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APPLICATION OF MULTI-CRITERIA DECISION-MAKING APPROACH FOR SUSTAINABILITY ASSESSMENT OF CHOSEN PHOTOVOLTAIC MODULES

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Abstract

A concern about the current state of relations between industry and the environment is often neglected. However, it is important to underline that industry and sustainability are not mutually exclusive. There are many industrial processes to blame when analyzing the negative impact on current socio-ecological environment. The emerging question is whether companies nowadays are ready to face challenges in the name of sustainability, the future of the planet and generations to come. In addition, an assessment of industrial processes may be very time-consuming and costly in financial terms. This fact allows developing sustainability assessment approach and its measures for keeping track on to evaluate scale of environmental, social and economic changes. The goal of the paper is to develop a multi-criteria decision-making approach for sustainability assessment of renewable energy technology. A sustainability assessment approach combines life cycle-based methods integrated with multi-criteria decision-making method based on analytical hierarchy process. The resulting assessment method allows finding a compromise between industry and the environment and identify potential intervention points for further research. As a result of decision-making process, string ribbon technology was considered as the most sustainable. The applicability of the proposed method is assessed based on photovoltaic panels.

Keywords

AHP, life cycle sustainability assessment, multicriteria decision-making, photovoltaic modules.

Introduction

Growing interest in sustainability assessment is ongoing topic discussed by stakeholders, including policy-makers, businesses etc. Many efforts also were achieved in manufacturing sector through dynamic changes in terms of technology, and its sustainability-oriented assessment methods [1]. As a result of these changes measurement methods and indicators are developed that assess sustainability meeting "three-pillar" or "triple bottom line" (TBL) concepts. They are characterized by important objectives that consider all aspects of the natural environment, human health, and economic factors [2]. Unfortunately, manufacturing sector is responsible for resource depletion (e.g. energy) and degradation of the natural environment having the negative impact on biodiversity and human health [3]. Improving the company performance requires effective ways of measurement of resource use in manufacturing processes and new methods for assessing these industrial activities in terms of sustainability [4]. Industrial companies have to face challenges and make progress in sustainability assessment methods to make conscious decisions. The available assessment methods for sustainability do not take into consideration all dimensions of sustainability as a whole [5], some of them are not constructed on life cycle approach or are built on combined methods (e.g. multicriteria) for decision-making regarding the sustainability assessment of manufacturing, process, systems.

From the other hand, the importance of the various indicators used to assess sustainability of processes or technology may help decision-makers defining sustainability objectives (e.g. decrease in energy use), assessing and selecting appropriate technology achieving those objectives [6].

Despite many research was done and valuable achievements in the development of sustainability assessments and associated indicators, none of them focused on an integrative relation between sustainability, industry, and assessment based on life cycle. In addition, an inherent difficulty and complexity in measuring sustainability force to assess technology using methods separately or least some of the dimensions of sustainability (e.g. environmental and social). Hence, there is a need to continue research to develop a new method for integrated sustainability assessment of energy renewable technology. The proposed method requires to place elements into a single approach for sustainability assessment. It will integrate various methods which could be considered the field of the photovoltaic for making remarkable decision in the industrial practice.

In this paper, the authors depict a sequence of assessment stages with chosen photovoltaic of how sustainability assessment can be made for making unbiased multi-criteria decisions. These decisions are made using various indicators of different functional units.

Sustainability assessment – state of the art

The sustainability assessment is an interest field from policy-makers to help making decision related to manufacturing processes or technologies, systems based on their assessment. Some of the definitions of sustainability with categorization of sustainability assessment approaches are presented in [7]. Methods that are presently accessible for evaluating production sustainability consider economic and environmental boundaries through a separate unified concept or integrated approach. Many methods based on MCDA like analytical hierarchy process (AHP) were applied in the most research where an inclusion of the sustainability pillars and associated indicators were achieved [8, 9]. The literature review on sustainable assessment methods shows that life cycle assessment – LCA (representing environmental performance), life cycle costing – LCC (representing economic one) and social life cycle assessment – SLCA (representing social one), being sustainability tool, are treated individually or integrated with each other to establish the overall life cycle sustainability assessment (LCSA).

As stated in many researches, "LCSA still requires improvement through the enhancement of life cycle methods or by support drawn from multi-criteria decision tools (MCDA) [10–12]. The difficulties, which occur in the integration of existing life cycle methods, are elevating the problems over the opportunity to comply with the requirements of sustainability [13]. A complexity of methods makes inherent difficulty in measuring sustainability. Many opportunities for extending current life cycle-based methods in terms of sustainability assessment exist with technologies, particularly through the use of other methods, especially AHP to cover environmental, economic and social aspects allowing a holistic sustainability approach. Then, the above-mentioned sustainability methods (AHP, life cycle-based approaches) are directly connected to decision-making processes that supports selection of the most sustainable types of renewable energy technology. Such decision will enable to achieve a trade-off among various criteria, as well as rank them on a basis of their importance.

The AHP allows making decision by comparing numerous criteria with each other.

