model has better stability and higher accuracy. The article by Wu et al. [35] presents the production capacity assessment and carbon reduction modeling technology of industrial processes by using radial basis function neural networks integrating multi-dimensional scaling. Han et al. [36] propose a novel energy consumption analysis and saving method for the building based on static and dynamic input-output models. Zakari et al. [37] proposed a combination of sustainable development goals with energy efficiency using the data envelopment analysis method. The panel correction standard error estimates found that sustainable economic development, sustainable financial development, and green innovation are associated with increased energy efficiency.

Noteworthy is also the paper by Aly [38], presenting a hybrid optimized model of an adaptive neuro-fuzzy inference system, recurrent Kalman filter, and neuro-wavelet for wind power forecasting driven by a doubly fed induction generator. Khan et al. [39] developed a comprehensive empirical analysis and applied advanced econometric methodologies. The authors concluded that energy transitions, renewable energy consumption, and natural resources improve environmental quality and curse economic growth. However, urbanization and non-renewable energy consumption deteriorate environmental quality and stimulate economic growth. Similarly, Khan et al. [40] noted that the obtained long-run random effect generalized least squares, generalized least square mixed effect models, and robust correlated panel corrected standard errors findings indicate trilemma energy balance, clean energy transition, and natural resource depletion enhance economic growth while clean energy discourages this growth. On the other hand, in the work of Saraswat and Digalwar [41], conventional and renewable energy sources for sustainable development of the energy sector are evaluated from multiple perspectives, including economic, technical, social, environmental, political, and flexible criteria. An integrated Shannon's entropy multi-criteria decision-making method has been used for the evaluation and assessment of these sources. Ahmad et al. [42] examined the dynamic interactive associations among sustainable investment in the energy sector, air pollution, and sustainable development. To this end, it employs a "one-step" system-generalized method of moments and a "one-step" differential-generalized method of moments estimators.

The presented literature review clearly indicates the wide application of various sustainability indices to study problems related to energy and energy sustainability. Therefore, it is important to understand the process of research and evaluation of sustainability, as well as a good knowledge of individual sustainability indices, so that their conscious selection for specific research problems related to energy can be possible.

3. Model of the Sustainability Assessment Process

The individual sustainability indices used in the literature have different purposes and structures. On the one hand, these indices usually differ in terms of the sustainability indicators used and the operations required to calculate the value of the index. On the other hand, almost all indices are based on overlapping procedures that can be generalized to certain models of activities undertaken in the sustainability assessment process. Models of the sustainability assessment process have been presented in particular in the publications of Juwan et al. [43], as well as Ibáñez-Forés et al. [44]. In addition, guidance on the most essential elements to be included in such a process is also discussed in the work of Diaz-Balteiro et al. [45], Singh et al. [46], and Böhringer and Jochem [47].

According to Juwan et al. [43], the sustainability assessment process consists of six steps: (1) selection of indicators and components, (2) obtaining the values of indicators and components (including value normalization), (3) obtaining the weights of indicators and components, (4) aggregation of indicators and components, (5) index resistance (sensitivity) analysis, and (6) interpretation of the final index value. On the other hand, Ibáñez-Forés et al. [44] define a seven-step process: (1) selection of evaluation criteria (indicators and components), (2) collecting information and data, (3) obtaining the value of the sustainability indicators, (4) normalization of indicators, (5) weighting the criteria, (6) comparing options and choosing the best one, and (7) sensitivity analysis. Diaz-Balteiro et al. [45], as well as Singh et al. [46] and Böhringer and Jochem [47], consider: (1) the selection of indicators and assessment components, (2) the normalization of the values of individual indicators, (3) the aggregation of indicators and components into the overall index value (assessment) and (4) the sensitivity analysis of the obtained solution as important elements of the sustainability assessment process. Singh et al. [46] and Böhringer and Jochem [47] emphasize that an important element of the sustainability assessment process is also (1) the determination of the weights of individual indicators and components. Moreover, according to Singh et al. [46], it is also important (1) to define the purpose of the evaluation.

The analysis of the cited models and guidelines shows that they are very similar to each other. In fact, they only differ in individual steps, which, depending on the model, are separated or included in another step. On the basis of the cited publications, it is possible to define a certain generalized model of the sustainability assessment process, comprising the following stages:

1. Defining the purpose of the assessment,
2. Selection of indicators and evaluation components,
3. Obtaining the values of the sustainability indicators and/or the data constituting the basis for their calculation,
4. Normalization of the indicator values,
5. Determining the weights of indicators and components,
6. Aggregation of the values of indicators and components into the overall value of the index,
7. Sensitivity analysis of the obtained solution,
8. Interpretation of the obtained results.

Defining the objective has a direct impact on the selection of indicators and components that should reflect the goal. The objectives should relate to the policy of sustainable development and, in particular, to the assessment or measurement of various aspects of sustainability (the objective may be, for example, the evaluation of social development) [46].

An index is a quantitative or qualitative measure of the facts or conditions of an index issue. Some indicators may be grouped into components or composed of more detailed sub-indicators [43]. Therefore, components, indicators, and sub-indicators can form a hierarchical structure [45]. The initial selection of indicators and components should be based on a literature review. It should take into account the indicators that were most often used to achieve similar evaluation objectives and take into account existing sets of indicators and components (e.g., used in different indices) [43,44]. This selection can be completed by adding other indicators and components that reflect the objective [44], and the final selection of indicators and components should be made on the basis of stakeholder discussions [43]. As part of this arrangement, some indicators or components may be removed, and others added. In addition, Juwana et al. [43], based on the publication by Liverman et al. [48], define the following seven characteristics that should be met by the indicators selected for the assessment of sustainability. It should be noted that the sustainability indicators do not have to have all of the features listed below but should comply with most of them.

