# REVIEW OF INDICATORS FOR SUSTAINABLE ENERGY DEVELOPMENT

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## Abstract
Sustainable energy development has become an international policy objective and an integral part of sustainable development. It is necessary to develop a robust and comprehensive set of indicators to monitor progress towards sustainable energy development. This analysis aimed to assess established indicator sets for sustainable energy development. The characteristics of a comprehensive and robust indicator set were identified to enable such an assessment and used as a basis for six assessment criteria; transparency of indicator selection and indicator application, conceptual framework, representative, linkages, and stakeholder engagement. A total of 57 indicator sets were found that monitor progress towards sustainable energy development or some aspects of it. All but one of these indicator sets were found to be lacking in some aspect, especially regarding a lack of transparency and consideration of linkages between indicators, presentation of an imbalanced picture, and no involvement of stakeholders during indicator development. The only indicator set that met all criteria were *Energy Indicators for Sustainable Development* developed jointly by multiple international agencies. Nonetheless, several flaws in this set were identified. The *Energy Indicators for Sustainable Development* could be considered as an initial basket of indicators for further refinement in the context where they will be applied to ensure their policy relevance and usefulness. The refinement process would benefit from more stakeholder input to take into account the specific context and make sure that there is a balance in the representation of the three dimensions of sustainable development.

## Highlights
- Sustainable energy development is a policy objective that needs robust indicators
- The characteristics of robust and comprehensive indicator sets were identified
- Most current indicators for sustainable energy development are found lacking
- Energy Indicators for Sustainable Development are a good first building block

## Keywords
Sustainable energy development; Sustainability indicators; Energy indicators; Indicator development; Literature review; Energy policy

# 1. Introduction

The importance of energy in achieving sustainable development was recognized when the concept was first introduced in the UN's *Our common future* report [1]. In 2000, the concept of sustainable energy development (SED) was put forward in the UN's *World Energy Assessment* (WEA) report with the introduction of a development paradigm where the economic, social, and environmental impacts of energy development were considered [2]. Since then, SED has become an international policy objective reflecting the various challenges facing modern energy systems, such as depleting fossil fuel sources, increasing energy consumption, and climate change. SED was solidified as an integral part of sustainable development with the introduction of goal seven of the UN's Sustainable Development Goals (SDG), "*Ensure access to affordable, reliable, sustainable and modern energy for all"* [3].

The challenges and actions towards SED can differ significantly from one country or energy system to the next. Generally, SED promotes social and economic well-being while ensuring sustainable utilization of resources and a clean environment [4]. In the UN's WEA report, an emphasis was placed on not "exceeding the carrying capacity of ecosystems" when producing and consuming energy to ensure the sustainability of energy development. Furthermore, the necessity of secure and reliable energy supply at an affordable price was highlighted [2].

Developing ways to track progress towards SED and assess whether policies are furthering desirable development is essential. The need for sustainability indicators was clearly defined in the UN's Agenda 21, which called on countries, as well as organizations, to develop indicators of sustainable development that can inform decision-making at all levels [5]. Carefully selected sustainability indicators can provide valuable information to monitor progress and inform policy. Multiple different indicators or indices have been developed in the context of SED. These vary greatly based on their purpose and what they are set out to measure [6]. Numerous challenges have hindered these efforts, such as uncertainties in what various terminology should entail, disagreement on methodological approaches, and whether stakeholders should be included in indicator development [7]. Research on established sustainability indicators for energy development has highlighted some of their limitations [6]. Current indicators have been criticized for their limited scope and perspective, lack of transparency, and not adequately capturing SED [8].

Several studies have evaluated the suitability and usefulness of one or more indicator sets for SED, e.g., Shortall and Davidsdottir's study of how to measure national energy sustainability performance [8], and Narula and Reddy's review of energy security and sustainability indices [6]. However, no one study has analyzed and compared all existing indicator sets for SED to the authors' knowledge. This study aims to assess the suitability of current indicator sets to measure progress towards sustainable energy development. For this purpose, the following objectives are laid out:

- identify what makes an indicator set comprehensive and robust

- provide a comprehensive overview and comparative analysis of existing indicator sets for SED

Indicator set assessment criteria are created based on existing guidelines for sustainability indicators. These criteria reflect characteristics or actions thought to make indicator sets comprehensive and robust. Different from prior studies of SED indicators, these criteria enable the assessment of a large number of indicator sets. A rating of current indicator sets for SED, and identification of sets that could be considered suitable is valuable. Progress is made by building on existing knowledge; in this case, insights on how indicator sets for SED could be improved. Therefore, this study is of value to decision-makers and stakeholders of energy systems as well as researchers in the field.

The paper is structured as follows: Section 2 briefly reviews the concept of SED, problems of existing indicator sets, and frameworks for indicator selection. Section 3 presents the methodology used to find and, subsequently, assess established indicator sets for SED. Section 4 lays out the results of the assessment of indicator sets. A discussion on the suitability and flaws of current indicator sets is provided in Section 5. Furthermore, the potential limitations of this study and future research guidelines are considered in the section. The paper is concluded in section 6, where the next steps are proposed.

# 2. Background

## *2.1. Sustainable energy development*

Ever since the introduction of sustainable development on the international policy agenda, the role of energy in promoting sustainable development has been increasingly more recognized [1]. Initially, energy development often was put in context with climate change and reducing greenhouse gas emissions, for instance, in the international treaties: Framework Convention on Climate Change and Kyoto Protocol [9–11]. Energy issues were viewed in isolation and not robustly connected to other development issues [11]. In 2000, the United Nations Development Programme (UNDP), in its World Energy Assessment (WEA) report, put forward a new development paradigm where the economic, environmental, and social impacts of energy development were considered, which forms the basis of SED [2]. In the WEA report, the importance of access to energy to promote economic growth and social equity were highlighted as well as the necessity of staying within the "carrying capacity of ecosystems" to ensure the sustainability of energy systems [2]. The need for energy to promote sustainable development was acknowledged with the introduction of the UN's SDG 7 on affordable and clean energy [3]. Over the past three decades, SED has evolved to become a comprehensive and essential policy objective worldwide [9].

The underlying challenges and actions towards SED can differ significantly between countries and energy systems [11,12]. Nonetheless, it is possible to identify common themes and goals of SED. The history and emerging themes of SED were analyzed by Gunnarsdóttir et al. in 2020 [11]. According to their study, the overarching goal of SED is to advance sustainability [11].

Furthermore, four inter-related themes of SED were presented: sustainable energy supply, access to affordable modern energy services, energy security, and sustainable energy consumption [11]. These inter-related themes broadly show what needs to be addressed and accomplished with SED. A diagram of SED can be seen in Figure 1.

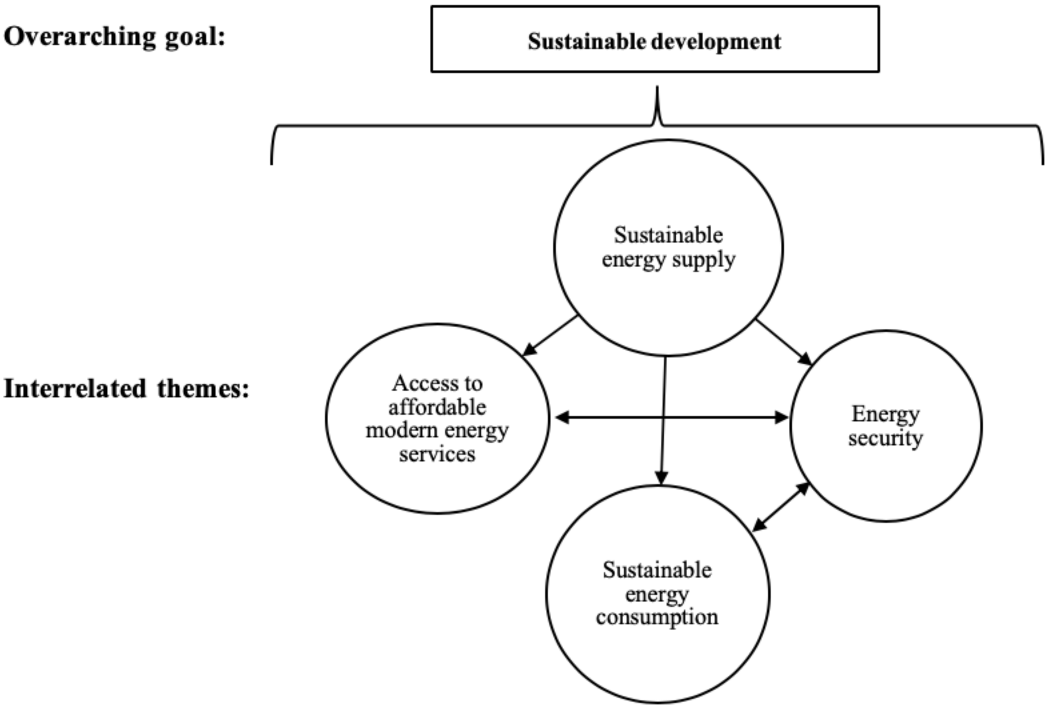


*Figure 1: **Themes of sustainable energy development.** Thematic map showing the overarching goal and interrelated themes of sustainable energy development. The arrows illustrate connections between the different themes. The direction of the arrows indicates whether a theme enables another theme. Diagram originally presented by Gunnarsdóttir et al. [11].*

These four themes touch on the environmental, social, and economic aspects of energy development [11]. SED cannot be achieved without equitable access to affordable modern energy services, which is vital to promote economic and social growth [2–4,11,13]. Without a secure supply of energy, sustainable development is not possible [2,11,13,14]. A transformation of the current energy system towards a sustainable energy supply is necessary to reduce its harmful environmental and health impacts [2,5,11,13,14]. This transformation will include a transition in energy generation towards environmentally sound technologies and modern renewables that are managed sustainably [2,10,11,15–17]. These technologies will have to become cost-competitive, and energy pricing needs to reflect the external costs of energy for this transformation to be realized [1,2,5,13,14]. A change in consumption patterns towards sustainable energy consumption will also be necessary, which will involve efforts to increase awareness of the potentially harmful impacts of current energy systems and to promote energy efficiency [1,2,5,11,13,14,16,18]. Actions towards SED need to be taken now by everyone at all levels [11].

### *2.2. Limitations of sustainability indicators*

Ever since the UN's Agenda 21, where the need for indicators was laid out, it has become increasingly more common to use indicators to track and inform actions [5]. Yet, there is no standardized way of selecting indicators. Many attempts have been made to develop indicators to track progress towards SED, as this study highlights. These vary from a single indicator to a long list of indicators that give a detailed picture of the energy system in question [6]. These efforts have made a case for the usefulness and necessity of indicators. However, they have also highlighted some of the challenges associated with creating sustainability indicators and the limitations of existing indicators. These limitations include ambiguities in the definition of SED, failure to capture unique national circumstances, an imbalanced representation of the dimensions of SD, inconsistent results, obscure methodology, and lack of stakeholder engagement. An identification of the potential downsides of current indicators and their methods can aid with the design of more effective sustainability indicators, which is one of the motivations behind this study [8].

Ambiguities, in the definition of SED and, similarly, sustainable development (SD), especially in the local context, have hindered efforts towards creating suitable sustainability indicators [6,8]. While the ultimate goal of SED remains the same, the path towards it and challenges on that path can vary, which highlights the necessity of context-specific indicators [19]. The premise of indicators is that they should be relevant to policy and inform better decision-making [20]. As policies are usually implemented at the national or regional level, indicators should ideally reflect issues within that context [8,21]. Nevertheless, some of the most prominent indicator sets for SED, e.g., the *Energy Trilemma Index (ETI)* and *Energy Architecture Performance Index*, are designed as national indicators for country comparisons without accounting for national conditions [8,19]. Narula and Reddy argue that with country comparisons, "homogeneity between the characteristics of the energy system of all countries" is assumed [6]. However, it is well known that energy systems can vary significantly, for instance, with regards to size, availability of natural resources, and level of industrialization [6]. A comparative assessment carried out by Narula and Reddy showed that the scores of three different energy indices are inconsistent and incomparable [6]. According to their evaluation, this inconsistency can be credited to the fact that the indices emphasize various aspects of SED and might not give a complete picture of the system by themselves.

Some indicator sets have been criticized for oversimplifying SED or presenting an imbalanced picture of SED. These faults have been connected with the aggregation of indicators into a single score, the number of indicators, and the omission of qualitative issues [7,21]. Even though the measurability of qualitative topics can often be challenging, it does not justify their exclusion from an indicator set. Shortall et al. evaluated three established indicator sets for SED, namely, *Energy Trilemma Index, Energy Architecture Performance Index, and Energy Indicators for Sustainable Development (EISD)* [8]. According to their analysis, the qualitative issue of wellbeing, arguably the ultimate goal of sustainable development, was neglected by the three indicator sets [8]. Connected to this, Narula and Reddy [6] discussed how most indices overly emphasize economic aspects of SED while overlooking social and environmental ones, thus presenting an imbalanced presentation of SED.

The engagement of stakeholders has been suggested to aid with the development of context-specific indicators that are relevant to policy and acceptable to stakeholders [7,8]. Thereby, a broad range of perspectives can be considered, ideally resulting in a more balanced and representative set of indicators. Sovacool argued that semi-structured interviews lend themselves well to a discussion on complex concepts, such as energy security and SED [7]. Additionally, he explained that through targeted discussions, it is possible to determine what a concept means in the context, including its qualitative issues [7]. Shortall et al. [8] stated that “the design of indicators requires the input of multiple actors, and should include local and lay knowledge. Such indicators need not be identical between each locality but should cover essential themes of sustainable energy development and should lend themselves to being used in models and multicriteria evaluations. Hence both qualitative and quantitative indicators are possible.”

A lack of methodological transparency, both regarding indicator selection and their application, is a common criticism of current indicators [8]. The legitimacy and credibility of indicators are heavily dependent on the transparency of their methods [8]. The developers of the *EISD* emphasized the transparency of methods to ensure the usefulness of indicators and, for instance, consistent data collection [4]. Shortall et al. argued that a lack of methodological transparency could hinder the connection of indicators with dynamic models and thereby the ability to look at the sustainability implications of alternative futures [8]. Thus, indicators are limited to being backward-looking.

### 2.3. Frameworks for indicator selection

Conceptual frameworks are often used to structure and understand complex problems and are considered the theoretical underpinnings of indicator sets [22]. At the most basic level, a framework provides a checklist for what issues should be considered and how they should be organized [23]. The benefits of frameworks are multiple, such as increased comparability, transparency of indicator selection, and minimized bias [24]. Numerous frameworks have been developed that vary on diverse elements, such as interpretation of sustainable development, the structure of the economy or society, and indicator selection and aggregation [25].