As the presence of evaluation methods for sustainability in manufacturing does not deliver a trade-off between industrial practices and the environment. First of all, their ongoing and undertaken activities require rather complex and comprehensive decision-making processes. Secondly, these industrial plants should focus on incorporating sustainability in their long-term strategies. Moreover, beside many disadvantages of assessment methods, advantages exceed these shortcomings. Therefore, it is needed to develop a new consistent method based on life cycle analysis, sustainability concept, multi-criteria approach for making responsible decisions to select sustainability-oriented technology.

Proposed assessment framework

The paper demonstrates the application of a methodological sustainability assessment framework based on multi-criteria decision-making approach. The proposed sustainability assessment framework should be developed according to a comprehensive structured sequence of activities (Fig. 1). This developed methodological framework includes methods based on life cycle approach (LCA, LCC, LCSA) and AHP to support decision-making process taking various criteria into account.

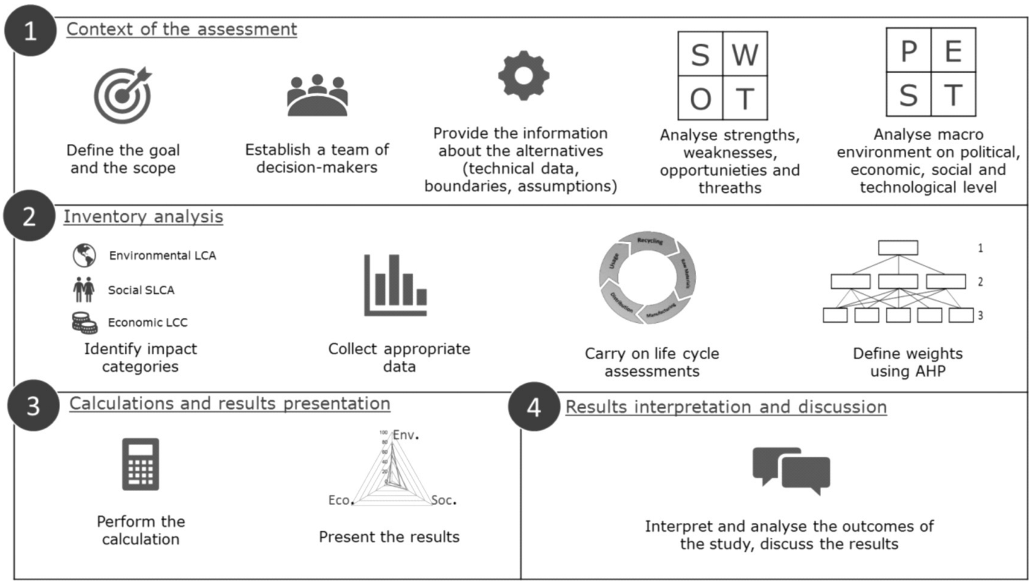

Fig. 1. Multi-criteria decision-making framework for the life cycle-based sustainability assessment.

The procedure for the proposed sustainability assessment is consisted of four phases, all of them are based on ISO 14040 standards as illustrated as follows [14]:

1) develop a context of the assessment,
2) analyse data inventory,
3) estimate and present results,
4) interprete results & discussion.

Phase 1. Develop a context of the assessment. In this phase information about actors, a justification of the assessment is provided. In other words, this phase is initiated with a few entry statements that would justify usage of the following framework. In this part, a specific goal and the scope is also identified. What that implies, is mainly recognition of a need for given product or process and building a proper argumentation for it. When it comes to the scope, the products' overall description should be provided, as well as the functionalities of a system. The essential issue is to choose appropriate stakeholders that will become decision-makers during the evaluation. Their role and status should be compatible with defined goal of the assessment within the considered company. The stakeholders' opinions and preferences will strongly influence the final product selection making unbiased assessment. The number of experts depends on complexity of the study and the size of the company.

Within this phase, the description of the system under assessment and its characteristic needs to be established. In addition, assumptions and limitations of system boundaries as well as functional units representing the performance of the system should be provided.

Then, SWOT and PEST analysis are carried out to validate an applicability of the proposed framework in the given context. By analyzing the conditioning from the perspective of the company (SWOT) and its environment (PEST) an applicability of the assessment methodology in terms of environmental, social, and economic perspectives can be examined. With accordance to the proposed methodology, PEST analysis will be focused on external forces with regard to the sustainability. It also allows to understand threats and opportunities on the macro level. Both methods provide a condensed summary about the project's environment by highlighting the set of the most crucial information.

At this stage of the assessment framework, the list of alternatives to be compared is provided. It should cover a description of specific types of products and the differences between them. At the same time, limitations are defined as constraints to be considered in this framework. Therefore, it also requires underlining that assumptions regarding the system that are strictly connected to the prior recognized limitations.

SWOT and PEST analysis

Strengths associated with conducting analysis described in this framework are mainly connected to the presence of the data of interest. It should be underlined that there are many sources available that focus on the environmental and economic areas of photovoltaic modules, as well when it comes to life cycle assessment.