- Sensitivity to volatility over time—the indicator should be observable in successive time series so that it is possible to determine how its value changes over time. An example of an indicator that is observed at regular intervals is the gross domestic product.
- Sensitivity to variability in space and in groups—the indicator should illustrate how its value changes in different places and social groups. For example, the gross domestic product says nothing about the development of individual regions of the country and different social groups.
- Predictability—the indicator should be able to predict sustainability problems. The forecast may be based on a time series or on the specificity of a specific indicator. For example, a high value of the emigration rate makes it possible to predict a decline in the value of social capital.
- Availability of reference values or thresholds—benchmarks should be known for the indicator to assess the level of its current value or threshold values to highlight potential problems. For an index describing earnings, the threshold may be, for example, the subsistence minimum.
- Impartiality—while it may be difficult or even impossible to establish completely objective indicators, one should ensure that indicators are, at best, slightly subjective.
- Data transformation—in most cases, the indicator value does not refer to raw data but to data that have been transformed in some way. Thanks to this, the indicator can, among others, provide more information. For example, the number of unemployed people carries less information than the unemployment rate.
- Complexity—complex indicators (e.g., the unemployment rate cited above) integrating different information is considered a useful tool for measuring sustainability. However, in the case of indicators aggregating various disproportionate information, special care should be taken to properly scale and weigh their components.

On the other hand, Böhringer and Jochem [47] indicate slightly different requirements for the indicators:

- A close link with the definitions of sustainability,
- Clarity of indicators representing individual domains,
- Reliability and measurability over time,
- Process orientation,
- Introducing political goals.

Obviously, after selecting the indicators and components to be used in the sustainability assessment, their values should be obtained or calculated from the source data. Therefore, the selected indicators should be characterized by reliability, as well as the availability of source data over longer time horizons [47], or, to put it simply, by the relative ease of collection and use [48]. The literature distinguishes several different ways of obtaining the values of indicators or data used to calculate them. They can be collected based on:

- Primary data obtained directly from the source,
- Secondary data from literature or commercial databases,
- Analogies, forecasts or simulations,
- Knowledge and opinions of field experts [44].

As the values of indicators can be measured in different units, it is necessary to normalize their values in order to express them on a common scale [45]. This makes it possible to compare the values of various indicators and aggregate them into the overall value of the index [44,47]. Standardization may be carried out using, among others, the following techniques:

- Ranking method—used when the values of indicators are presented on any measurement scale except for the nominal scale. This method consists in determining, for each indicator, a ranking of assessed opinions or actions. As a result, the normalized values of each indicator are expressed on an ordinal scale [43].

- Continuous rescaling—used when the values of indicators are expressed on an interval or ratio scale. In the case of an interval scale, it requires the indication of a maximum and minimum value, and in the case of a ratio scale, the maximum value is sufficient. These values are reference points whose values after the transformation are 0 and 1 (or, e.g., 0–100, depending on the form of the transformation). In turn, the considered index values are converted to relative values in the range [0, 1], keeping the original distribution. A typical transformation used in a linear transformation is represented by the formula:
$$In_j = \frac{x_j - x_{jmin}}{x_{jmax} - x_{jmin}}, \quad (1)$$
where: In_j is the normalized value of the j-th index, and x_j is the value of this index before normalization [43,44,46].
- Distance to a reference/target—used when the values of indicators are expressed on a quotient scale. This method requires the indication of the target value, which is the reference or ideal point. After rescaling, the values of the indicators are expressed in the form of the ratio of the given indicator value to the indicated reference point, which is presented by the formula:
$$In_j = \frac{x_j}{x_{jr}}, \quad (2)$$
where: x_{jr} denotes the reference value of the j-th indicator [43,44].
- Standard score—this method requires the determination of the mean value and standard deviation from the data. After conversion on the new scale, the mean value is marked as 0, and the standard deviation becomes 1. Z standard score is performed according to the formula:
$$In_j = \frac{x_j - \overline{x_j}}{\sigma_j}, \quad (3)$$
where: $\overline{x_j}$ is the mean value, and σ_j is the standard deviation of the j-th indicator [46].

Defining the weights of individual indicators and components is related to determining the relative significance of each of them. The priorities assigned to each indicator play one of the key roles in calculating the index value and must be used with caution as the final index value may vary considerably depending on the importance assigned to each indicator [44]. Weights can be implicit or explicit in nature. Implicit weights are used during the normalization process and are related to the manipulation of the measuring scale range at the beginning of the normalization process [46]. On the other hand, explicit weights may be equal for all indicators (or their use may be omitted), or they may assign different priorities to individual indicators or components [44]. The methods of defining weights can be divided into:

- Subjective, based on participation,
- Objective, based on statistical data.

In subjective methods, weights are defined based on the personal or collective judgments of experts. The subjective methods include, among others, the following methods [43,44]:

- Delphi method—composed of three stages, i.e.,: (1) identification and explanation of the purpose of the study and preparation of the questionnaire, (2) identification and selection of a panel of experts, and (3) iterative survey and analysis of responses, most often until a consensus is reached [49].
- Budget Allocation (BAL)—in which experts allocate a specific number of n points to individual indicators. Therefore, the indicators considered the most important

receive the greater part of the budget allocated for distribution. The weights are then calculated according to the distribution of the points awarded [50].