Three main types of frameworks have been utilized for the development of indicator sets for SED: causal chain, thematic, and system dynamics ones. In the early 2000s, causal chain frameworks were commonly used when developing sustainability indicators [25]. However, due to complexities and ambiguities in their application, they were abandoned for thematic frameworks [26]. Currently, most indicator sets are developed within thematic frameworks as it provides more flexibility than many prior frameworks and can be applied within different contexts. The main criticism of thematic frameworks is that inter-linkages or dynamic interactions of themes can be undervalued [27]. A system dynamics approach to indicator development has gained popularity where an entire energy system and dynamics within it are analyzed. A further description of the different types of frameworks is presented below in chronological order:

- Causal chain frameworks are all organized similarly, as cause and effect relationships (i.e., causal chains). Numerous causal chain frameworks exist which differ in the number of steps recognized in the chain, e.g., pressure-state-response, driving force-state-response, and driving force-pressure-state-impact-response [26]. By using a causal chain framework, it is possible to structure a problem into causality relationships and, thus, identify drivers and outcomes. The main criticism of them is difficulty in their application as they lack flexibility, and issues need to be relatively simple to be captured through a linear causal chain [4]. Furthermore, the interlinkages of problems were not adequately captured through causal chain frameworks [25]. These weaknesses resulted in the oversimplification of issues and unclear indicator selection [26]. In 2002, the IAEA presented its *Indicators for Sustainable Energy Development (ISED)* that were based within a causal chain framework [28].
- Thematic frameworks are those that group indicators into different issues or themes of sustainability. These types of frameworks are commonly used and often linked with policy targets, such as in the development of national indicator sets [25]. Following national testing, the *Expert Group on Indicators of Sustainable Development* decided to move away from causal chain frameworks to thematic ones to represent policy issues better and make the indicator selection process clearer at the national level [25]. A thematic framework was thought to "better assist national policy decision-making and performance measurement" [29]. Therefore, three years after the *ISED* indicators were put out, the *Energy Indicators for Sustainable Development (EISD)* were presented, which contained the same core set of indicators organized within different themes of SED [4].
- System dynamics frameworks consider the entire energy system and dynamics within it, which are often presented as stocks, flows, and feedback loops. Through systems thinking, it is possible to break down and understand complex problems, which has made it popular across different fields of study [30]. Nerini et al. argued that "a systems perspective is crucial to understanding the practical complexity of energy provision and use, and facilitates effective intervention strategies" [31]. Through a systems approach, it was possible to investigate the complex dynamics of SED and highlight that "energy systems… affect delivery of outcomes across all SDGs" [31]. Kettner et al. used a systems approach to develop indicators for SED for Austria (ISED-AT) [32]. Thus, they were able to illustrate the Austrian energy system through the energy services the system provides, which served as a basis for indicator selection [32].
- A mixed approach is the combination of different frameworks, usually a thematic framework mixed with some other method. By combining two different frameworks, it is possible to address

the weaknesses of individual frameworks and enhance the approach to conceptualizing the problem. Keirstead argued that a "combination framework should be developed to link key features" [33]. Therefore, Keirstead chose to combine systems dynamics and thematic framework when developing sustainability indicators for urban energy systems. Thus, the linkages between different indicators and issues were captured while the presentation of the framework was transparent through the various issues [33].

# 3. Methods

### *3.1. Literature search – SALSA framework*

A literature review was conducted to identify what indicators for SED exist. The main criterion for search results to be included was that indicator sets for SED were either presented in the publication or discussed in a literature review that could be used as a basis for the snowballing method. Due to the multidimensionality of SED, the objectives of identified indicator sets ranged from measuring SED and energy policy to assessing energy poverty and energy security. Some of these indicator sets enabled an evaluation of progress towards SED while others allowed for the assessment of the sustainability of the energy sector or its sub-sectors. While the emphasis was placed on finding indicator sets for SED, indicator sets measuring other aspects of SED; e.g., energy security, were included when found. Therefore, the list of indicator sets for the different underlying issues of SED is, most likely, not exhaustive. Furthermore, time and geographical scope did not limit this search. Nonetheless, it is important to note the difference between sustainability assessments of the energy sector and an assessment of the SED of a country, where the latter is much broader. The level of sustainability assessment is also critical, which can range from national to industry-specific or sub-sectors of the energy system.

Publications that only presented a single indicator for energy or SED or no indicators at all were not considered further. To limit the number of search results further, indicator sets that exclusively focused on energy sources were excluded, i.e., to select between different energy sources or assess the sustainability of a particular energy source. These indicator sets were often mainly focused on measuring the efficiency of an energy source, which is not the focus of this study.

A systematic search and review of the literature were carried out through the application of the **Search, Appraisal, Synthesis, and Analysis** (SALSA) framework [34,35]. According to Grant et al., a systematic search and review consist of a comprehensive search process and a critical review that results in a 'best evidence synthesis' [34]. The steps of the SALSA framework enable a robust analysis of the existing literature while minimizing the potential for bias [35]. A 'snowballing' method was applied between the Appraisal and Synthesis steps to ensure an exhaustive search, similar to Malinauskaite et al.'s review of *Ecosystem services in the Arctic* [36], as seen in Figure 2.

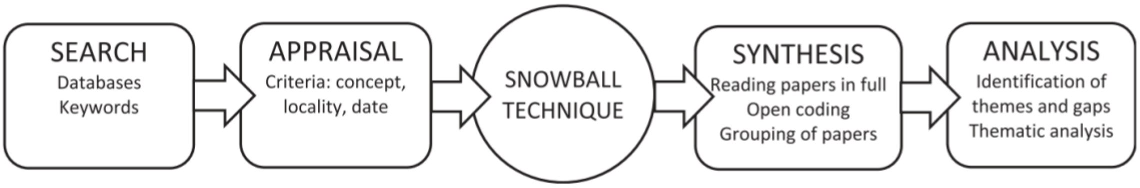


*Figure 2: **Modified SALSA framework.** The framework used for a systematic literature search and review; a modified SALSA framework with an additional step for snowballing. Diagram originally presented in Malinauskaite et al.'s study [36].*

The first step of the SALSA framework is a **search** for the relevant literature. Three different academic databases were searched: Science Direct, Web of Science, and Google Scholar, along with a general Google search as some indicator sets might not be found within the scientific literature. Three search keywords were defined: "indicators," "index," and "sustainable energy development," which resulted in the Boolean search string (("Indicators" OR "index") AND ("sustainable energy development")). Initially, a large amount of results was found: Science Direct (n = 698), Web of Science (n = 54), Google scholar (n = 7050) and Google (n = 264.000). Results were presented in order of relevance. All results found through the Web of Science and the first 100 search results of Science Direct, 60 of Google scholar, and 60 of Google were scoped to determine whether they should be analyzed further. The number of search results scoped was determined by whether search results were still found relevant past a certain number. The majority of initial search results were deemed not within the scope of this research as either no indicator set was presented, or SED was not the focus.

The second step of the SALSA framework, **appraisal**, involved further assessing whether search results fulfilled the above inclusion and exclusion criteria. For this purpose, the abstracts of identified papers and reports were read and, subsequently, the entire publication browsed. A total of 220 publications were scoped from the databases. Many results appeared in more than one search engine but were only counted where they first appeared. The resulting publications found appropriate for further analysis were 19 from Science Direct, 19 from Web of Science, six from Google Scholar, and nine from Google.

As mentioned above, to identify more relevant indicator sets, a step of '**snowballing'** was added to the SALSA framework [36]. The 'snowballing' approach involves using the references and citations of papers to identify more relevant literature. Review papers and background sections of publications found through the initial search served as a basis for snowballing to find more indicator sets. Through this method, 39 additional papers or reports were identified that were snowballed from nine different publications.

The results of the first three steps of the modified SALSA framework were indicators sets for SED presented in papers published in peer-reviewed journals and reports from international or national agencies and research institutes. A total of 82 relevant publications were found, where 57 different indicator sets were presented or applied. Out of the 82 publications, 54 were journal articles, and 28 were reports, as seen in Figure 3.

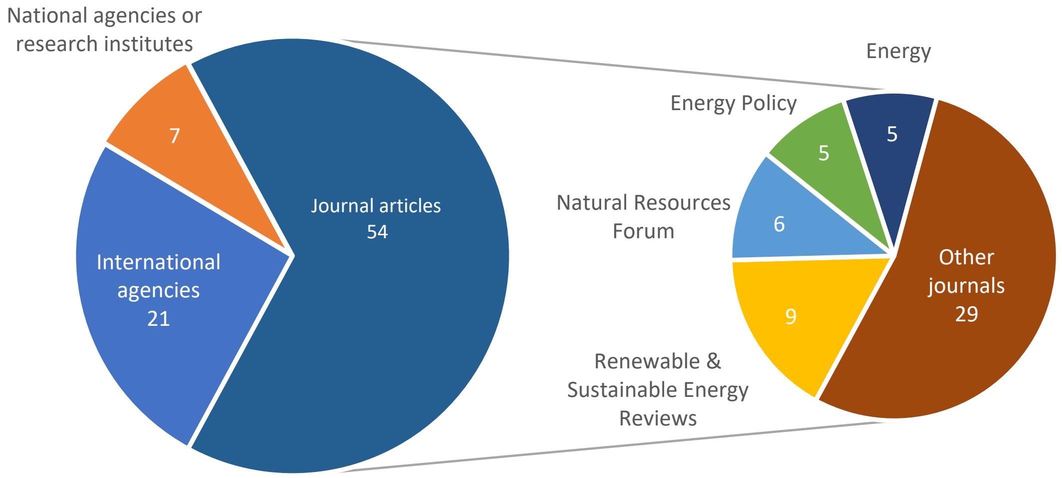


*Figure 3: **Sources of indicator sets**. Pie of pie showing where the 82 publications analyzed were published or by whom.*

Following the identification of relevant papers and reports, a step of **synthesis** was done. The identified publications were read and analyzed with an emphasis on the indicator sets and their methodology. Indicator sets presented in the different journal articles and reports were categorized based on their stated purpose or what they were set out to measure. Furthermore, the indicator sets were grouped based on their geographical scope, see Appendix A.

### *3.2. Assessment of indicator sets*

For the final step of the SALSA framework, **analysis**, a methodology for the assessment of indicator sets was developed; indicator set assessment criteria. For this purpose, many different guidelines and checklists for indicators and their selection were reviewed [24,25,37–39]. These often include a list of characteristics desirable in an effective indicator to ensure that the indicator can serve its purpose, such as informing policy and showing trends [40]. This analysis entails assessing established indicator sets and their development, as opposed to an individual indicator, which involved identifying characteristics found to make a set of indicators comprehensive and robust.

Most current checklists for indicators are focused on assessing individual indicators, not indicator sets. The only guidelines found to fit our purposes well were the *Bellagio Sustainability Assessment and Measurement Principles (Bellagio STAMP principles)*, see Figure 4 [41,42]. These principles consist of eight good-practice guidelines for developing ways to measure progress towards sustainable development [41,42]. An emphasis is placed on selecting a robust and representative set of indicators as opposed to being focused on the characteristic of individual indicators [41]. Therefore, the Bellagio STAMP principles were used as a basis for the development of the indicator set assessment criteria applied here.

**<u>Bellagio STAMP principles</u>**

1. **Guiding vision**
   Measure progress towards sustainable development
2. **Essential considerations**
   Consider all three dimensions of SD and their interactions, the governance structure, current trends & drivers of change, risks & uncertainties, and potential impact for decision making
3. **Adequate scope**
   Both consider long- and short-term effects and range from local to global
4. **Framework and indicators**
   Based on a conceptual framework, recent and reliable data, standardized measurement methods, and compared to benchmarks and targets.
5. **Transparency**
   Data, data sources, indicators, methods, and results are accessible to all. Rationale is provided for assessments and funding and potential conflicts are disclosed.
6. **Effective communication**
   Use clear and plain language and present results objectively through innovative visual tools and graphics, if possible.
7. **Broad participation**
   Reflect the views of stakeholders and engage with potential users of the assessment.
8. **Continuity and capacity**
   Demand repeated measurements, show changes over time, investments to allow for regular revisions and improvements.

*Figure 4: **Bellagio STAMP principles**. Overview of the Bellagio STAMP principles based on publications by Bakkes [39] and Pintér et al. [38].*

A few of the Bellagio STAMP principles did not fit this analysis and, therefore, were not included in the indicator set assessment criteria. Firstly, two of the Bellagio STAMP principles were not found to be measurable in an unbiased manner and, thus, were excluded: Principle 6: Effective communication and Principle 8: Continuity and capacity [41]. Secondly, two of the principles, 1: Guiding vision, and 3: Adequate scope, were excluded from the start as the criteria for the literature search already addressed them [41]. Since the literature search aimed to find indicator sets for SED, then, arguably, they should all meet the first principle of having a "guiding vision" [41]. The third principle of "adequate scope" emphasizes having an appropriate time scale and geographical scope. An "appropriate time horizon" depends on the objective of the indicator set, which was not a limitation of the above literature search [41]. It is both difficult to define and measure an appropriate time horizon, which is why it was not included in this analysis. The literature search was limited to indicator sets that measured the SED of an energy system or country, which addresses the geographical scope to some extent. Based on the four remaining Bellagio STAMP principles, the indicator set assessment criteria were developed.

The indicator set assessment criteria consist of six elements considered essential when developing a robust and comprehensive indicator set, see Table 1. All six criteria are weighted equally with a total score of one for each. An indicator set that meets all the criteria would receive a perfect score of 6 and, thus, could be thought comprehensive and robust. The transparency of an indicator set was assessed first as a lack of transparency hinders a further evaluation. The following criteria are listed in the order that they are usually met during indicator development and are all considered essential to capture a comprehensive, balanced, and unbiased picture of SED.

**Table 1**
Indicator set assessment criteria. Compiled by authors.

| Criteria | Rationale | Bellagio STAMP principle | Measurability |
|---|---|---|---|
| **1. Transparency of indicator selection** | It is necessary to make the methodological choices for indicator selection and the underlying indicators of an indicator set available to ensure the credibility and legitimacy of an indicator set. | Principle 5: Transparency | 1/2 - Individual indicators<br>1/2 - Methodology for indicator selection<br>0 - Neither of the above and no further analysis |
| **2. Transparency of indicator application** | The usefulness of an indicator set relies on disclosing the necessary information for indicator application and data sources. | Principle 5: Transparency | 1/2 - Methodology for indicator application<br>1/2 - Data sources<br>0 - Indicator set not easily calculated again |
| **3. Conceptual framework** | The application of a theoretical framework helps structure the problem and can increase comprehensiveness. The transparency of indicator selection can be improved, and bias minimized. | Principle 4: Framework and indicators | 1 - Conceptual framework<br>0 - No apparent framework |
| **4. Representative** | The indicator set needs to be representative of sustainable energy development, which includes the consideration of economic, social, and environmental dimensions. | Principle 2: Essential considerations | 1/3 - Economic<br>1/3 - Social<br>1/3 - Environmental<br>0 - None of the above |
| **5. Linkages** | To further enhance an indicator set, the linkages of individual indicators should be considered to show a complete picture and eliminate correlated indicators. | Principle 2: Essential considerations | 1 - Regression analysis of indicators or causal chain or systems framework or presentation of connected indicators or stated that linkages were considered<br>0 - Not considered |
| **6. Stakeholder engagement** | Stakeholder engagement during indicator selection increases the robustness and representativeness of an indicator set. It increases stakeholder acceptance and reduces the potential for bias in selection. | Principle 7: Broad participation | 1 - Stakeholders or external experts engaged<br>0 - No, not clear if was done |

The first assessment criterion highlights the importance of transparency in indicator selection based on the fifth Bellagio STAMP principle. The credibility and legitimacy of an indicator set are increased through transparency in methodology [8]. If choices and assumptions made during indicator selection are not made clear, the indicator set can be misused or misinterpreted [41]. For this analysis, the transparency of indicator selection is assessed by whether the individual indicators of an indicator set, and the methodology for indicator selection were made available. Adequate transparency includes an explanation of the indicator selection process and the different steps involved. The two sub-criteria are considered equally important and given half a point each. If neither sub-criteria are met, it is difficult to assess the indicator set as the necessary information is not made available.