On the contrary, its weakness lays in the absence of such data linked to the social area. When it comes to environmental and economic fields, the data is aggregated from numerous companies. Unfortunately, not every company exists in the photovoltaic market leading to some marginal error in averaged calculations aiming at assessment of PVs technologies in general. Therefore, approximation is needed to reduce a probability of these marginal errors. Moreover, the already developed studies or cases including PV modules assessment in the context of economy and environment are addressing similar sets of data, which at some cases might make it obsolete. The environmental analysis is a broad scope field to decide which of the indicators are the least relevant in terms of the study, so the overall amount of environmental oriented indicators will not outnumber the other dimensions present in the framework.

When it comes to opportunities, the visibly growing interest in the area of LCSA should be taken into account. It will most likely lead towards increased amount of data gathered globally and what it might bring along – data repositories used for academic and industrial purposes – for instance in scope of this framework. This process would be especially beneficial in the context of social dimension which is characterized by the least amount of information available – when it comes to PV modules.

Threats are mostly seen in the data being outdated and invalid which might not be verifiable at the time of its initial usage. The case of technical and scientific development is always beneficial from the general point of view, however in this study, a potentially emerging alternative might make it obsolete and irrelevant. Another threat is to be noted, is the danger resulted from the technical complexity of photovoltaics. Therefore, it might obscure the actual public opinion analysis when, for instance, answering a testing survey used for indicator calculation – for instance in case of "public acceptance" criterion. Table 1 summarizes all the aforementioned aspects.

In order to analyze macro environment of the study, PEST analysis has been conducted. Results of the analysis are summarised in Table 2. With regard to economic concerns, the aspects that may influence the study are sudden changes in energy cost or materials necessary for production of photovoltaic modules. Therefore, the economic part of sustainability assessment may become invalid.

Table 1
SWOT analysis for the sustainability assessment.

Strengths	Weaknesses
General: • implications for industrial sustainability assessment because they reflect different kinds of sustainability an industry intends to achieve. Environmental: • access to numerous LCA studies concerning PV cases; • access to tools for environmental assessment. Economic: • access to few existing papers evaluating selected PVs in terms of economic performance.	General: • differentiation of assessment boundaries; • lack of complete lifecycle stages data in LCA and SLCA; • limited access to specific data. Environmental: • approximation of the data; • exclusion of some criteria. Social: • lack of the appropriate data connected to the choice of photovoltaic module and social indicators. Economic: • approximation of data.
Opportunities	**Threats**
General: • growing interest of LCSA studies. Environmental: • free tools available for environmental impact assessment; • databases for life cycle inventory available online; • big number of research articles concerning LCA of photovoltaic. Social: • possible future research in social scope of PV thanks to already present awareness of lack of such data in academic field.	General: • possible errors in the publicly available data. Environmental: • incomplete data; • outdated data; • possible change in parameters; • possible development in the area that can make used method obsolete. Social: • unawareness of variety of PV technologies causing generalisation of public opinion that might influence social indicators. Economic: • huge variation of energy and resources costs that influence some indicators.

Table 2
PEST analysis for the given assessment.

Political
• financial support for assessments concerning sustainability; • implementation of 2030 Agenda for the Sustainable Development by 193 countries; • one of the Sustainable Development Goals addressing need for renewable energy sources; • probability of publishing similar studies by organisations supported by governments.
Social
• growing consciousness about necessity for renewable energy sources; • growing social awareness concerning potential impacts.
Economic
• changes in energy cost; • changes in costs of materials used for manufacturing of photovoltaic modules.
Technological
• possibility of new technology appearance; • significant improvement of properties of one of the analysed PV technologies.

On the other hand, if energy costs drastically increases people might start to look for alternative energy sources, including solar energy. Then, they will have look for the best solution in terms of PV technology. It could result in growing demand for evaluations as the one presented in the study.

Social part of the PEST study partially overlaps with economic concern. Recently, one could observe growing interest not only in environmental protection issues, but also, increasing consumer awareness. Society and customers in general are becoming more conscious what might be reflected in the growing interest in reports, same as in economic case, including products' impact analysis.

When it comes to technology aspects, there is possibility that some of the properties regarding one of the PV technologies will be significantly improved or even that will appear new solar alternative. Therefore, the recommendations resulting from the study might become less accurate or completely invalid.

Phase 2. Analyse data inventory. In the most complex stage, data collection as well as LCA-based methods in terms of the sustainability dimensions are described and depicted in Fig. 2. Each sustainability dimension is presented by using standalone methods – life cycle assessment (LCA), life cycle costing (LCC), and social life cycle assessment (SLCA) respectively. Within these methods, their associated indicators which stay in line with the predefined sustainability dimensions are identified. Once the data are collected from primary or secondary sources, criteria for sustainability can be selected. Primary data regarding company's production performance in environmental, societal, and economic context are measured directly by the organisation conducting the study. The secondary data might be gathered from companies' stakeholders, e.g. suppliers. Additional sources of information may derive from industry interviews, scientific literature, specific databases or by using statistics.