- Revised Simos' Procedure—based on physical cards used to assign points to individual indicators, each card represents one specific indicator, and the expert'S job is to arrange the cards in order from the least to the most important. Indicator weights are calculated based on the order of cards [43].
- Analytic Hierarchy Process (AHP)—allows determining the weights of indicators based on the matrix of comparisons in pairs. This matrix contains the relative weights of the indicators, expressed on the Saaty scale [1/9, 1/8 . . . , 1/2, 1, 2, . . . , 8, 9], where each value represents the preference of one of the indicators over another. This matrix is aggregated using the right-eigenvector method, resulting in a weight vector whose sum is 1. The AHP method allows for modeling hierarchical relationships between goals, components, indices, and sub-indices [51].
- Analytic Network Process (ANP)—this is a generalization of the AHP method, allowing us to model not only hierarchical relations but also horizontal relations and feedback between individual components and indicators. In this method, the final weights of indicators and components are obtained by aggregating the so-called super-matrix containing weight vectors obtained from individual matrices of pairwise comparisons [52].

The use of objective methods is related to the statistical analysis of data describing individual indicators. The following methods can be distinguished [43,44]:

- Regression analyses—this is a multidimensional technique that allows one to assess the relationship between a set of variables. This method allows us to determine the weights of indicators by determining the relationship between a set of indicators and a single output measure (index value) [50].
- Principal Component Analysis (PCA)—in this method, indicators are assigned to individual components based on the correlation between them. Additionally, the so-called factor loadings, which define the share of each indicator in the component to which the indicator was assigned, are defined. Each component is described by the value of the variance it explains. The weight of individual indicators is determined on the basis of the value of the factor load, and the variance explained [43].
- Unobserved Component Model (UCM)—is a statistical tool used in economics to construct collective indicators. The basis of this approach is the assumption that sustainability is difficult to observe directly and that the indicator is only an imperfect signal of the unobservable sustainability component. UCM aims to isolate the signal of the unobservable component, which is common for all indicators [50]. This approach is based on the values of variance determined separately for individual indicators and the sum of the variance of all other indicators. The weight of a given indicator increases with the decrease in the variance of this indicator and the increase in the variance of the remaining indicators [43].

Aggregating the values of indicators and components is aimed at obtaining an overall composite index value for each option or activity considered. Assuming that the index has a hierarchical structure formed by sub-indicators, indicators, and components, aggregation may be carried out in multiple stages at each subsequent level of the hierarchy. Therefore, the values of the sub-indicators are aggregated into the values of the indicators, which in turn are used to calculate the values of the components, the aggregation of which allows to obtain the overall value of the index. Nevertheless, in some indices, despite the presence of components, aggregation into the overall index value is performed at the level of indicators or sub-indicators, disregarding the highest level of the hierarchy, i.e., components [43]. Many different methods are used for the aggregation of indicators, depending on the purpose, nature, scope, and type of indicators [46]. However, there are two basic aggregation models that are used in almost all methods:

- Arithmetic model, also known as additive,

- Geometric model, otherwise known as multiplicative.

  The arithmetic model can be described by the general formula:

$$In = \sum_{j=1}^{n} w_j In_j, \tag{4}$$

where w_j is the weight of the j-th index. The arithmetic model assumes full substitution and compensation between indices. This means that the low values of some indicators may be compensated by the high values of other indicators. Therefore, the index may have the same values for two different options, for which the values of individual indicators differ to a large extent. In turn, the geometric model is described by the formula:

$$In = \prod_{j=1}^{n} In_j^{w_j}, \tag{5}$$

The geometric model, unlike the arithmetic model, does not provide full substitution and compensation between the values of the indicators. Therefore, two different options with different index values will have diverse aggregated index values. Therefore, it should be noted that the geometric model takes into account, during aggregation, the differences between the normalized values of individual indicators, while the arithmetic model does not take these differences into account [43]. Therefore, the geometric model is more in line with the concept of strong sustainability, while the arithmetic model is fully in line with the concept of weak sustainability.

The task of the sensitivity analysis is to assess the impact of changes in the values of the input variables on the final results and to indicate, most often quantitatively, which variability at the index input has the greatest impact on the variability of the final result [43]. The sensitivity analysis allows you to identify methodological errors and increase the transparency of the index. Depending on the weighting and aggregation method used, some indices may be very sensitive to indicators with very high volatility. In this situation, the index may suggest that the test item is less sustainable than others simply because the test item scored low on one or more highly variable indicators. Sensitivity analysis also identifies indicators that give the best chance of improving the results of the sustainability assessment [53]. The sensitivity analysis can be performed at any stage of the index calculation and for all input variables. In particular, it can be performed with reference to: the selection of indicators, values of individual indicators, their weights, input data normalization methods, aggregation methods, and other index parameters [44,45].

Interpreting the results is the final step in the sustainability assessment process. The results of applying the index can take the form of numerical values describing a single action or option and can represent a ranking of the options being assessed. These results can be interpreted, for example, by assigning individual options to qualitative categories describing their level of sustainability. One of the most important elements influencing the interpretation of the results is the previously performed sensitivity analysis, which may reveal the uncertainty of the obtained results. Moreover, some indices allow for a separate interpretation of the index values, components, and overall index value [43].

As already indicated, selected stages of the generalized model of the sustainability assessment process discussed above are used in various indices. Moreover, it should be noted that in individual indices, even if certain steps overlap, they may be implemented in different ways [44]. For example, one index may use linear transform normalization, and another may use a ranking method. The component stages and the methods used in them should be selected depending on the assumptions, goals, and tasks set for a given index.