The second criterion is also rooted in the fifth Bellagio STAMP principle, where the value of transparency in indicator application is emphasized [41]. The usefulness of an indicator set depends on this criterion as it is not possible to apply the set or replicate results without the necessary information [23]. The majority of indicator criteria emphasize that indicators should be simple and easy to both interpret and apply to ensure the utility of the indicators to potential users, stakeholders, and decision-makers [24,25,40,41,43]. Multiple established indicator guidelines highlight the importance of using high-quality data that is readily available or collected [24,41,43]. Similar to the first assessment criterion, the transparency of indicator application is assessed by whether two different sub-criteria are met; inclusion of the methodology for indicator application and data sources. The methods for indicator application is considered transparent if, for instance, the mathematical formulas for the individual indicators are provided. Disclosing data sources entails naming where data were found or how data should be collected. The two criteria were given an equal weight of half a point each.

The third criterion is the application of a conceptual framework for indicator selection and organization, which is largely the fourth Bellagio STAMP principle of “Frameworks and indicators” [41,42]. The Bellagio STAMP principles highlight the importance of theoretical frameworks to determine and adequately capture the problem or system in question [41]. Transparency can be increased with the application of a conceptual framework as the methodology and selection of indicators is made more explicit. This criterion is simply measured by whether a conceptual framework is applied or not. The different theoretical frameworks are not evaluated directly in this analysis. However, as conceptual frameworks guide the selection of indicators and what aspects of the system are captured, these frameworks are indirectly assessed by the next two criteria described.

The fourth criterion underscores that indicator sets need to be representative of what they are set out to measure, which is similar to the second Bellagio STAMP principle. Multiple different indicator guidelines prescribe that indicators should provide an unbiased, representative picture of the system in question and its sustainable development [24,25,43]. For simplification, the three dimensions of sustainable development, economic, social, and environmental, are used as a basis for how this criterion is measured. This simplification corresponds to the overarching goal of SED, sustainable development, as presented in section 2.1. above. An incomplete picture of SED is captured if an indicator set does not include indicators representing all three dimensions, where each dimension is given a third of a point. Some interpretation is required in the assessment of this criterion. For example, an indicator set is thought to consider the social dimension if it includes indicators measuring the accessibility of energy, the economic dimension if the affordability of energy is measured, and the environmental dimension if the environmental impacts of energy are measured. If all three dimensions are considered, the indicator set is thought to be representative of SED and receives a score of 1.

The fifth criterion highlights the consideration of linkages within an indicator set. The second Bellagio STAMP principle, “essential considerations,” states that the “system as a whole and the interactions among its components” should be considered [41]. Indicators can be meaningful on their own as well as together with other indicators of the set [43]. A single indicator only shows a partial picture, and the interpretation of two or more indicators together can shed more light on a problem [40]. By considering the linkages of indicators, it is also possible to identify overly correlated indicators. The inclusion of correlated indicators can result in overvaluing one aspect of the problem. According to the OECD’s *Checklist for building a composite indicator*, the linkages of indicators should be identified through a regression analysis that works as an alarm bell to identify correlated indicators. However, this approach does not capture causal relations [23]. By using a causal chain or systems framework, the dynamics and interconnections within a problem are considered from the start. As with other criteria here, how to measure whether linkages within an indicator set were considered is challenging. To determine whether this criterion was met, the following actions were searched for: correlation or regression analysis during indicator development, the application of a causal chain or systems framework, or explicitly stated that linkages were considered. The criterion was deemed to be met if one of these actions was done.

The sixth criterion is the engagement of stakeholders during the development of an indicator set based on the seventh Bellagio STAMP principle. By involving stakeholders, it is possible to identify and take into account multiple viewpoints, which significantly increases the robustness and representativeness of an indicator set [23]. Furthermore, it reduces the potential for the researchers’ bias in the selection of indicators. The process of involving stakeholders provides valuable insight into the sustainability goals and objectives that the various stakeholders find essential for SED. These goals dictate what should be measured and, thereby, what indicators should be selected [44]. Indicator sets need to be acceptable and of interest to stakeholders and the public for them to be applied [40,43]. Two main approaches for stakeholder engagement were considered; a participatory approach where stakeholders are engaged and expert approach where the opinion of external experts is considered [33]. This criterion is simply measured by whether stakeholders or experts were engaged or not during indicator development. If the criterion is met, the indicator set receives a score of one, the same as other criteria.

## 4. Results

A total of 57 indicator sets for SED or some aspect of it were found from 82 different publications. Some indicator sets were applied more than once within different contexts and by various researchers or institutions. Therefore, the indicator set assessment criteria were used 69 different times. Sometimes several publications were searched to assess an indicator set, which explains why the number of publications included exceeds the number of indicator sets. Four main categories of indicator sets were created based on what they were set out to measure, see Figure 5. A sub-category within the general SED category was included, which encompassed 11 indicator sets and 25 studies based on the *Energy Indicators for Sustainable Development* (EISDs) or its precursor *Indicators for Sustainable Energy Development (ISED)*.

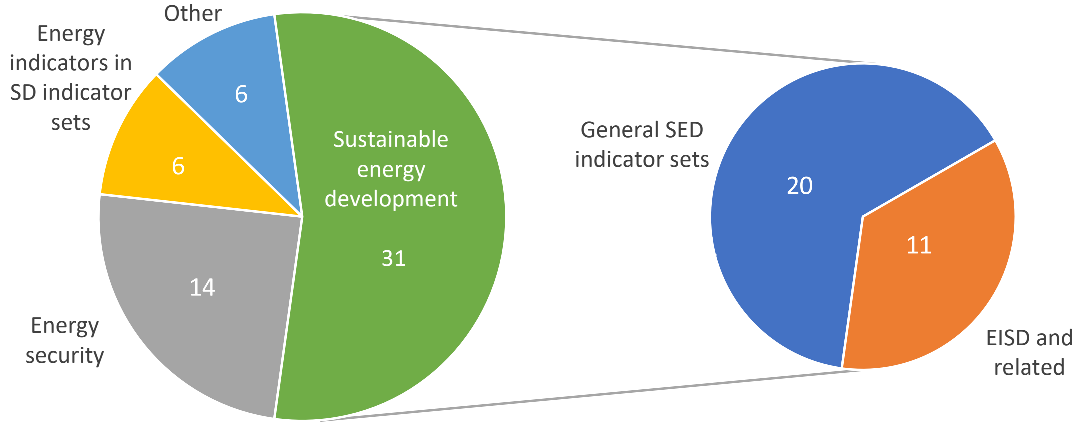


*Figure 5: **Categories of indicator sets**. The 57 identified indicators sets for SED were categorized into four groups based on their stated purpose or what they were set out to measure. A sub-group within indicator sets for SED was created for those connected to the Energy Indicators for Sustainable Development* [4]

The identified indicator sets were found in journal articles and reports published from 1997 to February 2019. Out of the 82 publications analyzed, 43 were published after 2010 and 19 after 2015. The average number of indicators was 25 and ranged from 2 to 372 indicators. Out of the 69 different assessments done, 47 contained fifteen or fewer indicators. The geographical scope was used to sort the indicator sets further within each category. The majority of indicators were developed at the national level, either for country comparison or specific to a country context. About a third of the indicator sets were designed for other scales or could be applied at various levels. Indicator sets that were developed to reflect a particular context or country did not allow for a comparison with other countries or systems. The different geographical scopes and their distribution can be seen in Table 2. Out of the 57 indicator sets identified, 27 of them were aggregated in some way to form an index or composite indicator. A complete list of the indicator sets for SED along with their source publication and other general information can be found in Appendix A.

**Table 2**
The various geographical scopes of SED indicator sets

| **Geographical scope** | **#** |
|---|---|
| *For comparison* | |
| National | 30 |
| National or regional | 2 |
| National, regional or local | 1 |
| Regional | 1 |
| Local | 1 |
| Rural | 2 |
| Cities | 3 |
| Urban areas | 1 |
| Households | 1 |
| Energy system | 3 |
| Variable | 1 |
| *Not for comparison* | |
| National | 17 |
| National and household level | 1 |
| Local | 1 |
| Residential sector | 2 |
| Energy system | 2 |

An analysis of these indicator sets was enabled through the application of the indicator set assessment criteria presented in Table 1. The following sections are organized in the order of assessment criteria applied. It is important to note that a lack of transparency could have led to an inaccurate assessment, as enough information was not made available.

### *4.1. Transparency of indicator selection*

The first criterion was focused on the transparency of indicator selection. A review of identified indicator sets showed that all of them made their underlying indicators available. The same transparency was not found regarding the methodology for indicator selection, where only 21 of the 69 assessments included a description of how indicators were developed. The results of this criterion can be seen in Figure 6.

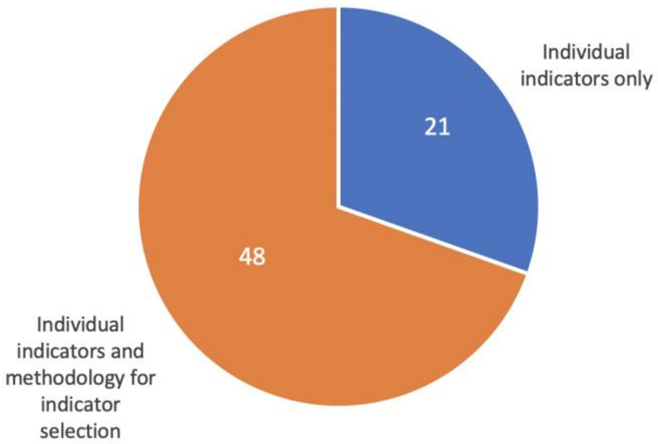


*Figure 6: **Transparency of indicator selection**. Either only the individual indicators were provided or both the indicators and methodology for indicator selection. No indicator set fulfilled neither sub-criteria.*

The indicator sets that were considered to have a transparent methodology for indicator selection often included an explanation and justification for the steps taken during indicator selection and sometimes even a diagram, e.g., *Sustainable Energy Development Index* by Iddrisu and Bhattacharyya, *Energy Sustainability Index (ESI)* by Mainali et al., *Aggregated Energy Security Performance Indicator (AESPI)* by Martchamadol and Kumar, and *Sustainability indicators for urban energy systems* by Keirstead [26,33,45,46]. Most of the studies that did not meet the sub-criterion lacked the necessary detail to be considered transparent, and some included no explanation at all of how indicators were selected. For instance, the original *ISED* did not meet the sub-criterion of a transparent methodology [28]. The only description of the indicator selection process included was that a causal chain framework was used to frame the problem, experts were brought together to review indicators, and indicator criteria developed by the UN were used [28]. There was no description of the different steps of the process, what decisions were made, or rationale for the selection of the final indicator set. A more detailed description of how the *ISED* were updated into the *Energy Indicators for Sustainable Development (EISD)* and what the indicator selection process entailed was provided in later publications, which is why the *EISD* were thought to meet this criterion fully [4,47].

### *4.2. Transparency of indicator application*

Two sub-criteria measured the transparency of indicator application: availability of a methodology for indicator application, and data sources used. The primary assessment of the prior sub-criterion was that enough information was provided so that indicator calculation could be replicated. Even if all of the identified indicator sets presented their underlying indicators, the clarity of the indicators varied significantly. The second sub-criterion was simply whether the necessary data sources were disclosed. The results of this criterion can be seen in Figure 7.

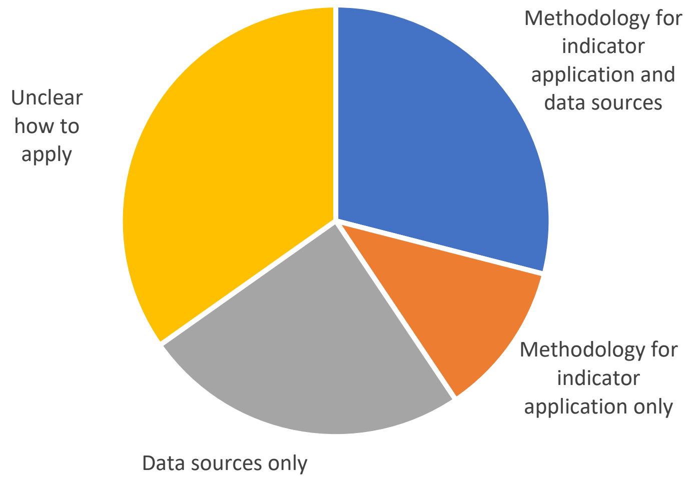


*Figure 7: **Transparency of indicator application.** Only 20 indicator sets included both the methodology for indicator application and data sources, and 25 sets included one of the two. The application of indicator sets that included neither was thought unclear.*

General descriptions of data sources such as the following: "Datasets are based on publicly available or purchased data, EY analysis or adjustments to third-party data" did not fulfill the criterion [48]. For some of the identified indicator sets, information on indicator application and data sources was included in methodological addendums or appendices of reports. A methodological addendum to the 2017 report for the *Energy Architecture Performance Index* included indicator metadata, which entailed detailed information on the indicators and their application, relevant data sources, and "technical notes" [49]. Another example is the *Energy Trilemma Index*, where only the names and categorization of indicators are included in their annual report. A reference was made to a "Methodology document" available on their website. However, this document was nowhere to be found and, thus, the indicator set was thought to lack transparency in indicator application [50]. In some cases, the data source sub-criterion was not met because the publication only presented an indicator set and not the use of said indicator set. Therefore, it might depend on the context that the indicator set is applied where the necessary data is found. For example, Keirstead presented an approach to measure the sustainability of urban energy systems that requires a wide range of data sources. These data sources were not listed in his study as the purpose of his paper was to present an approach to indicator selection rather than a finalized set of indicators [33].

### *4.3. Conceptual framework*

The third criterion was simply measured by whether a conceptual framework was used during indicator development or not. An assessment was made of whether a particular theoretical framework was mentioned in the publications, SED was structured, or indicators categorized per a framework. For instance, if indicators were categorized into the economic, social, and environmental dimensions or underlying issues of SED, it was assumed that a thematic framework was used. Out of the 69 indicator set assessments made, 60 were thought to have been developed through some conceptual framework.

The analysis of the indicator sets included identification of what conceptual frameworks were used, see Table 3. The thematic framework was by far the most popular choice as it was used for 55 different indicator sets, either by itself or mixed with another framework. The reason for this is perhaps because of the way the criterion was assessed. Indicators that were organized into the dimensions of sustainability or issues of SED were considered developed through a thematic framework. The few times some other conceptual approach was selected, it was clearly stated.

**Table 3**
Conceptual frameworks used

| **Conceptual framework** | **#** |
|---|---|
| *Thematic* | 43 |
| *Causal chain* | 3 |
| *Systems dynamics* | 1 |
| *Mixed approach* | 13 |
| *N/A* | 9 |
| ***Total that used a framework*** | **60** |

Variations of the causal chain approach were used eleven times by itself or mixed with another framework. The most recent application of the causal chain approach found was in the development of a *Sustainable Energy Development Index* (SEDI) in 2015 [26]. The results indicate that the causal chain approach has been abandoned for thematic frameworks or, more recently, systems dynamics ones. As mentioned earlier, the UN chose to move towards thematic frameworks due to complexities and ambiguities in the application of causal chain frameworks. In the development of *Indicators for Sustainable Energy Development for Austria (ISED-AT)*, Kettner et al. chose a combined thematic and systems approach [32]. The systems approach was used to structure the problem of SED in Austria based on energy services. The thematic framework was used to categorize indicators into the different dimensions of the problem, e.g., social, economic, and ecological dimensions of households. Through this combined approach, Kettner et al. were able to structure the issue in question clearly while capturing interactions between the different dimensions [32].