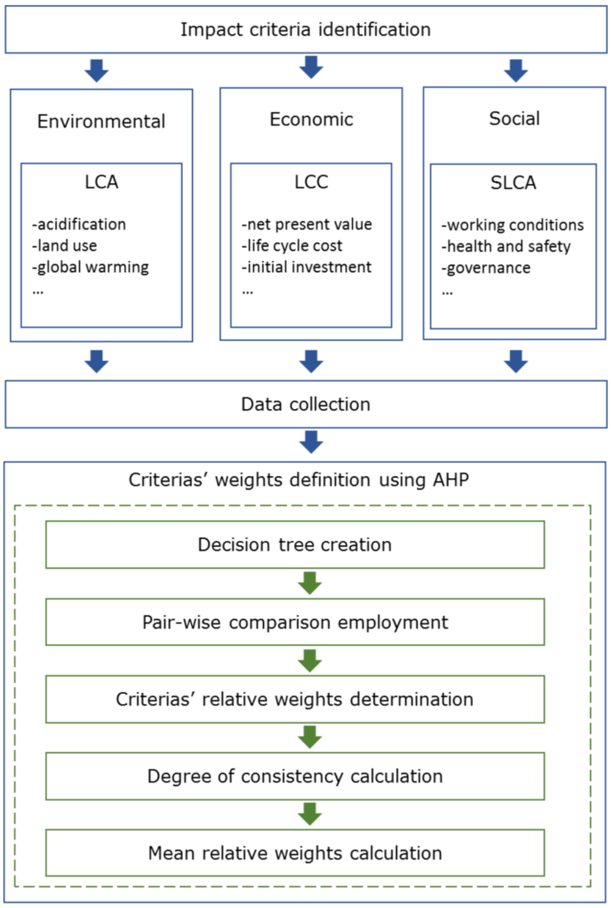

Fig. 2. Inventory analysis of the sustainability assessment based on [15].

LCC methodology does not provide a set of categories or specific criteria for costs evaluation, e.g.

initial investment or electricity price. The evaluation costs might entail pre-production, production and post-production costs. Moreover, LCC's criteria that describe the added value may include net present value or return on investment. A variety of environmental criteria and subcriteria that can be developed based on existing well-described life cycle assessment (LCA) like ReCiPe, TRACI was proposed in [16, 17].

For social related methodology, the most commonly used criteria are these criteria which are recommended by UNEP/SETAC guidelines [18]. They differentiate various stakeholders (such as workers, local communities, societies, consumers etc.) and assign different criteria (such as human rights, health and safety, working conditions etc.) to them. A literature on this topic contains wide variety of indicators that can be applied in LCSA [19].

Decision-makers assigned to the study can select criteria on the basis of organisation's circumstances and their preferences. They can be addressed to single workers as well as to whole society on which organisation has the impact. It makes that general sustainability assessment is becoming to be a complex task to evaluate it. This process is even more complicated when one wants to present data for each criterion with distinguishing products' life cycles and including preferences of each of the decision-makers. In order to ease the evaluation of the complex life cycle studies, while respecting the opinions and expertise of people involved, the application of analytical hierarchy process (AHP) is recommended. With a use of this tool, prioritization of criteria becomes possible and rather straightforward, by determining weight for each of the previously defined criterion.

When using AHP method, a hierarchy tree should be created. With regard to the AHP theory, the main goal should be associated with sustainability (i.e. most sustainable product) – this derives from the main subject of the study. On the next level of the hierarchy, objectives should be stated. These will be sustainability dimensions to examine the performance of technologies in every of these aspects. The next third level should contain selected criteria for the assessment. On the bottom level there are alternatives, that in this case will be different type of technologies.

After developing the hierarchy tree, a pairwise comparison between criteria must be conducted according to the following procedure [15]. Decision-makers should give qualitative judgments on the relative importance of criteria on both levels. The comparison matrix should be developed for every group of criteria on each hierarchy level (1). The assumption (2) tells that the matrix M is a $n \times n$ matrix, where n is the number of criteria to be considered

$$M = \begin{bmatrix} C_{1,1} & C_{1,2} & \cdots & C_{1,n} \\ C_{2,1} & C_{2,2} & \cdots & C_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ C_{n,1} & C_{n,2} & \cdots & C_{n,n} \end{bmatrix}, \tag{1}$$

$$[c_{ij}] \quad \text{where} \quad i,j = 1,2,3,...,n, \tag{2}$$

$$c_{ij} = \frac{1}{c_{ij}} \quad \text{for} \quad i \neq j, \tag{3}$$

$$c_{ij} = 1 \quad \text{for} \quad i = j. \tag{4}$$

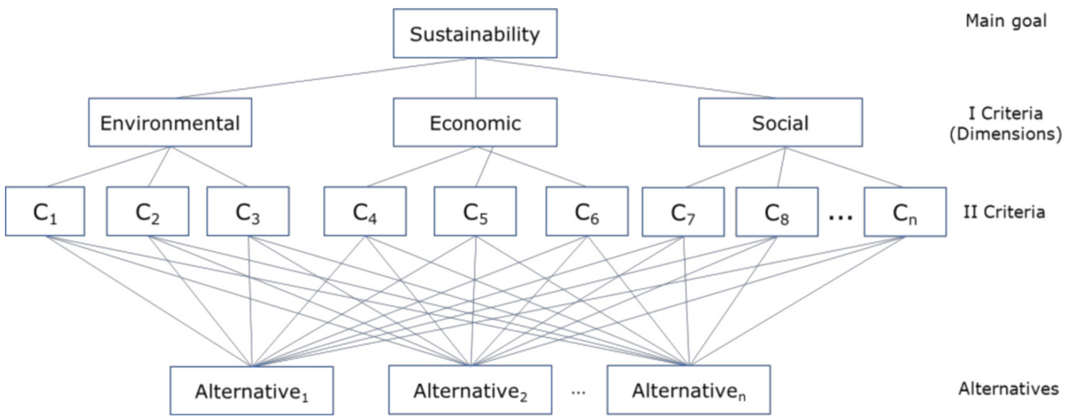

Fig. 3. AHP hierarchy tree.