4. Applied Sustainability Indices

There are many different sustainability indices in the literature. They are characterized, among others, in the reviews: [43,46,47,53–58]. On the basis of the above-mentioned works, the sustainability indices most frequently used and quoted in the literature can be indicated, which include:

- Green Gross Domestic Product—GGDP,
- Environmentally Adjusted Net Domestic Product—EDP,
- Genuine Savings—GS,
- Index of Sustainable Economic Welfare—SEWI,
- Genuine Progress Indicator—GPI,
- Human Development Index—HDI,
- Environmental Sustainability Index—ESI,
- Environmental Performance Index—EPI,
- Environmental Vulnerability Index—EVI,
- Ecological Footprint—EF,
- Living Planet Index—LPI,
- City Development Index—CDI,
- Well-Being Index—WI,
- Dow Jones Sustainability Index—DJSI.

Table 1 presents review publications with individual indices.

Table 1. Sustainability indices included in individual reviews.

Index	[47]	[53]	[54]	[46]	[43]	[57]	[58]	[55]	[56]
GGDP		X				X	X		
EDP	X		X	X			X		
GS	X	X	X	X		X			
SEWI	X	X	X	X		X			
GPI	X	X	X			X	X		
HDI	X		X	X	X	X	X		
ESI	X	X	X	X	X	X			
EPI	X		X	X		X			
EVI	X		X	X					
EF	X	X	X	X		X			
LPI	X		X	X					
CDI	X		X	X					
WI	X	X		X					
DJSI				X				X	X

Singh et al. [46] propose the division of sustainability indices into different categories, depending on the field they concern. On the basis of the aforementioned division, the previously mentioned indices can be classified into individual categories:

- market and economic indices: GGDP, EDP, GS,
- development indices: SEWI, GPI, HDI,
- environmental indices for policies, nations, and regions: ESI, EPI, EVI,
- indices based on ecosystems: EF, LPI,
- indices for cities and societies: CDI, WI,
- industry sustainability indices: DJSI.

GGDP is, in fact, a term for a group of indices based on the Gross Domestic Product (GDP) minus some additional values relating to environmental factors. This is due to the fact that GDP is usually negatively correlated with environmental quality, and its positive correlation with social welfare indicators disappears when GDP reaches a certain high level [57]. GGDP takes into account the diminution of available ecosystem goods and services related to human economic activity and takes into account the economic resources spent on mitigating environmental damage [53]. Mori and Christodoulou (2012) [54] and Harris and Roach (2013, 2018) [58,59] equate GGDP with the EDP index. On the other hand, Mayer [53] includes, among others, the following to the group of GGDP indices: SEWI, GS, EF.

The EDP index was developed as part of the Integrated Environmental and Economic Accounting System implemented by the United Nations Environmental Program.

Bohringer and Jochem (2007) [47] distinguish three versions of EDP: (1) EDP I, in which the depreciation of natural resources is subtracted from the Net National Income (DNN), (2) EDP II, in which the costs necessary to maintain the state of the environment at the same level for a given period of time are subtracted from the DNN, (3) EDP III, in which the costs of environmental destruction are subtracted from the DNN. On the other hand, Harris and Roach (2013) [58] propose to calculate the EDP by subtracting the depreciation of natural capital from the Net Domestic Product. Therefore, two indices are used in the EDP, which differ according to the index version. In all versions of the EDP, environmental losses, as well as revenues, are expressed in monetary terms, so there is no data normalization. Aggregation is performed here with the use of an arithmetic model [47], and the index result, as a result of the previously performed normalization, is expressed in monetary values.

The GS index was developed by the World Bank, and its value is determined by the following capitals: economic, natural, and social [53]. Additionally, the following indicators are used: Gross National Income (GNI), consumption, current transfers, and pollution. As in the case of EDP, also in GS, all factors are expressed as monetary values, and aggregation is performed using an arithmetic model [47]. Moreover, analogous to the EDP, also here, the overall index value is expressed in the form of monetary values. If the GS value is positive, it means that the country or region surveyed is balanced over the period considered. On the other hand, a negative value of the index indicates a lack of balance [57].

The GPI Index is derived from the Measure of Economic Welfare (MEW), later developed into the Sustainable Economic Welfare Index (SEWI) [53]. Currently, the second version of the GPI index (GPI 2.0) is used based on economic, social, and natural capital minus: non-welfare expenditure, natural capital reduction, pollution, social costs of economic activity, and welfare decline due to risk and uncertainty. All capitals and adjustments are expressed as monetary values and are aggregated using an arithmetic model. The results are presented as GPI values per person [60].

The HDI index was developed by the United Nations Development Program to assess the level of human and social development of individual countries. Its basic assumption is to consider economic development on the basis of social policy and not only on the basis of national income. HDI is used in the annual Human Development Reports published by a designated United Nations agency [57]. HDI consists of three components with equal weights, which are: health and life expectancy, knowledge and education, and standard of living expressed by the value of GNI per person. Additionally, the knowledge and education component consists of two indicators, i.e., expected years of study and average years of study. These indicators also have equal weights. It uses normalization based on a linear transformation, with the use of predefined constants and maximum and minimum values. The aggregation of indicators into components is performed with the arithmetic mean, while the aggregation of components into the index is based on the geometric mean. As a result of using the index, a country ranking is obtained, and the general values of the index, expressed on a scale [0,1], have their qualitative interpretation of the level of development: [0–0.55)—low; [0.55–0.7)—medium; [0.7–0.8)—high; [0.8–1]—very high [61,62].