### *4.4. Representative*

The fourth criterion was an assessment of how representative the indicator set was, whether economic, social, and environmental indicators were included. In most cases, the evaluation of this criterion was reasonably straightforward, especially when indicators were categorized into the three dimensions already. Sometimes, an assessment had to be made of what dimensions indicators reflected. For instance, indicators measuring the affordability and accessibility of energy were thought to be social ones. Out of the 69 assessments made, 45 were found to consider all three dimensions of sustainable development. The rest of them only presented a partial picture where one or more dimension was not included, see Figure 8. Only two indicator sets did not include economic indicators, 19 did not consider the social dimension, and 10 excluded environmental indicators. These results confirm Narula and Reddy's criticism that many energy indices lean towards the economic aspects of sustainable development while undervaluing the environmental and social ones [6].

As is the case with most indicator sets for sustainable development, indicators representing the social dimension were fewer than the other two. An example of this is the application of the *EISD* indicators to analyze energy development in the Baltic States [51]. The indicators used in the analysis were only those that reflected priority areas of energy development in the area, which resulted in the elimination of all social indicators from the *EISD* set [51]. Surprisingly, two indicator sets only measured the social side of energy development. Nussbaymer et al. developed the *Multidimensional Energy Poverty Index (MEPI)* to measure energy poverty, which is a social issue within SED [52]. The *Occupational Entropy and Mind Indicators for Sustainable Energy Development* were developed to measure behavioral changes towards energy sustainability and thought of as an addition to the *ISED* [53].

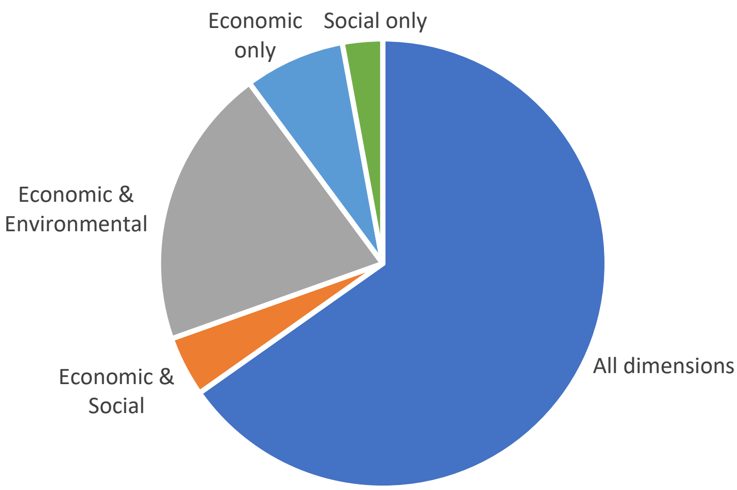


*Figure 8:* ***Representative.*** *Most indicator sets considered all three dimensions of sustainable development, although some only considered a partial picture and were not considered representative of SED.*

### *4.5. Linkages*

The fifth assessment criterion assesses the consideration of linkages within an indicator set. This criterion was met if the correlation of indicators was analyzed, a causal chain or systems frameworks were applied, or if it was stated that interconnections were examined. Despite the explicit assessment method, it was found quite challenging to assess this criterion. According to this approach, linkages were considered in 41 of the 69 studies, see Figure 9. To meet this criterion, Doukas et al. [54] emphasized the importance of uncorrelated indicators in the development of an *Energy*

*Sustainability Index,* and Neves et al. [55] made sure to eliminate repetitions of indicators when selecting *Local energy sustainability indicators*. HELIO International's *Sustainable Energy Watch* and the WEC's *ETI* were thought to consider linkages as the trade-offs between indicators were analyzed [50,56]. The original *ISEDs* were developed through a causal chain framework and, thus, were thought to consider linkages of indicators [28]. A thematic framework was used for the development of the subsequent *EISDs*. However, it was explicitly stated the interlinkages within the set were considered and, therefore, the criterion was met [4].

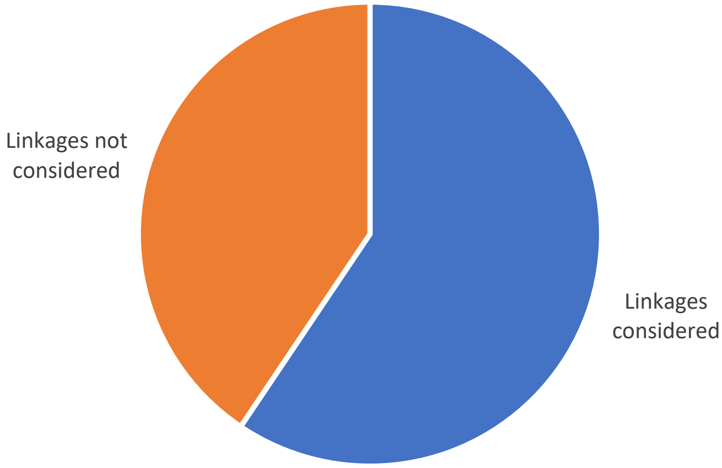


*Figure 9: **Linkages**. Just over half of the indicator sets considered linkages and interconnections between indicators within a set.*

### *4.6. Stakeholder engagement*

The final criterion was simply whether stakeholders or external experts were engaged during indicator development or not. This criterion was met the least often, where the inclusion of stakeholder or expert opinion to inform indicator development was only mentioned 20 times, see Figure 10. Sovacool met this criterion when developing an *Energy Security Index*, as energy security and its underlying dimensions were defined based on semi-structured interviews, a survey, a workshop, and a literature review [57]. Consultation with stakeholders and relevant agencies is encouraged in the development of *EISDs* to fit the national context, which is why the indicator set met the criterion. The process is believed to increase the relevancy of the indicator set for national policies and coordinate efforts in data collection [4]. In the development and review of the *Energy*

*Architecture Performance Index*, experts and stakeholders were interviewed to inform the selection of weights and identify areas for improvement, which was found sufficient to meet the criterion [49].

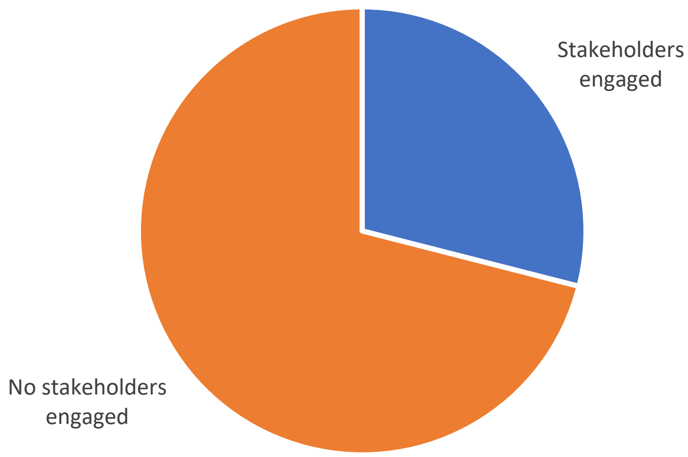


*Figure 10: **Stakeholder engagement.** No stakeholders were engaged during indicator selection for the majority of indicator sets. A lack of transparency for some indicator sets might affect these results.*

### *4.7. Comprehensive and robust indicator set for sustainable energy development*

The indicator set assessment criteria consist of six elements or characteristics considered essential in an indicator set for SED. Thus, a comprehensive and robust indicator set should receive a perfect score of six. The results of this analysis show that one indicator set for SED exists that meets all the criteria; the *Energy Indicators for Sustainable Development (EISD)* developed by the IAEA, UN DESA, IEA, Eurostat, and EEA [4]. The *Energy Architecture Performance Index* received a 5,5 as it only lacked transparency in indicator selection [49,58] Thirteen different indicator sets received a score of 5 with all but two in the sustainable energy development category. The average score was 3,69, with a minimum score of 1,66 and maximum, the previously mentioned, 6. The lowest score was given to four different indicator sets that all showed a partial picture, lacked transparency, did not consider linkages or stakeholder opinion: *Urban Energy Sustainability Index* by Marquez-Ballesteros et al., *Indicators for sustainable energy development in Chinese Villages* by Mortimer and Grant, *Energy Security Indicators* by the Asia Pacific Energy Research Center and *Indicators of long-term energy supply* security by Jansen et al. [59–62]. The distribution of scores can be seen in Table 4, and the scores for each indicator set can be seen in Appendix B.

**Table 4**
Distribution of indicator set scores

| Score range | # of indicator sets |
|---|---|
| < 1 | 0 |
| $1 \leq x < 2$ | 7 |
| $2 \leq x < 3$ | 9 |
| $3 \leq x < 4$ | 21 |
| $4 \leq x < 5$ | 17 |
| $5 \leq x < 6$ | 14 |
| 6 | 1 |
| Average | 3,69 |
| Max | 6,00 |
| Min | 1,66 |

The identified indicator sets were split into five categories according to their stated purpose. The average scores between the different categories varied significantly, see Table 5. The indicator sets that were derived from the *ISEDs* or *EISDs* received the highest average score, which is logical considering the *EISDs* received a perfect score. Energy security indicator sets received the lowest average score. They were often found to present a partial picture as all dimensions of sustainable development were not considered, especially the social side. Energy security is sometimes defined more narrowly than SED.

**Table 5**
Average scores by indicator set category

| **Category** | **Total Score** |
|---|---|
| Sustainable energy development | 3,71 |
| sub-category: EISD and indicator sets based on EISDs | 4,20 |
| Energy Security | 2,95 |
| Energy indicators in general SD indicator sets | 3,89 |
| Other | 3,42 |

## 5. Discussion

The implications of this study are an identification of the desirable characteristics of indicator sets as well as a comprehensive assessment of existing indicator sets for SED. According to the analysis carried out, the suitability of existing indicator sets varies considerably. One indicator set fulfilled all of the assessment criteria laid out and, therefore, could be considered comprehensive and robust – The *Energy Indicators for Sustainable Development.* The *EISD* were thought to be transparent since a detailed description of how indicators were selected and should be applied was provided. A thematic framework was used in its development, which ensured that all three dimensions of sustainable development were accounted for, and the indicator set was representative of SED. Linkages between the different indicators and themes were considered, apparent by the fact that some indicators were within more than one theme. Finally, experts and stakeholders were consulted during the development of both the original *ISED* and, the subsequent, *EISD.* Thus, the *EISDs* met all the assessment criteria and can be considered a comprehensive and robust indicator set [4].

The *EISD* aim to enable countries to assess their progress towards SED, not necessarily to compare their progress to other countries. Shortall and Davidsdottir did not find the *EISD* to adequately capture the Icelandic context with its unique energy mix and emphasized that indicators need to reflect the national conditions to be useful to policy-makers and stakeholders [8]. The *EISD* are described as “a recommended rather than complete core set of energy indicators” [4]. Therefore, stakeholder engagement is encouraged to refine the *EISDs* further to fit the national context and coordinate efforts in data collection [4]. This refinement must not result in the omission of too many indicators or entire dimensions, as was the case with the application of the *EISD* in the Baltic States [51]. Therefore, the *EISD* could be considered as a robust and comprehensive building block for further development that shapes that the indicator set to reflect the context and make it useful to stakeholders.

The *EISD* are not flawless, despite receiving a perfect score in this study. The indicator set has been criticized for, e.g., capturing an imbalanced picture of SED, and having demanding data requirements [8,26]. However, perhaps one of the main weaknesses of the indicator set is that it does not seem to be used by many, which might be because of its lack of effective communication. The use of other, lower scoring, indicator sets for SED, e.g., *Energy Trilemma Index (ETI),* is much more widespread. The *ETI* has become an established measurement tool within the energy field despite lacking rationale for indicator selection and application and only receiving a score of 3,5. If a criterion on effective communication of indicators and their results had been included in this study, the *EISD* would not have received a perfect score, and the *ETI* would have scored better. The flaws of the *EISD* and potential reasons for its lack of use are discussed in the following paragraphs.

A quick analysis of the *EISD* indicator set reveals that the dimensions of sustainable development are not balanced as there are four social indicators, sixteen economic indicators, and ten environmental ones [4]. Shortall and Davidsdottir [8] found the *EISD* indicators to be more comprehensive and better capture the various issues of SED than the WEC's *ETI* and the WEF's *Energy Architecture Performance Index*. However, they argue that none of these three established indicators sets for SED adequately account for human wellbeing or capture impacts on a smaller scale, such as the local level [8]. A suitable indicator set accounts for all dimensions of sustainable development and the interlinkages between the different goals to capture a representative picture of SED.

Iddrisu and Bhattacharayya further criticized the *EISD* indicators for demanding data requirements due to the large number of indicators that make them impractical and difficult to interpret [26]. The *EISDs* are not aggregated, which is frequently done with indicator sets and thereby remain multi-dimensional [4]. In this analysis, 27 of the 57 identified indicators were aggregated in some way, often to form an index. The aggregation of indicators can be a complicated process. Assigning weights and, thus, quantifying the relative significance of indicators is a politically sensitive and value-laden process that can lead to subjectivity [63]. An aggregated index reports the status of an entire system while it might not reflect the health of the different dimensions of the system and hinders an in-depth analysis [64]. That is, through aggregation, a lot of information can be lost due to the "information iceberg" effect unless data for underlying indicators are shown as well [65].

The most visible difference between the *EISD* and the *ETI* is their presentation. The *EISD* are presented as a list of indicators organized within dimensions, themes, and sub-themes of SED [4]. The *ETI* are presented as three core elements of a sustainable energy system – energy security, energy equity, and environmental sustainability, see Figure 11 [50]. The results of the *ETI* are presented within the triangle. Countries are ranked on an A-B-C scale for each element based on the results of aggregated underlying indicators. The presentation of the *ETI* is much more visually appealing and easier to understand at a glance than the *EISD*, despite the lack of methodological transparency. This difference in presentation might be the deciding factor for why the *ETI* is used much more than the *EISD*. The developers of the *EISD* do not discuss how the indicators should be presented, and their results reported. Effective and transparent communication of indicators can ensure their application and usefulness [25]. The OECD highlights the significance of visualization of the results as it can influence interpretability [23]. Graphics of results can be useful to stakeholders as opposed to raw data that might be technical [43]. It is beneficial to accompany these graphics by short summaries or explanations for general stakeholders, while decision-makers could receive more detailed descriptions when appropriate [43].