The matrix is filled with values that represent prioritization between each pair of criteria. The prioritization can be determined by using the Saaty's scale covering numbers from 1 to 9 [20]. Each element c_{ij} of the matrix M is equal to intensity of importance of the ith criterion relative to j-th criterion. It is important to note that reciprocal relationships between criteria are also possible (3). If $c_{ij} > 1$, that means the i-th criterion is more important than the j-th criterion, in the contrary if $c_{ij} < 1$, then the i-th criterion is less important than the j-th criterion. The last characteristic is based on the identity principle (4). When comparing two equal elements, there is no preference to be noted.

For relative weights determination, the eigenvector is calculated. The M matrix is normalised and converted into pairwise comparison matrix $M_{\text{norm}} = [b_{ij}]_{n\times n}$. The elements of this matrix are determined according to the equation:

$$b_{ij} = \frac{c_{ij}}{\sum\limits_{k=1}^{n} c_{kj}}. \tag{5}$$

Finally, preferences between criteria are calculated by averaging the entries from each row of the normalised comparison matrix M_{norm}. As the result of performing the formula (6) the eigenvector (that is an n-dimensional column vector) is obtained

$$w_i = \frac{\sum\limits_{j=1}^{n} b_{ij}}{n}. \tag{6}$$

In the next step, the consistency of decision-makers' evaluations, that build the pairwise comparison matrix, needs to be calculated and checked. For that, one can use a metrics called the consistency index. It is evaluated with the formula (9)

$$s_i = \sum_{i=1}^{n} c_{ij}, \tag{7}$$

$$\lambda_{\max} = \sum_{i=1}^{n} s_i w_i, \tag{8}$$

$$\text{CI} = \frac{\lambda_{\max} - n}{n-1}. \tag{9}$$

As one can see, to establish the value of CI, firstly the needs to be defined by obtaining a sum of each column in pairwise comparison matrix M (7) and multiplying resulting vector by the weight vector in (8). Afterwards, it is being used to calculate the CI values as presented by Eq. (9).

For the decision to be consistent CI should always be equal to zero. However, minor inconstancy can be allowed as well. The maximum value that the CI might get is determined by the constant Random Index (RI) [24]. The ratio between CI and RI should be smaller than 0.1 (10%)

$$\frac{\text{CI}}{\text{RI}} < 0.1. \tag{10}$$

When relative weights of criteria and consistency of the evaluations made by each decision-maker are evaluated, the mean relative weights (W) should be calculated. It can be done by averaging the relative weights, calculated by each of the decision-makers, for every criterion. Relative mean of weights for i-th criterion can be obtained by calculating the following equation:

$$W_i = \frac{\sum\limits_{j=1}^{m} w_{ij}}{n}, \tag{11}$$

where m – number of decision-makers.

Phase 3. Estimate and present results. This step of the methodology accounts for the calculation procedure for impact assessment of technology. In this phase, all the data necessary for the evaluation needs to be normalised and analysed with regards to weights developed in the previous step. Furthermore, an output of the calculation should be presented. The process that is being carried out within the fourth step is shown in Fig. 4.

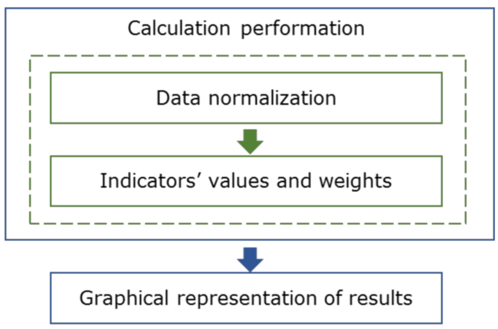

Fig. 4. Step 4 – calculations and impact assessment.

Once all the data, addressing impact on each sustainability dimension, is provided, it is mandatory to conform it in a way that will allow further comparisons. The data concerning different criteria has surely various units and scales. Therefore, it is important to convert all the present values into dimensionless and unitary equivalents. It can be achieved by normalisation, represented by Eqs (12) and (13). Formula (12), called a "benefit function" is used if the importance of an alternative increases with an increase of specific criterion value, i.e. number of workplaces created by an organisation. In the contrary the Eq. (13), also known under the term "cost function"

[15], is dedicated for a case of alternatives in which the importance decreases with an increase of criterion value, i.e. amount of produced greenhouse gases

$$z_i = \frac{x_i}{\sqrt{\sum_{i=1}^{N} x_i^2}}, \tag{12}$$

$$z_i = 1 - \frac{x_i}{\sqrt{\sum_{i=1}^{N} x_i^2}}, \tag{13}$$

where x_i – collected data, z_i – normalised data.