The ESI index was led at the Yale and Columbia universities in consultation with the World Economic Forum and the Joint Research Centre of the European Commission [57]. The ESI aims to measure the overall performance of environmental sustainability in countries around the world, with an emphasis on protecting valuable environmental resources over the next few decades [43]. It uses five main components relating to the environment, i.e., environmental systems, environmental loads, people's sensitivity to pollution, taking up environmental challenges by society and institutions, and international cooperation. The assigned weights are equal for all indicators included in a given component and equal for all sub-indicators making up a specific indicator. Data normalization in ESI is carried out using the standard score, and aggregation is carried out at the level of indicators, omitting the level of components, using the arithmetic mean. As a result of using the ESI index, a country ranking is obtained, and the index value can be interpreted as the probability that a given country will be able to effectively protect the environment in the next few decades [63]. The ESI index was determined in 2001, 2002, and 2005 [47], and since 2006 it has been replaced by the EPI [57]. It is the only index among the discussed indices where a sensitivity analysis is performed that allows for the modification of the weights of the indicators [63].

The EPI is appointed every two years, and its latest version is from 2018 [64]. As mentioned earlier, it is a continuation of the ESI reports, but unlike the ESI, the EPI index focuses on the assessment of the current environmental conditions and not their long-term assessment [57]. In particular, the EPI assesses the effectiveness of policies in reducing the environmental burden on human health and in the proper management of natural resources [47]. It uses 10 main components assigned to two groups. Among the components describing the environment, the following are distinguished: air quality, water and sanitation, and heavy metals. In turn, the components characterizing the vitality of the ecosystem include: biodiversity and habitats, forests, fisheries, climate and energy, air pollution, water resources, and agriculture [65]. The EPI index uses the weights of components and indicators determined using principal components analysis and by experts [46,47]. Normalization is performed based on a linear transformation, and aggregation of indicators is performed using the arithmetic mean. As in the case of HDI and ESI indices, the results of the EPI index are also presented in the form of country rankings [64].

The development of the EVI index is justified by the interpretation of the Action Program for the Sustainable Development of Small Island Developing Countries, also known as the Barbados Action Program. This index was developed by the South Pacific Commission on Applied Geosciences (SOPAC) [66]. Its purpose is to assess the likelihood of potential damage caused by environmental problems, and it includes three components that reflect: threats, resilience, and environmental damage [46]. The EVI index does not use index and component weights. Due to the fact that the values of individual indicators are expressed in EVI on a point scale [1–7], their normalization is not required. The indicators are aggregated using the arithmetic mean, but in the absence of data, a specific indicator is omitted [67]. The results of the EVI index can take values in the range [0–700], and the percentage of the availability of data used to determine the EVI for a given country is also given next to the result. The EVI index values have a qualitative interpretation, describing the susceptibility to the occurrence of environmental problems: [0–215)—resistant; [215–265)—risk; [265–315)—sensitive; [315–365)—very sensitive; —extremely sensitive [68].

EF is a measure of how much natural resources are spent on people's needs. In particular, it indicates what land and sea area is required to support a specific human population indefinitely by providing the necessary energy and material resources and absorbing all waste and pollution. It may be determined for individual persons, as well as on a local and global scale [57]. The EF consists of six indicators: agricultural and livestock production, fisheries, timber production, built-up areas, and carbon dioxide emissions [69]. All indicators are expressed in hectares, so there is no need to normalize them. On the other hand, aggregation is performed using an arithmetic model [70]. During aggregation, a conversion factor is used, which allows different weights to be assigned to different indicators. If the overall index value for the examined object is greater than 1, it means that the object is not sustainable, and thus living standards violate the principles of sustainable development [47].

The LPI index was developed by the World Wildlife Fund as a global measure of biodiversity [46]. It shows trends in the population abundance of different species of vertebrates. The data used to calculate it are time series: population size, density (population size per unit area), abundance (number of individuals per sample), or abundance index. The 2016 report presenting the LPI values included as many as 14,152 populations and 3706 species of vertebrates. It takes into account three components that correspond to the habitat of vertebrates: land, freshwater, and sea. Four groups of vertebrates are distinguished therein:

fish, amphibians and reptiles, birds, and mammals. Due to the time needed to collect and process data, their publication takes place with a delay of several years; e.g., the 2016 report uses data from the 1970–2012 years [71]. As all index indicators refer to changes in the number of species, no method of normalization is used here [47]. In the LPI index, the geometric mean is used for aggregation. It should also be noted that apart from the LPI index, which does not take into account the weights, the LOI-D index is also used, in which the weights correspond to the estimated percentage of species represented by a given group [72].

The CDI index was proposed by the United Nations Program for Human Settlements [47]. It is a measure of the average level of access to urban facilities and the well-being of the urban community. Moreover, it is considered to allow the measurement of human and physical capital resources of cities on the basis of expenditure related to urban services and infrastructure. In particular, the CDI takes into account factors related to: municipal production, infrastructure, education, residents' health, and waste, reflected in 5 components and 11 indicators. The weights of individual indicators are determined using principal component analysis, but it should be noted that the weights of all components are equal. The indicators are normalized using a linear transformation, and aggregation is an arithmetic mean [73].

The WI index was developed in cooperation with the International Union for Conservation of Nature and the International Centre for Research on Development [53]. It is based on the premise that a healthy environment is essential for human health. For this reason, it includes two components, i.e., Human Well-Being Index (HWI) and Ecosystem Well-Being Index (EWI) [47]. The human well-being component includes 5 indicators characterized by 36 sub-indicators. In turn, the component describing the well-being of the ecosystem consists of 5 indicators and 51 sub-indicators. All sub-indicators included in a specific component, as well as the components themselves, have equal weights. Normalization in the WI index is a distance from the target, and aggregation is performed using the arithmetic mean, disregarding the level of the indicators. The results are presented on a scale covering the range [0–100], and they can be interpreter linguistically in relation to the quality of life: [0–20]—very bad; [20–40]—bad; [40–60]—average; [60–80]—good; [80–100]—very good [74].