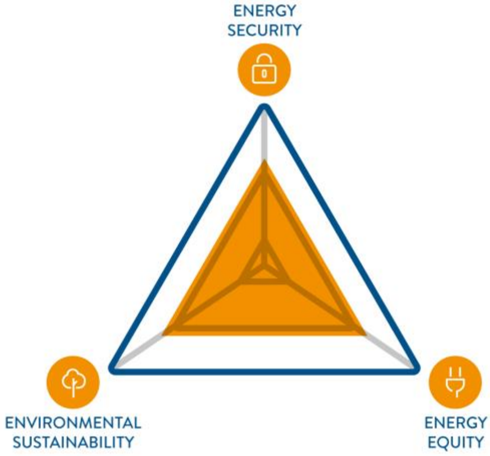


*Figure 11: **The Energy Trilemma**. Presentation of one of the most commonly used energy indicator sets, the Energy Trilemma Index, within the energy trilemma - energy security, environmental sustainability, and energy equity [48].*

The *EISD* were developed as a pool of indicators for SED to be "read in the context of each country's economy and energy resources" [4]. While detailed descriptions are provided of the methodology for each indicator, more guidance might be needed on how the EISD should be "read in the context" [4]. For instance, stakeholder consultation is recommended; however, no further guidance is given on how, which, or why stakeholders should be engaged. Establishing a coordinating mechanism to "liaise with all of the relevant organizations in the country and to coordinate their activities with the EISD effort" is suggested [4]. Issues covered by the *EISD* are likely connected to multiple agencies and organizations and, therefore, such a mechanism is undoubtedly necessary. However, ownership of the *EISD* is similarly important, although never mentioned in the *EISD* guidelines. The responsibility for refining the *EISD* to reflect the context, collecting data from the various sources, reporting the indicators, and updating them periodically could be given to one governmental body, and not be shared among multiple agencies and organizations. In comparison, the *ETI* is managed by the WEC, which collects data annually from the relevant national agencies. Thereby, the WEC bears all the responsibility, and national agencies only have to provide them with data.

Another fault of the *EISD* is the absence of institutional indicators [4]. Vera et al. [47] stated that "institutional indicators assess the availability and adequacy of the institutional framework necessary to support an effective and efficient energy system." Therefore, institutional indicators measure issues vital to the realization of SED, such as the effectiveness of policies and action plans, the level of investment in capacity building, education, and research and development [4,47]. The developers of the *EISD* explained that it can be challenging to measure institutional issues as they can be qualitative or relate to the future, which is why no institutional indicators were included [4]. Nonetheless, an attempt could be made to measure progress towards these crucial aspects of SED. A fitting first institutional indicator would be ownership of the *EISD*.

There are a few potential weaknesses to this study, particularly regarding the indicator set assessment criteria. Creating a system for measuring these criteria was challenging. The literature was reviewed to identify what actions or characteristics were though to enable each criterion, which made up the different sub-criteria. The number of criteria and sub-criteria was kept to a minimum to address this, and only criteria based on the most important attributes to develop a robust indicator set were included. For simplification, all the criteria were weighted equally, which could have resulted in some criteria being over- or under-valued. A lack of transparency in either indicator selection or application could have hindered an accurate assessment in some cases, which even further highlights the importance of transparency.

A few aspects of a successful indicator sets were not included in the criteria. Two Bellagio STAMP principles were not considered, namely, principle 6 on effective communication and principle 8 on continuity and capacity [41,42]. The necessity of effective communication of indicators is highlighted in the above discussion. The continuity of an indicator set refers to repeated measurements and regular revisions of indicators. However, it was challenging to measure what effective communication and the continuity of an indicator set would entail.

Although the necessity of taking account of the national context is highlighted throughout this paper, a more detailed analysis of how representative of SED the indicator sets were remains for further analysis. Representativeness includes taking account of the national context to ensure policy relevance and usefulness to stakeholders. Furthermore, the scope or level of different indicator sets is identified, but no assessment is made related to this.

The following steps and considerations for the development of an indicator set for SED are suggested to set future research guidelines. It is beneficial to keep transparency as a guiding light throughout the process. The usefulness of indicators or an approach to indicator selection is entirely dependent on how effectively they are presented and whether stakeholders and policymakers can apply them. An effective and transparent presentation includes disclosing the relevant formulas and data sources as well as methodology for indicator selection. Furthermore, reporting indicator results in a visually appealing way can aid with understanding. The *EISD* can serve as an appropriate starting basket of indicators for any context. However, to increase the usefulness and policy relevance of the indicator set and take account of multiple viewpoints, stakeholders and experts could be engaged for the further refinement of the indicator set. The final set of indicators should represent all three dimensions of sustainable development; economic, social, and environmental, and consider the underlying issues of SED. It is valuable to examine the interconnections between issues and indicators for SED. A mixed approach of a thematic and systems framework seems to be a useful way to capture the multi-dimensional problem that SED is, although this requires further research. The analysis presented here, and the steps outlined can be used to form a comprehensive and robust indicator set for SED within any context.

Giving the responsibility of reporting and maintaining the resulting indicators to one governmental body is advantageous. Indicators connected to the relevant policy goals, both national and international, are valuable to measure progress towards those targets and ensure policy relevance. For instance, the indicators could be connected with the SDGs as energy relates to some extent to all 17 SDGs [31]. Additionally, the indicators could be connected to a country's particular SED goals. To further add relevance to the indicator set, the developers of the *EISD* recommend linking the indicators to dynamic models [20]. Thereby, the indicators are not limited to being backward-looking but can also be used to create scenarios, assess the potential implications of different policy actions, and identify development trends. Finally, as stated by Taylor et al. [66], it is good to keep in mind that ”while goals and indicators can be very useful tools to support government policymaking and to assist the public in holding those governments to account, they are just that — tools — and their blind pursuit should not become an end in itself.”

## 6. Conclusion

This study aimed to assess the suitability of existing indicator sets for SED. For this purpose, the study identified established indicator sets for SED, and developed indicator set assessment criteria based on characteristics found to make an indicator set comprehensive and robust. Multiple different SED indicator sets exist for various purposes and of variable quality. All but one of the 57 indicator sets were found to be lacking in some aspect. A common issue was a lack of transparency in both indicator selection and application. Most indicator sets were developed through some conceptual framework; although, further analysis could be done of what framework works best for a SED indicator set. The indicator sets often presented an imbalanced picture of SED with emphasis on the economic impacts of energy developments and less or no recognition of environmental or social ones. Some considered linkages and interrelations of indicators; however, further attention could be given to how this can be done well. Stakeholder engagement in decision-making and the development of indicators to ensure policy relevance and stakeholder acceptance is increasingly more recognized. Nevertheless, most indicator sets were developed without any stakeholder input whatsoever.

The only indicator set that met all criteria and, therefore, could be considered comprehensive and robust were the *Energy Indicators for Sustainable Development*. The *EISD* were transparent and clear, based within a conceptual framework, representative of SED, considered interconnections within the set, and based on stakeholder input. Yet, this set is used by few, and the use of other, lower scoring, indicator sets is much more widespread. Several flaws to the *EISD* were identified that require further improvement to the set. No attention is given to the communication of the indicators and their results, which may be the reason for its lack of use. Effective communication of indicators can influence interpretability and aid with understanding. The *EISD* have been criticized for capturing an imbalanced picture of SED, where economic implications are overemphasized and social issues undervalued. Additionally, no institutional indicators measuring vital aspects of SED, such as the effectiveness of policies and action plans, are included. Clear guidance on how to implement the set at the national level, including giving ownership of the indicators to the relevant agency, seems to be missing as well. Data requirements of the *EISD* have been found burdensome, which can make the indicator set less attractive and useful to stakeholders and decision-makers.

It is valuable to keep in mind what the purpose of an indicator set is. If the indicator set is supposed to measure progress towards SED and inform decision-making and policy development at the national level, the indicator set must reflect the national context and goals set in the country as revealed through stakeholder engagement. The *EISD* could be used as a comprehensive and robust initial pool of indicators for further development, not as a finalized set of indicators. It is beneficial to keep the identified flaws of the *EISDs* in mind and tackle them when the set is updated. In this study, future research guidelines on the development of indicators for SED are laid out. A logical next step would be to develop an indicator set based on these guidelines in addition to a more in-depth analysis of high scoring indicator sets. This more thorough analysis would include, for instance, an assessment of how representative an indicator set is of SED in a particular context and how effectively results are communicated.

## Acknowledgments

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# Appendix A: Identified indicator sets for sustainable energy development

| Category | Name of the indicator set | Authors | Paper | Year | Scope | # of indicators | Aggregation | Conceptual framework |
|---|---|---|---|---|---|---|---|---|
| Sustainable energy development | Sustainable Energy Development Index (SEDI) | Iddrisu, Bhattacharyya | Sustainable Energy Development Index: A multi-dimensional indicator for measuring sustainable energy development [26] | 2015 | National (for country comparisons) | 11 | Yes | Causal chain (Process cycle) & issue-or theme-based |
| | Indicators for assessing sustainable energy development scenarios | Papadaki, Siskos et al. | Assessing different scenarios for sustainable energy supply in the island of Crete [67] | 2001 | National (not for country comparisons) | 11 | No | Issue- or theme-based |
| | Synthetic Index of Sustainable Energy Development (SISED) | García-Álvarez, Moreno, Soares | Analyzing the sustainable energy development in the EU-15 by an aggregated synthetic index [68] | 2016 | National (for country comparisons) | 33 | Yes | Issue- or theme-based |
| | Energy sustainability indicators | Latin American Energy Organization et al. | Energy and Sustainable Development in Latin America and the Caribbean: Approaches to energy policy [69] | 1997 | National (for country comparisons) | 8 | No | Issue- or theme-based |
| | | | Energy and Sustainable Development in Latin America and the Caribbean: Guide for Energy Policymaking [70] | 2000 | | | | |
| | | Sheinbaum-Pardo, Ruiz-Mendoza et al. | Mexican energy policy and sustainability indicators [71] | 2012 | | | | |
| | Sustainable Energy Watch (SEW) | HELIO International | Sustainable Energy Watch (SEW) Indicator Selection and Rationale [56] | 2000 | National (for country comparisons) | 10 | No | Issue- or theme-based |
| | | Spalding-Fecher | Indicators of sustainability for the energy sector: A South African case study [72] | 2003 | | | | |
| | | Hossain, Tamim | Energy and Sustainable Development in Bangladesh [73] | 2006 | | | | |
| | | Rezaei, Chaharsooghi, Abbaszadeh | The Role of Renewable Energies in Sustainable Development: Case Study Iran [74] | 2013 | | | | |
| | Energy Architecture Performance Index | World Economic Forum | Global Energy Architecture Performance Index Report 2017 [58] | 2017 | | 18 | Yes | Issue- or theme-based |

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|---|---|---|---|---|---|---|---|
| | | The Global Energy Architecture Performance Index Report 2017: Methodological addendum [49] | | National (for country comparisons) | | | |
| Regulatory Indicators for Sustainable Energy (RISE) | World Bank, ESMAP, Sustainable Energy for All | RISE Readiness for Investment in Sustainable Energy - A tool for policymakers [75] | 2014 | National (for country comparisons) | 27 | Yes | Issue- or theme-based |
| | World Bank, ESMAP, Climate Investment Funds, Sustainable Energy for All | Regulatory indicators for sustainable energy - A global scorecard for Policy Makers [76] | 2016 | | | | |
| | | Policy Matters - Regulatory Indicators for Sustainable Energy [77] | 2018 | | | | |
| Energy indicators for sustainable development through policy | Hannan, Begum, Abdolrasol et al. | Review of baseline studies on energy policies and indicators in Malaysia for future sustainable energy development [78] | 2018 | National (not for country comparisons) | 14 | No | Issue- or theme-based |
| Assessment Index (AI) (precursor for energy trilemma) | World Energy Council | World Energy and Climate Policy: 2009 Assessment [79] | 2009 | National (for country comparisons) | 46 | Yes | Issue- or theme-based |
| Energy Sustainability Country Index (ESCI) (precursor for energy trilemma) | World Energy Council | Pursuing sustainability: 2010 Assessment of country energy and climate policies [80] | 2010 | National (for country comparisons) | 21 | Yes | Issue- or theme-based |
| Energy Trilemma Index | World Energy Council | World Energy Trilemma Index 2018 [50] | 2018 | National (for country comparisons) | 35 | Yes | Issue- or theme-based |
| Energy Development Index (EDI) | International Energy Agency | World Energy Outlook 2010 [81] | 2010 | National or regional (for comparison) | 4 | Yes | N/A |
| | Mandelli, Birgieri, Mattarolo, Colombo | Sustainable energy in Africa: A comprehensive data and policies review [82] | 2014 | | | | |

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|---|---|---|---|---|---|---|---|
| Regional Sustainable Energy Development Evaluation Indicator System | Yu, Zhao, Chen | Construction of Regional Sustainable Energy Development Evaluation Indicator System [83] | 2010 | Regional (for comparison) | 24 | No | Causal chain (DSR) & Issue or theme-based |
| Local energy sustainability indicators | Neves, Leal | An exploratory study on energy sustainability indicators for local energy planning [84] | 2009 | Local (for comparison) | 18 | No | Issue- or theme-based |
| | | Energy sustainability indicators for local energy planning: Review of current practices and derivation of a new framework [55] | 2010 | | | | |
| Indicators for sustainable energy development in Chinese Villages | Mortimer, Grant | Evaluating the prospects for sustainable energy development in a sample of Chinese villages [60] | 2008 | Local (not for comparison) | 2 | No | N/A |
| Energy Sustainability Index | Doukas et al. | Assessing energy sustainability of rural communities using principal component analysis [54] | 2012 | Rural (for comparison) | 9 | Yes | N/A |
| Energy Sustainability Index (ESI) | Mainali, Pachauri et al. | Assessing rural energy sustainability in developing countries [45] | 2014 | Rural (for comparison) | 13 | Yes | Issue- or theme-based |
| Urban Energy Sustainability Index (UESI) | Marquez-Ballesteros, Mora-López et al. | Measuring urban energy sustainability and its application to two Spanish cities: Malaga and Barcelona [59] | 2019 | Cities (for comparison) | 12 | Yes | Issue- or theme-based |
| Sustainable energy indicators for cities | Zen, Lima, et al. | Sustainability, Energy and Development: A Proposal of Indicators [85] | 2012 | Cities (for comparison) | 26 | No | Issue- or theme-based |
| Sustainability indicators for urban energy systems | Keirstead | Selecting sustainability indicators for urban energy systems [33] | 2007 | Cities (for comparison) | 42 | No | Systems dynamics & issue- or theme-based |

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|---|---|---|---|---|---|---|---|---|
| **EISD and indicator sets based on EISDs** | Indicators for sustainable energy development (ISED) (precursor for EISD) | IAEA, and IEA | Indicators for Sustainable Energy Development [28] | 2002 | National (not for country comparisons) | 41 | No | Causal chain (DSR) & issue or theme-based |
| | *Application of ISEDs* in Brazil | Schaeffer, Szklo et al. | Indicators for sustainable energy development: Brazil's case study [86] | 2005 | National (not for country comparisons) | 53 | No | Causal chain (DSR) & issue or theme-based |
| | *Application of ISEDs* in Cuba | Pérez, López, Berdellans | Evaluation of energy policy in Cuba using ISED [87] | 2005 | National (not for country comparisons) | 35 | No | Causal chain (DSR) & issue or theme-based |
| | *Application of ISEDs* in Russia | Aslanyan, Molodtsov, Iakobtchouk | Monitoring the sustainability of Russia's energy development [88] | 2005 | National (not for country comparisons) | 15 | No | Causal chain (DSR) & issue or theme-based |
| | *Application of ISEDs* in Lithuania | Streimikiene | Indicators for sustainable energy development in Lithuania [89] | 2005 | National (not for country comparisons) | 12 | No | Causal chain (DSR) & issue or theme-based |
| | *Application of ISEDs* in Thailand | Todoc, Todoc, Lefevre | Indicators for sustainable energy development in Thailand [90] | 2005 | National (not for country comparisons) | 36 | No | Causal chain (DSR) & issue or theme-based |
| | | IAEA, UN DESA, IEA, Eurostat, and EEA | Energy Indicators for Sustainable Development: Guidelines and Methodologies [4] | 2005 | | | | |
| | | Vera, Langlois, et al. | Indicators for sustainable energy development: An initiative by the International Atomic Energy Agency [47] | 2005 | | | | |
| | Energy indicators for sustainable development (EISD) | Vera, and Abdalla | Energy Indicators to Assess Sustainable Development at the National Level: Acting on the Johannesburg Plan of Implementation [91] | 2006 | National (not for country comparisons) | 30 | No | Issue- or theme-based |
| | | Vera, and Langlois | Energy indicators for sustainable development [13] | 2007 | | | | |