At this point weights of the criteria and normalised data should be provided. Then, a final score for each criterion, as well as the level of achieving the sustainability goals is calculated. The normalised values of each criterion must be multiplied by the corresponding weight value (level II weights), achieving a criterion score. The final result for each of the selected alternatives consists of sum of partial results for every sustainability dimension multiplied by its relative weights (level I weights).

To better understand the assessment results, the graphical representation of the outcomes should be presented using a radar chart enabling to compare alternatives.

Phase 4. Interpret results & discussion. Results are investigated with accordance to the stated goal of the study. Moreover, in this section, the discussion about the assessment and its ‘outcomes are provided. This crucial step summarises the knowledge gathered during the whole application phase of the framework.

Methodology use

This section provides multi-criteria decision making LCA-oriented approach for sustainability assessment of different photovoltaic modules technologies, called Energy Technology Life Cycle Sustainability Assessment (LCSA). The undertaken evaluation uses the proposed methodology to select the most sustainable solar technology.

The goal of the sustainability assessment is to check which type of selected solar technologies is characterized by the highest level of complying to the environmental, social and economic issues.

This study is not being based on the singular data from specific companies, but on averaged data. Due to the fact that the performance of photovoltaics may vary, the assessment may be not representative within the context of technology evaluation. Therefore, the assessment is being conducted upon aggregated data that is available in various reports, research papers and publicly accessible academic datasets.

The study focuses on the crystalline silicon solar cells, that can be distinguished between two types of crystalline – polycrystalline (multi-Si) and monocrystalline (mono-Si). The evaluation considers also string ribbon (Ribbon-Si) solar panels belonging to the polycrystalline silicon family [21].

The data used for life cycle assessment comes from the EcoInvent database available online. These data are used as an input for impact assessment calculations conducted by the WebService-Energy to measure environmental performance of PV systems. It provides the impact assessment for photovoltaic systems which are small-scale plants of 3 kWp capacity. These concerns PV modules which are laminated, integrated and installed on roof with 30 year-operation system lifetime. For the sake of the assessment, it was assumed that the analysed modules are located in Poland. Figure 5 depicts all process stages within selected PV lifecycle that are included in the examined LCSA. Boundaries for each of the LCSA components differentiate what results from the limited access to the data.

Table 3 summarizes data sources enabling the assessment of selected PV modules in terms of providing general view on the market situation.

Table 3
Sources of data taken into account in the study.

Stage of assessment	Resources
Life cycle inventory	Averaged data derived from databases and interviews with 11 companies worldwide
Assessment input data	EcoInvent database
Assessment tool	WebService-Energy
Assessment method	Eco Indicator 99
Impact weights	Studies and interviews conducted among numerous scientists and experts

All these resources state for databases with averaged data based on various information gathered worldwide. This analysis is used as a relevant starting point to more complex sustainability assessment of photovoltaics.

The hierarchy characteristic of the analysed case is depicted in Fig. 6. Each sustainability dimension has its own corresponding weight of importance. These weights are further used as a multiplier for the value that is being constructed by the assessment of specific indicators. The process of calculating sustainability indicators starts in the bottom and propagates upwards creating the final result.