DJSI was jointly developed by the Dow Jones indices (now Standard & Poor's Dow Jones Indices) and SAM Sustainability Group (now RobecoSAM) in 1999 as a group of indices measuring the sustainable development of corporations from various sectors of the economy and from different regions of the world [46,75]. DJSI includes the following components: environmental, social, and economic [76]. A total of 2500 corporations with the largest market capitalization in various sectors are invited to participate in the global survey every year [55]. Corporations ranked in the top 10% of enterprises from each of the 60 sectors are invited. This list is then supplemented by additional corporations included in the regional indices. Therefore, about 3400 enterprises are invited to the study. The results are obtained on the basis of questionnaires tailored to the specifics of each sector [76]. Due to the use of a common scale across all survey questions, data normalization is not required here. In addition, expert weights are used, which differ depending on the sector of the economy in which a given enterprise operates [77]. The survey results are aggregated into individual component scores and an overall score using the arithmetic mean [78].

Tables 2–4 summarize the most important information about each index, taking into account the next steps in the sustainability assessment process, defined in Section 3. In particular, these tables contain information on: (1) the main purpose of the index application; (2) the number of components, indicators, and sub-indicators and their relationship to the primary dimensions of sustainability; (3) proposed and used data sources for each index; (4) the data normalization method used; (5) structure of indicator and component weights; (6) the method of aggregation of indicators used in the overall assessment; (7) using the sensitivity analysis; (8) interpretation of the index results.

Table 2. Comparison of selected sustainability indices (part 1).

Index	Purpose of Evaluation	Number of Sub-Indicators/Indicators	Number of Components	Sustainability Dimensions
EDP	Measurement of the size of the economy taking into account natural capital	3	-	Environmental, economic
GS	Measuring the economy sustainability	8	-	Environmental, social, economic
GPI (2.0)	Measurement of the economic well-being of a population in a given year	67/13	3	Environmental, social, economic
HDI	Measurement of social development	4	3	Social, economic
ESI	Measurement of the long-term ability to protect the environment	76/21	5	Environmental, social
EPI	Measurement of the current environmental capacity	24	10 (2 groups)	Environmental, social
EVI	Measurement of the sensitivity of the natural environment	50	3	Environmental, social
EF	Measurement of environmental resources	6	-	Environmental
LPI	Measurement of the biodiversity status of populations and species	14,152 populations/ 3706 species	3	Environmental
CDI	Measurement of the quality of life in cities	11	5	Environmental, social, economic
WI	Quality of life measurement	87/10	2	Environmental, social
DJSI	Enterprise sustainability measurement	Depending on the sector (60 sectors)	3	Environmental, social, economic

Table 3. Comparison of selected sustainability indices (part 2).

Index	Data Sources	Normalization	Weights	Aggregation
EDP	Secondary, e.g., statistical offices	None (capitals as monetary values)	None	Arithmetic
GS	Secondary, e.g., statistical offices	None (capitals as monetary values)	None	Arithmetic
GPI (2.0)	Primary, secondary, expert, among others: ESRI, EPA	None (capitals as monetary values)	None	Arithmetic
HDI	Secondary: UNDESA, UNESCO, UNICEF, OECD, WB, IMF, UNSD	Linear transformation	Equal at the level of indicators and components	Arithmetic (indicators within the component), geometric (components)
ESI	Primary, secondary, among others: OECD, UNHABITAT, WHO, EEA, WRI, WWF, UNEP, FAO, UNFCCC, UNSD, WB, WEF, WTO, UNICEF, UNDP, DJSG, ITU, UNESCO, UNCCD, UNCBD	Standard score	Equal at the level of sub-indicators and indicators (expert)	Arithmetic (excluding the level of components)
EPI	Primary, secondary, expert, forecasts, among others: WB, IEA, IMF, WRI, IHME, WWF, OECD, Eurostat, UNSD	Linear transformation	PCA/expert	Arithmetic
EVI	Secondary, among others: WRI, FAO, WB, UNEP, OECD, UNDP, EEA, EPA	None (point scale 1–7)	None	Arithmetic (in the absence of data, the indicator is omitted)
EF	Secondary, among others: FAO, IEA, UNSD, UNDP	None (environmental capital in hectares)	Expert (conversion parameter)	Arithmetic
LPI	Secondary (over 3000 different data sources)	None (indicators as changes in the number of species)	None/percentage of species in a given group	Geometric
CDI	Secondary, among others: UNSD, UNDP, UNESCO, WHO, IEA, WB, OECD	Linear transformation	PCA	Arithmetic
WI	Secondary, among others: EEA, GADM	Distance to target	Equal at the level of sub-indicators and components	Arithmetic (excluding the level of indicators)
DJSI	Primary	None (point scale 0–100)	Expert	Arithmetic

Table 4. Comparison of selected sustainability indices (part 3).