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|---|---|---|---|---|---|---|---|
| *Application of EISDs* in the Baltic States | Streimikiene, Ciegis, and Grundey | Energy indicators for sustainable development in Baltic States [51] | 2007 | National (not for country comparisons) | 12 | No | Issue- or theme-based |
| *Application of EISDs* in Brazil | Pereira Jr. Soares et al. | Energy in Brazil: Toward sustainable development? [92] | 2008 | National (not for country comparisons) | 30 | No | Issue- or theme-based |
| *Application of EISDs* in Thailand | Shoram, Hirunlabh et al. | Critical analysis of Thailand's past energy policies towards the development of a new energy policy [93] | 2018 | National (not for country comparisons) | 3 | No | Issue- or theme-based |
| *Application of EISDs* in Africa | Mandelli, Birgieri, Mattarolo, Colombo | Sustainable energy in Africa: A comprehensive data and policies review [82] | 2014 | National (not for country comparisons) | 17 | No | Issue- or theme-based |
| Energy indicators in the EU sustainable development strategy | Streimikiene, Ciegis | Framework of indicators for monitoring implementation of interrelated targets of the EU Sustainable Development Strategy [94] | 2007 | National (for country comparisons) | 12 | No | Issue- or theme-based |
| Sustainable energy development indicators for EU energy policy 1 | Streimikiene, Sivickas | The EU sustainable energy policy indicators framework [95] | 2008 | National (for country comparisons) | 15 | No | Issue- or theme-based |
| Sustainable energy development indicators for EU energy policy 2 | Streimikiene | Impact of environmental taxes on sustainable energy development in Baltic States, Czech Republic and Slovakia [96] | 2015 | National (for country comparisons) | 7 | No | Issue- or theme-based |
| Sustainable energy development indicators for EU energy policy 3 | Siksnelyte, Zavadskas, Bausys, Streimikiene | Implementation of EU energy policy priorities in the Baltic Sea Region countries: Sustainability assessment based on neutrosophic MULTIMOORA method [97] | 2019 | National (for country comparisons) | 17 | No | Issue- or theme-based |
| Sustainable energy index | Zhou, Ang, and Poh | A mathematical programming approach to constructing composite indicators [98] | 2007 | National (for country comparisons) | 3 | Yes | Issue- or theme-based |
| | Wang | A generalized MCDA–DEA (multi-criterion decision analysis–data envelopment analysis) approach to construct slacks-based composite indicator [99] | 2015 | | | | |
| | Wang, Zhou, and Wang | Constructing slacks-based composite indicator of sustainable energy development for China: A meta-frontier nonparametric approach [100] | 2016 | | | | |

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|---|---|---|---|---|---|---|---|---|
| | Aggregated energy security performance indicator (AESPI) | Martchamadol, Kumar | An aggregated energy security performance indicator [46] | 2013 | National (for country comparisons) | 25 | Yes | Issue- or theme-based |
| | Indicators for sustainable energy development (PASHMINA) | Kettner, Kletzan-Slamanig et al. | PASHMINA – Paradigm Shifts Modelling and Innovative Approaches Development. Indicators for Sustainable Energy Development - The PASHMINA Approach [101] | 2012 | Energy system (for comparison) | 40 | No | Systems dynamics & issue- or theme-based |
| | Composite index for sustainable energy development | | | | Energy system (for comparison) | 40 | Yes | Systems dynamics & issue- or theme-based |
| | Sustainability assessment indicators for energy systems | Zolfani, Saparauskas | New application of SWARA method in prioritizing sustainability assessment indicators of energy system [102] | 2013 | Energy system (for comparison) | 14 | Yes | Issue- or theme-based |
| | Indicator for Sustainable Energy Development for Austria (ISED-AT) | Kettner, Kletzan-Slamanig, and Köppl | Indicators for sustainable energy development for Austria: Residential Buildings and Electricity and Heat Supply [32] | 2015 | Residential sector (not for comparison) | 71 | No | Systems dynamics & issue- or theme-based |
| | Sustainable energy development index for Austria | | | | Residential sector (not for comparison) | 19 | Yes | Systems dynamics & issue- or theme-based |
| **Energy Security** | Supply-demand S/D index | Scheepers et al. | EU standards for energy security of supply-updates on the crisis capability index and the supply/demand index quantification for EU-27 [103] | 2007 | National (for country comparisons) | 20 | Yes | Systems dynamics |
| | Crisis capability index | | | | National (for country comparisons) | 66 | Yes | Issue- or theme-based |
| | Energy Security Indicators | Asia Pacific Energy Research Centre | A quest for Energy Security in the 21st Century Resources and, Constraints [61] | 2007 | National (for country comparisons) | 5 | No | N/A |
| | Energy Security Matrix | Kisel, Hamburg, et al. | Concept for Energy Security Matrix [104] | 2016 | National (for country comparisons) | 27 | No | Issue- or theme-based |

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|---|---|---|---|---|---|---|---|
| Energy Security Assessment Model | Murakami, Motokura, Kutani - Institute of Energy Economics, Japan (IEEJ) | An analysis of major countries' energy security policies and conditions – quantitative assessment of energy security policies [105] | 2011 | National (for country comparisons) | 14 | No | Causal chain (Supply chain) |
| Energy Affinity Index | Marín Quemada and Muños Delgado | Affinity and Rivalry: Energy Relations of the EU [106] | 2011 | National (for country comparisons) | 5 | Yes | N/A |
| The U.S. Energy Security Risk (Index) | Global Energy Institute - U.S. Chamber of Commerce | Index of U.S. Energy Security Risk: Addressing America's Vulnerabilities in A Global Energy Market - 2018 edition [107] | 2018 | National (not for country comparisons) | 37 | Yes | Issue- or theme-based |
| International Index of Energy Security Risk | | International Index of Energy Security Risk: Assessing Risk in A Global Energy Market - 2018 edition [108] | 2018 | National (for country comparisons) | 29 | Yes | Issue- or theme-based |
| Risky External Energy Supply (REES) index | Le Coq and Paltseva | Measuring the security of external energy supply in the European Union [109] | 2009 | National (for country comparisons) | 7 | No | N/A |
| Electricity generation security of supply indicators | Portugal-Pereira and Esteban | Implications of paradigm shift in Japan's electricity security of supply: A multi-dimensional indicator assessment [110] | 2014 | National (not for country comparisons) | 9 | No | Issue- or theme-based |
| Simple and Complex Energy Security Indicators and Metrics | Sovacool and Mukherjee | Conceptualizing and measuring energy security: A synthesized approach [111] | 2011 | Variable (for comparison) | 372 | No | Issue- or theme-based |
| Energy security index 1 | Sovacool, Mukherjee et al. | Evaluating energy security performance from 1990 to 2010 for eighteen countries [57] | 2011 | National (for country comparisons) | 20 | Yes | Issue- or theme-based |
| Energy security index 2 | Sovacool | An international assessment of energy security performance [112] | 2013 | National (for country comparisons) | 20 | Yes | Issue- or theme-based |
| Indicators of long-term energy supply security | Jansen et al. | Designing indicators of long-term energy supply security [62] | 2004 | National or regional (for comparison) | 4 | No | N/A |
| Energy Security Indicators | Asian Institute of Technology, Global Network on Energy for Sustainable Development (GNESD) | Energy Security in Thailand [113] | 2010 | National and household level (not for comparison) | 9 | No | N/A |

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|---|---|---|---|---|---|---|---|---|
| **Energy indicators in general SD indicator sets** | Indicators for Sustainable Development Goal 7 | United Nations | A/RES/71/313 Resolution adopted by the General Assembly on Work of the Statistical Commission pertaining to the 2030 Agenda for Sustainable Development [114] | 2017 | National, regional or local (for comparison) | 6 | No | Issue- or theme-based |
| | | UN DESA Statistics Division | Metadata for each indicator [115] | 2016 | | | | |
| | EU sustainable development indicators - energy | Streimikiene, Mikalauskiene, Mikalauskas | Comparative assessment of sustainable energy development in the Czech Republic, Lithuania and Slovakia [116] | 2016 | National (for country comparisons) | 4 | No | Issue- or theme-based |
| | Energy indicators in Taiwan's Sustainable Development Indicators (TSDI) | Tsai | Energy sustainability from analysis of sustainable development indicators: A case study of Taiwan [117] | 2010 | National (not for country comparisons) | 2 | No | Causal chain (PSR) |
| | Energy indicators from the German sustainability strategy | German Federal Government | Perspectives for Germany - Our strategy for sustainable development [118] | 2002 | National (not for country comparisons) | 15 | No | N/A |
| | Index of Sustainable Energy Development (ISUD) | Schlör, Fischer, Hake | Methods of measuring sustainable development of the German energy sector [119] | 2013 | Energy system (not for comparison) | 15 | Yes | Issue- or theme-based |
| | Standardized sustainability energy index (SSEI) | | | | Energy system (not for comparison) | 15 | Yes | Issue- or theme-based |
| **Other** | Occupational Entropy and Mind Indicators for Sustainable Energy Development | Pop-Jordanov, Markovska, et al. | Occupational Entropy and Mind Indicators for Sustainable Energy Development [53] | 2004 | National (for country comparisons) | 3 | No | Causal chain (PSR) |
| | Renewable Energy Country Attractiveness Index (RECAI) | Ernst & Young | recai May 2018 - From black gold to green power [120] | 2018 | National (for country comparisons) | 15 | No | Issue- or theme-based |
| | | | Ernst & Young website – RECAI methodology [48] | 2019 | | | | |
| | Renewable Energy Sustainability Index | Cirstea, Moldovan-Teselios et al. | Evaluating Renewable Energy Sustainability by Composite Index [121] | 2018 | National (for country comparisons) | 23 | Yes | Issue- or theme-based |
| | Renewable Energy Responsible Investment Index (RERII) | Lee, Zhong | Construction of a responsible investment composite index for renewable energy industry [122] | 2015 | National (for country comparisons) | 17 | Yes | Issue- or theme-based |
| | Multi-dimensional Energy Poverty Index (MEPI) | Nussbaumer, Bazilian, and Modi | Measuring Energy Poverty: Focusing on What Matters [52] | 2012 | Households (for comparison) | 6 | Yes | Issue- or theme-based |

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|---|---|---|---|---|---|---|---|
| Sustainable Mobility Indicators | Nicolas, Pochet et al. | Towards sustainable mobility indicators: application to the Lyons conurbation [123] | 2003 | Urban areas (for comparison) | 22 | No | Issue- or theme-based |

## Appendix B: Analysis of indicator sets for energy development

| Category | Name of indicator set | Indicator set assessment criteria: Transparency of indicator selection<br>1/2 - Individual indicators (a)<br>1/2 - Methodology for indicator selection (b)<br>0 and no further analysis - Neither of the above | Transparency of indicator application<br>1/2 - Methodology for indicator application (a)<br>1/2 - Data sources (b)<br>0 - Unclear how to apply indicators | Conceptual framework<br>1 - Framework used<br>0 - No apparent framework used | Representative<br>1/3 - Economic (a)<br>1/3 - Social (b)<br>1/3 - Environmental (c)<br>0 - None of the above | Linkages<br>1 - Linkages considered<br>0 - Not considered | Stakeholder engagement<br>1 - Stakeholders or experts engaged<br>0 - No, not clear if was done | Total score |
|---|---|---|---|---|---|---|---|---|
| Sustainable energy development | Sustainable Energy Development Index (SEDI) [26] | a, b = 1 | a, b = 1 | 1 | a, b, c = 1 | 1 | 0 | **5** |
| | Indicators for assessing sustainable energy development scenarios [67] | a = 1/2 | 0 | 1 | a, b, c = 1 | 0 | 0 | **2,5** |
| | Synthetic Index of Sustainable Energy Development (SISED) [68] | a = 1/2 | a, b = 1 | 1 | a, c = 2/3 | 1 | 0 | **3,16** |
| | Energy sustainability indicators [69–71] | a = 1/2 | 0 | 1 | a, b, c = 1 | 1 | 0 | **3,5** |
| | Sustainable Energy Watch (SEW) [56,72–74] | a = 1/2 | a = 1/2 | 1 | a, b, c = 1 | 1 | 0 | **4** |
| | Energy Architecture Performance Index [49,58] | a = 1/2 | a, b = 1 | 1 | a, b, c = 1 | 1 | 1 | **5,5** |
| | Regulatory Indicators for Sustainable Energy (RISE) [75–77] | a, b = 1 | a, b = 1 | 1 | a, b, c = 1 | 0 | 1 | **5** |
| | Energy indicators for sustainable development through policy [78] | a = 1/2 | 0 | 1 | a, b, c = 1 | 0 | 0 | **2,5** |