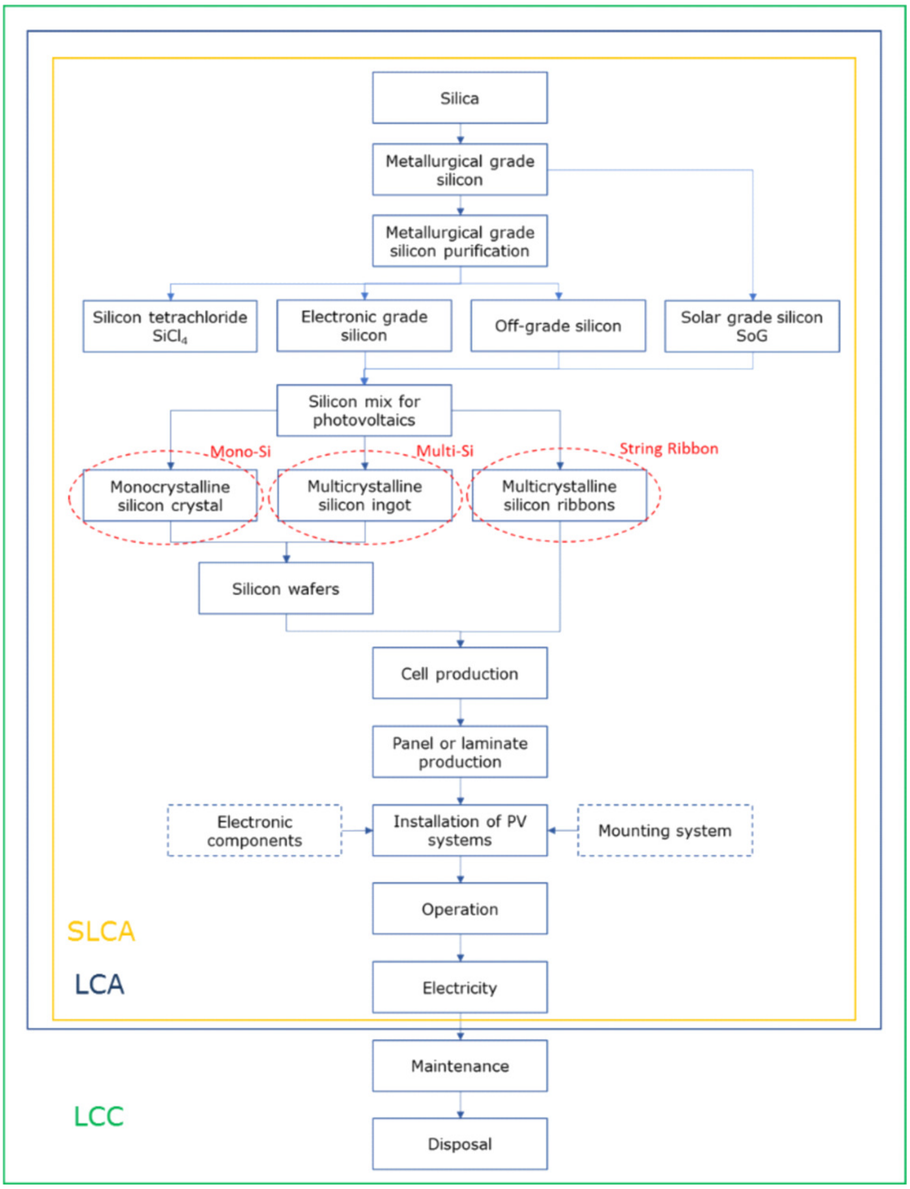

Fig. 5. Boundaries for the life cycle sustainability assessment based on [22].

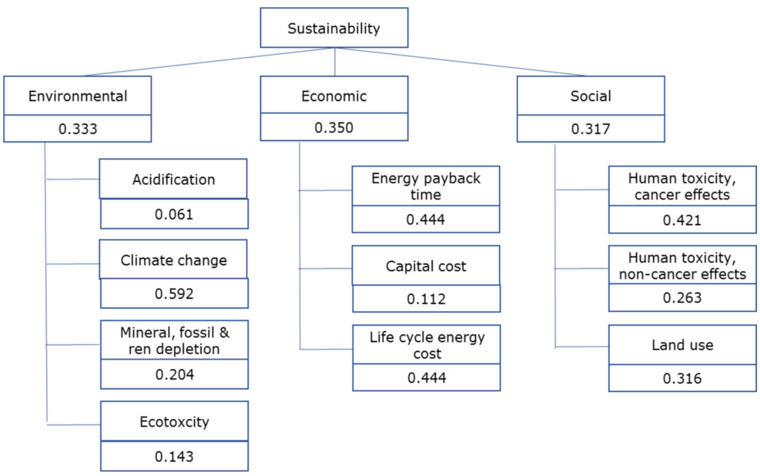

Fig. 6. Hierarchy tree of weights related to the examined case.

Priorities of the indicators are very often a crucial strategic data that companies do not want to share. To keep the current study valid, the weights of criteria have been determined based on scientific research. A research that aimed to assess solar photovoltaic technologies using hierarchical decision modelling was used to determine the weights of sustainability dimensions. For criteria included in environmental and social dimension another study was used. For environmental and social criteria, the paper has presented sets of weights that could have been applied in the midpoint impact categories that are acidification, climate change, mineral, fossil and ren depletion, ecotoxicity, human toxicity, cancer and non-cancer effects, as well as land use. The indicators' weights were determined using AHP based on judgments gathered during Stakeholders Panel, including nine producers, users and LCA experts. In the case of economic criteria, the subjective priorities were made basing on desk research.

Results

Figure 7 shows the performance of selected PV modules concerning each sustainability dimension. The results present that each of assessed PVs holds the same position for each sustainability dimension. The general outcome suggests that the best sustainable technology beats other one in every of analyzed dimensions. The same dependency applies for the worst of analyzed alternatives.

For environmental dimension, ribbon-Si amounted at 0.151, multi-Si – 0.144, while mono-Si – got 0.129.

The biggest differences in scores can be seen within the economic dimension, where ribbon-Si was 0.208, multi-Si – 0.171, and mono-Si with score of 0.090. The value of string ribbon in this case is significantly higher than for monocrystalline PV (almost twice higher). The final scores regarding the compatibility with the sustainability are presented in Table 4.

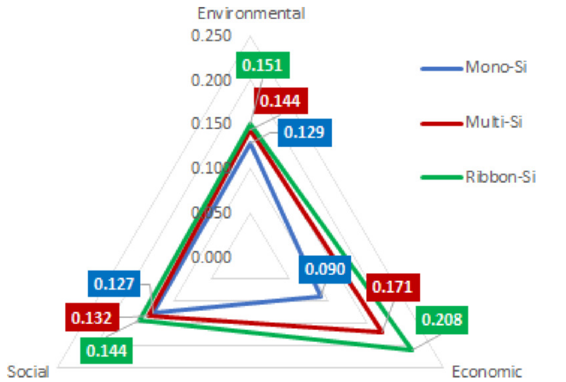

Fig. 7. The scores for the selected PV technologies concerning sustainability dimensions.