Index	Sensitivity Analysis	Interpretation of Results	Source
EDP	None	Monetary value	[47,58]
GS	None	Monetary value; A negative value indicates no sustainability	[57,79,80]
GPI (2.0)	None	Monetary value (GPI per person)	[60]
HDI	None	Ranking of countries; 0–1 scale is projected on a 4-point qualitative scale of development level	[61,62]
ESI	Yes	Ranking of countries; 0–100 scale; Probability that the country will be able to protect the environment effectively in the coming decades	[63]
EPI	None	Ranking of countries; 0–100 scale	[46,47,64,65]
EVI	None	Ranking of countries; 0–700 scale is projected on the 5-point qualitative scale of susceptibility to environmental problems; The result and data availability for indicators are reported; The results for the components are also provided	[66–68]
EF	None	Standardized global hectares (corresponding to average biological productivity); Value > 1 indicates the unsustainability	[47,69,70]
LPI	None	Value < 1 indicates a downward trend, and >1—increasing species diversity; Confidence intervals are determined for the index	[47,71,72]
CDI	None	0–100 scale for the index and each of the give components	[47,73]
WI	None	0–100 scale is projected onto a 5-point qualitative scale describing the quality of life	[47,74]
DJSI	None	0–100 scale for the index and each of the components and indicators; Comparison with the median and the best score	[76–78,81]

Abbreviations: ***DJSG***—Dow Jones and SAM Sustainability Group companies (now: Standard & Poor's Dow Jones Indices and RobecoSAM); ***EEA***—European Environment Agency; ***EPA***—Environmental Protection Agency; ***Esri***—software manufacturer (e.g., ArcGIS); ***Eurostat***—European Statistical Office; ***FAO***—United Nations Food and Agricultural Organization; ***GADM***—Database of Global Administrative Areas; ***IEA***—International Energy Agency; ***IHME***—Institute for Health Metrics and Evaluation; ***IMF***—International Monetary Fund; ***ITU***—International Telecommunication Union; ***OECD***–Organisation for Economic Co-operation and Development; ***UNCBD***—United Nations Convention on Biological Diversity; ***UNCCD***—United Nations Convention to Combat Desertification; ***UNDESA***—United Nations Department of Economic and Social Affairs; ***UNDP***—United Nations Development Programme; ***UNEP***—United Nations Environment Programme; ***UNESCO***—United Nations Educational Scientific and Cultural Organization; ***UNFCCC***—United Nations Framework Convention on Climate Change; ***UNHABITAT***—United Nations Human Settlements Programme; ***UNICEF***—United Nations Children's Fund; ***UNSD***—United Nations Statistics Division; ***WB***—World Bank; ***WEF***—World Economic Forum; ***WHO***—World Health Organization; ***WRI***—World Resources Institute; ***WTO***—World Trade Organization; ***WWF***—World Wildlife Fund.

The analysis of Table 2 shows that the scope of the purpose of individual indices is very narrow. They are not universal, but the area of application of each index is strictly defined. Indices, such as ESI, EPI, EVI, EF, and LPI, are aimed at the environment and ecology. EDP, GS, GPI, and DJSI are economic indices, while HDI, CDI, and WI are socially oriented. Most indices cover only selected dimensions of sustainability. All basic dimensions of sustainability, i.e., the environmental, social, and economic dimensions, are included only in the following indices: GS, GPI 2.0, CDI, and DJSI.

When analyzing Table 3, it should be noted that different indices share many of the same secondary data sources due to the small number of global datasets available with sustainability-related elements [53]. Such a similarity is visible, for example, in the case of ESI and EPI, HDI, EVI, EF, and CDI indices. Moreover, some of the indices discussed do not use any method of normalization, which means that it is the responsibility of the evaluator to correctly transform the various data to a common scale. This problem applies to a lesser extent to the EF and LPI indices, where the data transformation method is precisely defined, but in the case of the EDP, GS, and GPI indices, estimating the financial value of environmental or social capital may be problematic. Similarly, in the case of the EVI and DJSI indices, the expression of the values of the indicators on a point scale may be subject to relatively high uncertainty. For all of these indices, the subjective judgment of the index user can have a large impact on the results of converting the index values to a common scale. Many indices do not use weights, which means that the decision-maker has no influence on determining the significance of individual components and indicators.

This remark applies in particular to the following indices: EDP, GS, GPI, EVI, HDI, WI, and, to a lesser extent, ESI and LPI. The dominant aggregation method used in indices is the arithmetic model, which makes them consistent with the concept of weak sustainability. This can be viewed as a disadvantage, given that strong sustainability is more scientifically preferred [82–84]. Meanwhile, the concept of strong sustainability is taken into account only in the HDI and LPI indices, which use geometric aggregation. Moreover, no index gives the possibility to regulate the strength of sustainability expected by the decision-maker.

The analysis of Table 4 shows that the only index that clearly indicates the need for a sensitivity analysis is ESI. In the remaining indices, the sensitivity or robustness of the solution to changes in evaluation parameters is not tested. When it comes to interpreting the results of individual indices, many indices use a quantitative scale describing the final assessment of the examined objects (countries, cities, areas, enterprises, populations, or ecosystems). In particular, in the EDP, GS, and GPI indices, final assessments are expressed in terms of monetary values, and in the EF index, final values are expressed in hectares. The point scale is used in the HDI, ESI, EPI, EVI, CDI, WI, and DJSI indices, but in the HDI, EVI, and WI indices, quantitative scales are projected as qualitative scales. A qualitative scale is also used in the LPI index.

It should be noted that indices are adapted to the implementation of specific goals, and therefore they are characterized by very little flexibility, not allowing the choice of the applied sustainability indicators. Meanwhile, sustainability requirements may be perceived differently in different countries or areas. Therefore, the selection of the indicators used may depend on the specificity of a particular country or the problem studied [47]. Additionally, note that none of the indices takes into account the interactions between the indices. This is a significant disadvantage because, without a clear understanding of how indicators interact with each other and influence the performance of an index, decisions based on the index could increase economic disparities and environmental damage, reducing the possibility of achieving sustainability [53].