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|---|---|---|---|---|---|---|---|---|
| | Assessment Index (AI) (precursor for energy trilemma) [79] | a = 1/2 | b = 1/2 | 1 | a, b, c = 1 | 1 | 0 | **4** |
| | Energy Sustainability Country Index (ESCI) (precursor for energy trilemma) [80] | a = 1/2 | 0 | 1 | a, b, c = 1 | 1 | 0 | **3,5** |
| | Energy Trilemma Index [50] | a = 1/2 | 0 | 1 | a, b, c = 1 | 1 | 0 | **3,5** |
| | Energy Development Index (EDI) [81,82] | a = 1/2 | a, b = 1 | 0 | a, b, c = 1 | 0 | 0 | **2,5** |
| | Regional Sustainable Energy Development Evaluation Indicator System [83] | a = 1/2 | 0 | 1 | a, b, c = 1 | 1 | 0 | **3,5** |
| | Local energy sustainability indicators [55,84] | a, b = 1 | 0 | 1 | a, b, c = 1 | 1 | 1 | **5** |
| | Indicators for sustainable energy development in Chinese Villages [60] | a = 1/2 | b = 1/2 | 0 | a, b = 2/3 | 0 | 0 | **1,66** |
| | Energy Sustainability Index [54] | a, b = 1 | a = 1/2 | 0 | a, c = 2/3 | 1 | 1 | **4,16** |
| | Energy Sustainability Index (ESI) [45] | a, b = 1 | a, b = 1 | 1 | a, b, c = 1 | 1 | 0 | **5** |
| | Urban Energy Sustainability Index (UESI) [59] | a, b = 1 | 0 | 1 | a, c = 2/3 | 0 | 0 | **2,66** |
| | Sustainable energy indicators for cities [85] | a = 1/2 | 0 | 1 | a, b, c = 1 | 0 | 1 | **3,5** |
| | Sustainability indicators for urban energy systems [33] | a, b = 1 | 0 | 1 | a, b, c = 1 | 1 | 1 | **5** |
| **EISD and indicator sets based on EISDs** | Indicators for sustainable energy development (ISED) (precursor for EISD) [28] | a = 1/2 | 0 | 1 | a, b, c = 1 | 1 | 1 | **4,5** |
| | *Application of ISEDs* in Brazil [86] | a = 1/2 | b = 1/2 | 1 | a, b, c = 1 | 1 | 1 | **5** |
| | *Application of ISEDs* in Cuba [87] | a = 1/2 | b = 1/2 | 1 | a, b, c = 1 | 1 | 1 | **5** |
| | *Application of ISEDs* in Russia [88] | a = 1/2 | 0 | 1 | a, c = 2/3 | 1 | 1 | **4,16** |
| | *Application of ISEDs* in Lithuania [89] | a = 1/2 | b = 1/2 | 1 | a, b, c = 1 | 1 | 1 | **5** |
| | *Application of ISEDs* in Thailand [90] | a = 1/2 | b = 1/2 | 1 | a, b, c = 1 | 1 | 1 | **5** |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Energy indicators for sustainable development (EISD) [4,13,47,91] | a, b = 1 | a, b = 1 | 1 | a, b, c = 1 | 1 | 1 | **6** |
| *Application of EISDs* in Baltic States [51] | a = 1/2 | a = 1/2 | 1 | a, c = 2/3 | 1 | 0 | **3,66** |
| *Application of EISDs* in Brazil [92] | a = 1/2 | b = 1/2 | 1 | a, b, c = 1 | 1 | 0 | **4** |
| *Application of EISDs* in Thailand [93] | a = 1/2 | 0 | 1 | a, b, c = 1 | 0 | 1 | **3,5** |
| *Application of EISDs* in Africa [82] | a = 1/2 | a = 1/2 | 1 | a, b, c = 1 | 1 | 0 | **4** |
| Energy indicators in the EU sustainable development strategy [94] | a = 1/2 | 0 | 1 | a, b, c = 1 | 1 | 0 | **3,5** |
| Sustainable energy development indicators for EU energy policy 1 [95] | a, b = 1 | b = 1/2 | 1 | a, c = 2/3 | 1 | 0 | **4,16** |
| Sustainable energy development indicators for EU energy policy 2 [96] | a, b = 1 | b = 1/2 | 1 | a, c = 2/3 | 1 | 0 | **4,16** |
| Sustainable energy development indicators for EU energy policy 3 [97] | a, b = 1 | a, b = 1 | 1 | a, b, c = 1 | 1 | 0 | **5** |
| Sustainable energy index [98–100] | a = 1/2 | a, b = 1 | 1 | a, c = 2/3 | 0 | 0 | **3,16** |
| Aggregated energy security performance indicator (AESPI) [46] | a, b = 1 | a, b = 1 | 1 | a, b, c = 1 | 1 | 0 | **5** |
| Indicators for sustainable energy development (PASHMINA) [101] | a = 1/2 | 0 | 1 | a, b, c = 1 | 1 | 0 | **3,5** |
| Composite index for sustainable energy development [101] | a = 1/2 | 0 | 1 | a, b, c = 1 | 1 | 0 | **3,5** |
| Sustainability assessment indicators for energy systems [102] | a = 1/2 | 0 | 1 | a, b, c = 1 | 0 | 1 | **2,5** |
| Indicator for Sustainable Energy Development for Austria (ISED-AT) [32] | a = 1/2 | b = 1/2 | 1 | a, b, c = 1 | 1 | 0 | **4** |
| Sustainable energy development index for Austria [32] | a = 1/2 | b = 1/2 | 1 | a, b, c = 1 | 1 | 0 | **4** |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Energy Security | Supply-demand S/D index [103] | a = 1/2 | b = 1/2 | 1 | a, c = 2/3 | 1 | 0 | **3,66** |
| | Crisis capability index [103] | a = 1/2 | 0 | 1 | a = 1/3 | 0 | 0 | **1,83** |
| | Energy Security Indicators [61] | a = 1/2 | a = 1/2 | 0 | a, c = 2/3 | 0 | 0 | **1,66** |
| | Energy Security Matrix [104] | a = 1/2 | 0 | 1 | a, b = 2/3 | 0 | 0 | **2,16** |
| | Energy Security Assessment Model [105] | a = 1/2 | a, b = 1 | 1 | a = 1/3 | 1 | 0 | **3,83** |
| | Energy Affinity Index [106] | a = 1/2 | a, b = 1 | 0 | a = 1/3 | 0 | 0 | **1,83** |
| | The U.S. Energy Security Risk (Index) [107] | a, b = 1 | b = 1/2 | 1 | a, b, c = 1 | 0 | 0 | **3,5** |
| | International Index of Energy Security Risk [108] | a = 1/2 | b = 1/2 | 1 | a, c = 2/3 | 0 | 0 | **2,66** |
| | Risky External Energy Supply (REES) index [109] | a, b = 1 | a, b = 1 | 0 | a = 1/3 | 0 | 0 | **2,33** |
| | Electricity generation security of supply indicators [110] | a, b = 1 | a = 1/2 | 1 | a, c = 2/3 | 0 | 0 | **3,16** |
| | Simple and Complex Energy Security Indicators and Metrics [111] | a, b = 1 | 0 | 1 | a, b, c = 1 | 0 | 1 | **4** |
| | Energy security index 1 [57] | a, b = 1 | a, b = 1 | 1 | a, b, c = 1 | 0 | 1 | **5** |
| | Energy security index 2 [112] | a, b = 1 | a = 1/2 | 1 | a, b, c = 1 | 0 | 1 | **4,5** |
| | Indicators of long-term energy supply security [62] | a = 1/2 | a = 1/2 | 0 | a, b = 2/3 | 0 | 0 | **1,66** |
| | Energy Security Indicators [113] | a = 1/2 | a, b = 1 | 0 | a, b, c = 1 | 0 | 0 | **2,5** |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Energy indicators in general SD indicator sets** | Indicators for Sustainable Development Goal 7 [114] | a = 1/2 | a, b = 1 | 1 | a, b, c = 1 | 0 | 1 | **5** |
| | EU sustainable development indicators – energy [116] | a = 1/2 | a, b = 1 | 1 | a, c = 2/3 | 0 | 0 | **3,16** |
| | Energy indicators in Taiwan's Sustainable Development Indicators (TSDI) [117] | a = 1/2 | a, b = 1 | 1 | a, c = 2/3 | 1 | 0 | **4,16** |
| | Energy indicators from the German sustainability strategy [118] | a = 1/2 | b = 1/2 | 0 | a, b, c = 1 | 1 | 1 | **4** |
| | Index of Sustainable Energy Development (ISUD) [119] | a = 1/2 | 0 | 1 | a, b, c = 1 | 1 | 0 | **3,5** |
| | Standardized sustainability energy index (SSEI) [119] | a = 1/2 | 0 | 1 | a, b, c = 1 | 1 | 0 | **3,5** |
| **Other** | Occupational Entropy and Mind Indicators for Sustainable Energy Development [53] | a = 1/2 | 0 | 1 | b = 1/3 | 1 | 0 | **2,83** |
| | Renewable Energy Country Attractiveness Index [120] | a = 1/2 | 0 | 1 | a = 1/3 | 0 | 0 | **1,83** |
| | Renewable Energy Sustainability Index [121] | a, b = 1 | b = 1/2 | 1 | a, b, c = 1 | 1 | 0 | **4,5** |
| | Renewable Energy Responsible Investment Index (RERII) [122] | a, b = 1 | b = 1/2 | 1 | a, b, c = 1 | 1 | 0 | **4,5** |
| | Multidimensional Energy Poverty Index (MEPI) [52] | a, b = 1 | a, b = 1 | 1 | b = 1/3 | 0 | 0 | **3,33** |
| | Sustainable Mobility Indicators [123] | a = 1/2 | a, b = 1 | 1 | a, b, c = 1 | 0 | 0 | **3,5** |

## References


[1] World Commission on Environment and Development. Our Common Future. New York: 1987.

[2] UNDP, UN DESA, World Energy Council. World Energy Assessment: Energy and the Challenge of Sustainability. New York: 2000.

[3] United Nations General Assembly. Transforming our world: the 2030 Agenda for Sustainable Development. New York: 2015.

[4] IAEA, UN DESA, IEA, Eurostat, EEA. Energy indicators for sustainable development: Guidelines and methodologies. Vienna: 2005.

[5] United Nations Sustainable Development. Agenda 21. Rio de Janeiro: United Nations; 1992.

[6] Narula K, Reddy BS. Three blind men and an elephant: The case of energy indices to measure energy security and energy sustainability. Energy 2015;80:148–58. doi:10.1016/j.energy.2014.11.055.

[7] Sovacool BK. The methodological challenges of creating a comprehensive energy security index. Energy Policy 2012;48:835–40. doi:10.1016/j.enpol.2012.02.017.

[8] Shortall R, Davidsdottir B. How to measure national energy sustainability performance: An Icelandic case-study. Energy Sustain Dev 2017;39:29–47. doi:10.1016/j.esd.2017.03.005.

[9] United Nations. United Nations Framework Convention on Climate Change. New York: 1992.

[10] United Nations. Kyoto Protocol to the United Nations Framework Convention on Climate Change. 1998.

[11] Gunnarsdóttir I, Davíðsdóttir B, Worrell E, Sigurgeirsdóttir S. Sustainable Energy Development: History of The Concept and Emerging Themes. Manuscr Submitt Publ n.d.

[12] Cherp A, Jewell J. The concept of energy security: Beyond the four As. Energy Policy 2014;75:415–21. doi:10.1016/j.enpol.2014.09.005.

[13] Vera I, Langlois L. Energy indicators for sustainable development. Energy 2007;32:875–82. doi:10.1016/j.energy.2006.08.006.

[14] United Nations Development Programme, United Nations Department of Economic and Social Affairs, World Energy Council. World Energy Assessment: Overview 2004 Update. New York: 2004.

[15] Lund H. Renewable energy strategies for sustainable development. Energy 2007;32:912–9. doi:10.1016/j.energy.2006.10.017.

[16] Dincer I. Renewable energy and sustainable development: A crucial review. Renew Sustain Energy Rev 2000;4:157–75. doi:10.1016/S1364-0321(99)00011-8.

[17] United Nations. Report of the World Summit on Sustainable Development. A/CONF.199/20*, Johannesburg: 2002.

[18] Ki-moon B. Sustainable Energy for all: A Vision Statement by Ban Ki-moon Secretary-General of the United Nations. New York: 2011.

[19] Graymore MLM, Sipe NG, Rickson RE. Regional sustainability: How useful are current tools of sustainability assessment at the regional scale? Ecol Econ 2008;67:362–72. doi:10.1016/j.ecolecon.2008.06.002.

[20] OECD. OECD Core set of indicators for environmental performance reviews: A synthesis report by the Group on the State of the Environment. vol. No 83. Paris: 1993.

[21] Zeijl-rozema A Van, Ferraguto L, Caratti P. Comparing region-specific sustainability assessments through indicator systems: Feasible or not? Ecol Econ 2011;70:475–86. doi:10.1016/j.ecolecon.2010.09.025.

[22] Wallis AM, Graymore MLM, Richards AJ. Significance of environment in the assessment of sustainable development: The case for south west Victoria. Ecol Econ 2011;70:595–605. doi:10.1016/j.ecolecon.2010.11.010.

[23] OECD, JRC-European Commission. Handbook on Constructing Composite Indicators: Methodology and User Guide. vol. 3. OECD Publishing; 2008.

[24] Jain D, Tiwari G. Sustainable mobility indicators for Indian cities: Selection methodology and application. Ecol Indic 2017;79:310–22. doi:10.1016/j.ecolind.2017.03.059.

[25] UN DESA. Indicators of Sustainable Development: Guidelines and Methodologies. 3rd

Edition. New York: 2007.
[26] Iddrisu I, Bhattacharyya SC. Sustainable Energy Development Index: A multi-dimensional indicator for measuring sustainable energy development. Renew Sustain Energy Rev 2015;50:513–30. doi:10.1016/j.rser.2015.05.032.
[27] Stanners D, Dom A, Gee D, Martin J, Ribeiro T, Rickard L, et al. Frameworks for policy integration indicators, for sustainable development, and for evaluating complex scientific evidence. Sustain. Indic. A Sci. Assess., Island Press; 2007, p. 145–62.
[28] International Atomic Energy Agency. Indicators for Sustainable Energy Development. New York: 2001.
[29] United Nations Department of Economic and Social Affairs. Indicators of sustainable development: framework and methodologies. New York: 2001.
[30] Hjorth P, Bagheri A. Navigating towards sustainable development: A system dynamics approach. Futures 2006;38:74–92. doi:10.1016/j.futures.2005.04.005.
[31] Nerini FF, Tomei J, To LS, Bisaga I, Parikh P, Black M, et al. Mapping synergies and trade-offs between energy and the Sustainable Development Goals. Nat Energy 2018;3:10–5. doi:10.1038/s41560-017-0036-5.
[32] Kettner C, Kletzan-Slamanig D, Köppl A. Indicators for Sustainable Energy Development for Austria (ISED-AT). Residential Buildings and Electricity and Heat Supply. 2015.
[33] Keirstead J. Selecting sustainability indicators for urban energy systems. Int. Conf. Whole Life Urban Sustain. its Assessmen, Glasgow: 2007.
[34] Grant MJ, Booth A, Centre S. A typology of reviews : an analysis of 14 review types and associated methodologies 2009:91–108. doi:10.1111/j.1471-1842.2009.00848.x.
[35] Booth A, Sutton A, Papaioannou D. Systematic Approaches to A Successful Literature Review. 2nd editio. London: SAGE Publications Inc.; 2016.
[36] Malinauskaite L, Cook D, Davíðsdóttir B, Ögmundardóttir H, Roman J. Ecosystem services in the Arctic : a thematic review. Ecosyst Serv 2019;36:1–14. doi:10.1016/j.ecoser.2019.100898.
[37] Wang JJ, Jing YY, Zhang CF, Zhao JH. Review on multi-criteria decision analysis aid in sustainable energy decision-making. Renew Sustain Energy Rev 2009;13:2263–78. doi:10.1016/j.rser.2009.06.021.
[38] Cook D, Saviolidis NM, Davíðsdóttir B, Jóhannsdóttir L, Ólafsson S. Measuring countries' environmental sustainability performance—The development of a nation-specific indicator set. Ecol Indic 2017;74:463–78. doi:10.1016/j.ecolind.2016.12.009.
[39] SDSN. Indicators and a Monitoring Framework for Sustainable Development Goals: Launching a data revolution for the SDGs. 2014.
[40] Brown D. Good Practice Guidelines for Indicator Development and Reporting. Stat. Knowl. Policy, Charting Progress, Build. Visions, Improv. Life, Busan: 2009.
[41] Pintér L, Hardi P, Martinuzzi A, Hall J. Bellagio STAMP: Principles for sustainability assessment and measurement. Ecol Indic 2012;17:20–8. doi:10.1016/j.ecolind.2011.07.001.
[42] Bakkes J. Bellagio SusTainability Assessment and Measurement Principles (BellagioSTAMP) – Significance and Examples from International Environmental Outlooks. In: Elgar E, editor. Sustain. Dev. Eval. Policy-Making, Cheltenham: 2012, p. 241–60. doi:10.4337/9781781953525.00023.
[43] Schirnding Y von. Construction of Indicators. Heal. Sustain. Dev. Plan. Role Indic., Geneva: World Health Organization; 2002, p. 47–68.
[44] Shortall R, Davíðsdóttir B, Axelsson G. Development of a sustainability assessment framework for geothermal energy projects. Energy Sustain Dev 2015;27:28–45. doi:10.1016/j.esd.2015.02.004.
[45] Mainali B, Pachauri S, Rao ND, Silveira S. Assessing rural energy sustainability in developing countries. Energy Sustain Dev 2014;19:15–28. doi:10.1016/j.esd.2014.01.008.
[46] Martchamadol J, Kumar S. An aggregated energy security performance indicator. Appl Energy 2013;103:653–70. doi:10.1016/j.apenergy.2012.10.027.
[47] Vera IA, Langlois LM, Rogner HH, Jalal AI, Toth FL. Indicators for sustainable energy development: An initiative by the International Atomic Energy Agency. Nat Resour Forum 2005;29:274–83. doi:10.1111/j.1477-8947.2005.00140.x.
[48] Ernst & Young. EY - Renewable Energy Country Attractiveness Index - RECAI Methodology

n.d. https://www.ey.com/uk/en/industries/power---utilities/ey-renewable-energy-country-attractiveness-index-methodology (accessed April 3, 2019).
[49] World Economic Forum. The Global Energy Architecture Performance Index 2017: Methodological addendum. 2017.
[50] World Energy Council, Oliver Wyman. World Energy Trilemma Index 2018. 2018. doi:10.1089/jpm.2004.7.865.
[51] Streimikiene D, Ciegis R, Grundey D. Energy indicators for sustainable development in Baltic States. Renew Sustain Energy Rev 2007;11:877–93. doi:10.1016/j.rser.2005.06.004.
[52] Nussbaumer P, Bazilian M, Modi V, Yumkella KK. Measuring energy poverty: Focusing on what matters. Renew Sustain Energy Rev 2012;16:231–43. doi:10.1016/j.rser.2011.07.150.
[53] Pop-Jordanov J, Markovska N, Pop-Jordanova N, Simoska SM. Occupational Entropy and Mind Indicators for Sustainable Energy Development. Int J Green Energy 2004;1:327–35. doi:10.1081/IJGE-200033616.
[54] Doukas H, Papadopoulou A, Savvakis N, Tsoutsos T, Psarras J. Assessing energy sustainability of rural communities using Principal Component Analysis. Renew Sustain Energy Rev 2012;16:1949–57. doi:10.1016/j.rser.2012.01.018.
[55] Neves AR, Leal V. Energy sustainability indicators for local energy planning: Review of current practices and derivation of a new framework. Renew Sustain Energy Rev 2010;14:2723–35. doi:10.1016/j.rser.2010.07.067.
[56] Helio International. Sustainable Energy Watch (SEW) - Indicator Selection and Rationale. 2000.
[57] Sovacool BK, Mukherjee I, Drupady IM, D'Agostino AL. Evaluating energy security performance from 1990 to 2010 for eighteen countries. Energy 2011;36:5846–53. doi:10.1016/j.energy.2011.08.040.
[58] World Economic Forum. Global Energy Architecture Performance Index Report 2017. Cologny/Geneva: 2017.
[59] Marquez-Ballesteros MJ, Mora-López L, Lloret-Gallego P, Sumper A, Sidrach-de-Cardona M. Measuring urban energy sustainability and its application to two Spanish cities: Malaga and Barcelona. Sustain Cities Soc 2019;45:335–47. doi:10.1016/j.scs.2018.10.044.
[60] Mortimer ND, Grant JF. Evaluating the prospects for sustainable energy development in a sample of Chinese villages. J Environ Manage 2008;87:276–86. doi:10.1016/j.jenvman.2006.10.027.
[61] Asia Pacific Energy Research Centre. A Quest for Energy Security in The 21st Century - Resources and Constraints. Tokyo: 2007.
[62] Jansen JC, Arkel WG Van, Boots MG. Designing indicators of long-term energy supply security. 2004.
[63] Narula K, Reddy BS. A SES (sustainable energy security) index for developing countries. Energy 2016;94:326–43. doi:10.1016/j.energy.2015.10.106.
[64] Jónsson JÖG, Davíðsdóttir B, Jónsdóttir EM, Kristinsdóttir SM, Ragnarsdóttir KV. Soil indicators for sustainable development: A transdisciplinary approach for indicator development using expert stakeholders. Agric Ecosyst Environ 2016;232:179–89. doi:10.1016/j.agee.2016.08.009.
[65] Molle F, Mollinga P. Water policy indicators: conceptual problems and policy issues. Water Policy 2003;5:529–44.
[66] Taylor PG, Abdalla K, Quadrelli R, Vera I. Better energy indicators for sustainable development. Nat Energy 2017;2. doi:10.1038/nenergy.2017.117.
[67] Papadaki M, Siskos I, Andonidakis E, Tsoutsos T, Stavrakakis G. Assessing different scenarios for sustainable energy supply in the island of Crete. Renew. Energies Islands - Towar. 100% RES Supply, Chania, Crete, Greece: OPET island; 2001.
[68] García-Álvarez MT, Moreno B, Soares I. Analyzing the sustainable energy development in the EU-15 by an aggregated synthetic index. Ecol Indic 2016;60:996–1007. doi:10.1016/j.ecolind.2015.07.006.
[69] Latin American Energy Organization, Economic Commission for Latin America and the Caribbean, Deutsche Gesellschaft fur Zusammenarbeit. Energy and sustainable development in Latin America and the Caribbean: Approaches to energy policy. Quito: 1997.

[70] Latin American Energy Organization, Economic Commission for Latin America and the Caribbean, Deutsche Gesellschaft fur Technische Zusammenarbeit. Energy and Sustainable Development in Latin America and the Caribbean: Guide for Energy Policymaking. 2000.
[71] Sheinbaum-Pardo C, Ruiz-Mendoza BJ, Rodríguez-Padilla V. Mexican energy policy and sustainability indicators. Energy Policy 2012;46:278–83. doi:10.1016/j.enpol.2012.03.060.
[72] Spalding-Fecher R. Indicators of sustainability for the energy sector: a South African case study. Energy Sustain Dev 2003;7:35–49. doi:10.1016/S0973-0826(08)60347-6.
[73] Hossain I, Tamim M. Energy and Sustainable Development in Bangladesh. Bangladesh: 2006.
[74] Rezaei M, Chaharsooghi SK, Abbaszadeh P. The Role of Renewable Energies in Sustainable Development : Case Study Iran. Iran J Energy Environ 2013;4:320–9. doi:10.5829/idosi.ijee.2013.04.04.
[75] World Bank Group, Sustainable Energy for All. RISE Readiness for Investment in Sustainable Energy - A tool for policymakers. Washington DC: 2014.
[76] World Bank Group, ESMAP, Climate Investment Fun, Sustainable Energy for all. Regulatory Indicators for Sustainable Energy. A Global Scorecard for Policy Makers - Executive summary. Washington DC: 2016.
[77] ESMAP, The World Bank Group. Regulatory Indicators for Sustainable Energy. ESMAP Report. Policy matters. Washington, DC: 2018.
[78] Hannan MA, Begum RA, Abdolrasol MG, Lipu MSH, Mohamed A, Rashid MM. Review of baseline studies on energy policies and indicators in Malaysia for future sustainable energy development. Renew Sustain Energy Rev 2018;94:551–64. doi:10.1016/j.rser.2018.06.041.
[79] World Energy Council. World Energy and Climate Policy: 2009 Assessment. London: 2009.
[80] World Energy Council. Pursuing sustainability: 2010 Assessment of country energy and climate policy. 2010.
[81] International Energy Agency, OECD/IEA. World Energy Outlook 2010. Paris, France: 2010.
[82] Mandelli S, Barbieri J, Mattarolo L, Colombo E. Sustainable energy in Africa: A comprehensive data and policies review. Renew Sustain Energy Rev 2014;37:656–86. doi:10.1016/j.rser.2014.05.069.
[83] Yu Y, Zhao D, Chen Y. Construction of regional sustainable energy development evaluation indicator system. Proc - 2010 Int Conf Digit Manuf Autom ICDMA 2010 2010;1:437–40. doi:10.1109/ICDMA.2010.304.
[84] Neves AR, Leal V. An exploratory study on energy sustainability indicators for local energy planning. Sustain Dev Plan 2009;IV:611–22. doi:10.2495/SDP090572.
[85] Zen AC, Lima A, Bianchi AL, Babot L. Sustainability , Energy and Development: A Proposal of Indicators. Int J Infonomics 2012;5:537–41.
[86] Schaeffer R, Szklo A, Cima F, Machado G. Indicators for sustainable energy development: Brazil’s case study. Nat Resour Forum 2005;29:284–97.
[87] Pérez D, López I, Berdellans I. Evaluation of energy policy in Cuba using ISED. Nat Resour Forum 2005;29:298–307. doi:10.1111/j.1477-8947.2005.00142.x.
[88] Aslanyan G, Molodtsov S, Iakobtchouk V. Monitoring the sustainability of Russia’s energy development. Nat Resour Forum 2005;29:334–42. doi:10.1111/j.1477-8947.2005.00145.x.
[89] Streimikiene D. Indicators for sustainable energy development in Lithuania. Nat Resour Forum 2005;29:322–33. doi:10.1111/j.1477-8947.2005.00140.x.
[90] Todoc JL, Todoc MJ, Lefevre T. Indicators for sustainable energy development in Thailand. Nat Resour Forum 2005;29:343–59. doi:10.1111/j.1477-8947.2005.00140.x.
[91] Vera I a, Abdalla KL. Energy Indicators to Assess Sustainable Development at the National Level: Acting on the Johannesburg Plan of Implementation. Energy Stud Rev 2006;14:154–69.
[92] Pereira Jr. AO, Soares JB, Oliveira RG De, Queiroz RP De. Energy in Brazil: Toward sustainable development? Energy Policy 2008;36:73–83. doi:10.1016/j.enpol.2007.08.022.
[93] Shoram B, Hirunlabh J. Critical analysis of Thailand’s past energy policies towards the development of a new energy policy. Energy Effic 2018:713–32.
[94] Štreimikienė D. Framework of indicators for monitoring implementation of interrelated targets of the EU Sustainable Development Strategy. Ekologija 2007;53:34–40.
[95] Streimikiene D, Šivickas G. The EU sustainable energy policy indicators framework. Environ Int 2008;34:1227–40. doi:10.1016/j.envint.2008.04.008.

[96] Štreimikiene D. Impact of Environmental Taxes on Sustainable Energy Development in Baltic States, Czech Republic and Slovakia. Econ Manag 2015. doi:10.15240/tul/001/2015-4-001.
[97] Siksnelyte I, Kazimieras E, Bausys R, Streimikiene D. Implementation of EU energy policy priorities in the Baltic Sea Region countries: Sustainability assessment based on neutrosophic MULTIMOORA method. Energy Policy 2019:90–102.
[98] Zhou P, Ang BW, Poh KL. A mathematical programming approach to constructing composite indicators. Ecol Econ 2007;2:0–6. doi:10.1016/j.ecolecon.2006.12.020.
[99] Wang H. A generalized MCDA-DEA (multi-criterion decision analysis-data envelopment analysis) approach to construct slacks-based composite indicator. Energy 2015;80:114–22. doi:10.1016/j.energy.2014.11.051.
[100] Wang H, Zhou P, Wang Q. Constructing slacks-based composite indicator of sustainable energy development for China: A meta-frontier nonparametric approach. Energy 2016;101:218–28. doi:10.1016/j.energy.2016.02.039.
[101] Kettner C, Kletzan-Slamanig D, Köppl A, Köberl K. PASHMINA – Paradigm Shifts Modelling and Innovative Approaches Development. Indicators for Sustainable Energy Development - The PASHMINA Approach. 2012.
[102] Zolfani SH, Saparauskas J. New Application of SWARA Method in Prioritizing Sustainability Assessment Indicators of Energy System. Eng Econ 2013;24:408–14.
[103] Scheepers M, Seebregts A, de Jong J, Maters H. EU standards for Energy Security of Supply: Updates on the Crisis Capability Index and the Supply/Demand Index Quantification for EU-27. Petten: 2007.
[104] Kisel E, Hamburg A, Härm M, Leppiman A, Ots M. Concept for Energy Security Matrix. Energy Policy 2016;95:1–9. doi:10.1016/j.enpol.2016.04.034.
[105] Murakami T, Motokura M, Kutani I. An Analysis of Major Countries' Energy Security Policies and Conditions – Quantitative Assessment of Energy Security Policies –. 2011.
[106] Marín Quemada JM, Muñoz Delgado B. Affinity and rivalry: Energy relations of the EU. Int J Energy Sect Manag 2011;5:11–38. doi:10.1108/17506221111120884.
[107] Global Energy Institute, U.S. Chamber of Commerce. Index of U.S. Energy Security Risk: Addressing America's Vulnerabilities in a Global Energy Market. 2018 edition. Washington: 2018.
[108] Global Energy Institute, U.S. Chamber of Commerce. International Index of Energy Security Risk - Assessing risk in a global energy market. Washington: 2018.
[109] Le Coq C, Paltseva E. Measuring the security of external energy supply in the European Union. Energy Policy 2009;37:4474–81. doi:10.1016/j.enpol.2009.05.069.
[110] Portugal-Pereira J, Esteban M. Implications of paradigm shift in Japan ' s electricity security of supply: A multi-dimensional indicator assessment. Appl Energy 2014;123:424–34. doi:10.1016/j.apenergy.2014.01.024.
[111] Sovacool BK, Mukherjee I. Conceptualizing and measuring energy security: A synthesized approach. Energy 2011;36:5343–55. doi:10.1016/j.energy.2011.06.043.
[112] Sovacool BK. An international assessment of energy security performance. Ecol Econ 2013;88:148–58. doi:10.1016/j.ecolecon.2013.01.019.
[113] Global Network on Energy for Sustainable Development (GNESD), Asian Institute of Technology. Energy Security in Thailand. 2010.
[114] United Nations. A/RES/71/313 Resolution adopted by the General Assembly on Work of the Statistical Commission pertaining to the 2030 Agenda for Sustainable Development 2017:1–13. doi:10.1109/TNSRE.2015.2480755.
[115] United Nations Department of Economic and Social Affairs - Statistics Division. Metadata for SDG 7: Ensure access to affordable, reliable, sustainable and modern energy for all. 2016.
[116] Štreimikienė D, Mikalauskienė A, Mikalauskas I. Comparative Assessment of Sustainable Energy Development in the Czech Republic, Lithuania and Slovakia. J Compet 2016;8:31–41. doi:10.7441/joc.2016.02.03.
[117] Tsai WT. Energy sustainability from analysis of sustainable development indicators: A case study in Taiwan. Renew Sustain Energy Rev 2010;14:2131–8. doi:10.1016/j.rser.2010.03.027.
[118] The German Federal Government. Perspectives for Germany: Our Strategy for Sustainable Development. 2002.

[119] Schlör H, Fischer W, Hake JF. Methods of measuring sustainable development of the German energy sector. Appl Energy 2013;101:172–81. doi:10.1016/j.apenergy.2012.05.010.
[120] Ernst & Young. recai From black gold to green power. 2018.
[121] Cîrstea SD, Moldovan-Teselios C, Cîrstea A, Turcu AC, Darab CP, Cirstea A, et al. Evaluating Renewable Energy Sustainability by Composite Index. Sustainability 2018;10. doi:10.3390/su10030811.
[122] Lee CW, Zhong J. Construction of a responsible investment composite index for renewable energy industry. Renew Sustain Energy Rev 2015;51:288–303. doi:10.1016/j.rser.2015.05.071.
[123] Nicolas J, Pochet P, Poimboeuf H. Towards sustainable mobility indicators: application to the Lyons conurbation. Transp Policy 2003;10:197–208. doi:10.1016/S0967-070X(03)00021-0.