5. Conclusions

The article reviews various models of the sustainability assessment process and summarizes their generalized, comprehensive form. This form was the basis for the comparative analysis of sustainability indices for different purposes. Based on the generalized model of the sustainability assessment process, the characteristics describing the sustainability indices were indicated, and the indices used in the literature were described using these characteristics. The characteristics used make it possible to define the needs of a specific sustainability measurement and select the index most suited to the needs of this particular measurement. Such a choice can be made on the basis of the description of the indices presented in Tables 2–4. For example, if an expert needs an index to measure human development based on a poorly sustainable paradigm, then he or she may choose the WI index, but if he or she wishes to use strong sustainability for such a measurement, the HDI index would be more appropriate. Similarly, if an expert would like to measure economic aspects by expressing the results as monetary values, then he has the choice of EDP, GS, and GPI indices. However, if he would like to include all dimensions of sustainability in the measurement, then only the GS and GPI indices remain to choose from.

Based on the results of the analysis of sustainability indices, several important conclusions were drawn:

- the indices are quite varied in terms of the degree of complexity of the assessment (only some indices took into account the: environmental, social, and economic dimensions at the same time),
- indices are limited from the point of view of applying a systemic approach to the analysis of the analyzed problem (no interactions between the indicators were taken into account),

- the secondary nature of the indicators used to build various indices is visible—the goal is not always to build new solutions from scratch but to skillfully use the existing ones,
- the methodology of some indices does not take into account the stage of normalization of indicators, assigning to the assessor the responsibility for correct adjustment of various data to a common scale and determination of the significance (ranks) of individual components and indicators,
- the dominant aggregation method used in indices is the arithmetic model, consistent with the concept of weak sustainability,
- almost all analyzed indices (except ESI) do not take into account the sensitivity analysis of the solution and do not provide the possibility of regulation and simulation of the sustainability strength expected by the decision-maker.

Bearing in mind the presented conclusions and other related aspects included in the analysis, it should be stated that the construction of any of the 14 analyzed sustainability indices is not fully compliant with the generalized, comprehensive model of the sustainability assessment process (proposed in Section 3) and at the same time meeting the postulate of strong sustainability. Summing up the considerations, it should be stated that the research area undertaken in the article is developmental. An extensive literature analysis of energy sustainability assessment confirms that researchers are still testing indicators, redefining them, refining them, and creating dedicated assessment aggregates. In this context, the presented results of the analysis of sustainability indices may be a stimulus for further research. An interesting possibility is the use of multi-criteria decision analysis methods in the sustainability assessment [85,86]. These methods offer much more flexibility and functionality than the classical sustainability indices in terms of almost all stages of the sustainability assessment process [87]. Another interesting research direction, in line with the concept of strong sustainability, may be the use of a systemic approach in the evaluation process, which, in addition to hierarchical (vertical) connections, requires taking into account relations and interactions (horizontal) between various, often interdisciplinary, indicators. A system approach will make the construction of models for the sustainability assessment process more complex, and the models will more fully reflect reality.

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Abbreviations

Abbreviation	**Expansion of the abbreviation**
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
ASEAN	Association of South-East Asian Nations
BAL	Budget Allocation
BRICS	Brazil, Russia, India and China
CBA	Cost–Benefit Analysis
CDI	City Development Index
DJSG	Dow Jones and SAM Sustainability Group companies (now: Standard & Poor's Dow Jones Indices and RobecoSAM)

DJSI	Dow Jones Sustainability Index
EDP	Environmentally Adjusted Net Domestic Product
EEA	European Environment Agency
EF	Ecological Footprint
EnSI	Energy Security Index
EPA	Environmental Protection Agency
EPI	Environmental Performance Index
ESI	Environmental Sustainability Index
Esri	Software manufacturer (e.g., ArcGIS)
Eurostat	European Statistical Office
EVI	Environmental Vulnerability Index
EWI	Ecosystem Well-Being Index
FAO	United Nations Food and Agricultural Organization
GADM	Database of Global Administrative Areas
GGDP	Green Gross Domestic Product
GGDP	Green Gross Domestic Product
GNI	Gross National Income
GPI	Genuine Progress Indicator
GS	Genuine Savings
HDI	Human Development Index
HWI	Human Well-Being Index
IEA	International Energy Agency
IHME	Institute for Health Metrics and Evaluation
IMF	International Monetary Fund
ITU	International Telecommunication Union
LPI	Living Planet Index
LPI-D	Diversity-Weighted LPI
MCA	Multiple Criteria Analysis
MEW	Measure of Economic Welfare
NDP	Net Domestic Product
NNI	Net National Income
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
PCA	Principal Component Analysis
SAM	sustainable Asset Management
SEDI	Sustainable Energy Development Index
SEWI	Sustainable Economic Welfare Index
SOPAC	South Pacific Commission on Applied Geosciences
UCM	Unobserved Component Model
UNCBD	United Nations Convention on Biological Diversity
UNCCD	United Nations Convention to Combat Desertification
UNDESA	United Nations Department of Economic and Social Affairs
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
UNHABITAT	United Nations Human Settlements Programme
UNICEF	United Nations Children's Fund
UNSD	United Nations Statistics Division
WB	World Bank
WEF	World Economic Forum
WHO	World Health Organization
WI	Well-Being Index
WRI	World Resources Institute
WTO	World Trade Organization
WWF	World Wildlife Fund

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