The relations between the selected modules and their sustainability scores are depicted on Fig. 8. From the selected technologies the highest result was obtained by string ribbon PV technology with a score equal to 0.503. The second-best module being in line with the study assumptions are multicrystalline silicon photovoltaics (0.447). Monocrystalline silicon PV was proven to be the least sustainable with the result of 0.346. This value is significantly lower than the results obtained by the alternative technologies.

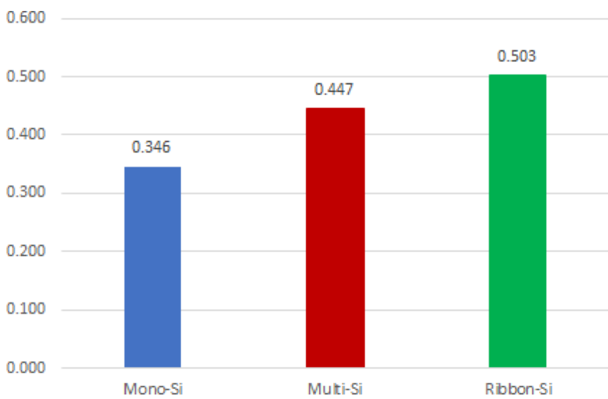

Fig. 8. Sustainability score for each of the selected PV technologies.

Table 4
Final sustainability scores for every type of PV technology.

Sustainability dimension	Total value			Weight level I	Score (normalised value × weight level I)		
	Mono-Si	Multi-Si	Ribbon-Si		Mono-Si	Multi-Si	Ribbon-Si
Environmental	0.386	0.433	0.453	0.333	0.129	0.144	0.151
Economic	0.258	0.488	0.594	0.350	0.090	0.171	0.208
Social	0.401	0.415	0.454	0.317	0.127	0.132	0.144
				$\sum$	0.346	0.447	0.503

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Conclusions and discussion

The presented methodology is considered as a method for assessing sustainability of energy technology or systems based on multi-criteria decision making. The assessment framework and indicators were applied to specific types of renewable energy technology.

The results showed that the string ribbon technology achieved the best outcomes in all the three sustainability dimensions with the highest overall sustainability score. The least sustainable occurred to be monocrystalline silicon photovoltaic modules, with just a little worse outcome on environmental and social dimensions, but with significantly smaller score compared to the economic aspect. Moreover, the performance of selected modules is comparable in terms of environmental and social one. The reasons behind it can be as follows:

- The study's aim was to assess the technology using "averaged data", not taken from a specific company. Therefore, the manufacturing process of the analysed system is very much alike. It differentiates in one stage – processing the silicon. The environmental and social dimensions are strongly connected with resources used for technology manufacturing as well as energy and water required for processing. The best performance was achieved for the economic dimension represented by the string ribbon PV (numerical value). It is due to generation of the material waste during the production process of this type of photovoltaic cells.
- The economic performance of monocrystalline silicon modules significantly varies from two other technologies (numerical value vs. numerical value). It is almost twice time smaller than in the case of string ribbon PV.
- In general, the character of sustainability assessments is highly dependent on criteria and associated indicators, that in most cases are selected subjectively. From the other hand, the same set of products to be assessed can bring completely different results if using different criteria. To avoid such situation indicators should be developed and considered individually against evaluated product. Therefore, the proposed indicators can be treated as a starting point for further research.
- Data availability and their quality published by manufactures are big problem to be considered in this study. This data regarding products may not represent a real performance correctly due to a high competition in the industrial sector. Potential rivals might take advantage of public data. From these reasons, the acquirement of the analysed company's data occurred is limited. From the other hand, it is difficult to acquire data or information from individual producers.
- In this case, the collection of data might be rather time consuming. A comparison of specific products, for instance specific models of PV modules, should not be as problematic as it does not require as much data and additional normalization that is implied by numerous sources specifying different characteristics in different units and measures. Moreover, when analysing general sets of products, it might be tricky to focus on insufficient data because of possible margin errors cause by the information bias. In order to ensure accuracy of the assessment numerous criteria should be used. The more criteria will be considered, the more authentic evaluation will be. It can lead to necessity of looking for data for dozens of indicators, what usually requires a huge effort. This problem is even stronger in an evaluation that have similar aim as the example provided in this study. It means basing on averaged data derived from various subjects.
- The paper puts less attention to measurement of social aspects of sustainability. This dimension is very problematic to measure which has already been identified in many research papers (e.g. [10]). The reason behind it could be a marginal number of research dealing with social aspects, and not examined in depth in comparison to other dimensions (economic and environmental). Moreover, this aspect strongly depends on a region and local customs, and habits.

The sustainability assessment approach may serve as a useful foundation for industrial companies to make viable multi-criteria decisions regarding selection of photovoltaic modules, whilst considering environmentally beneficial technologies and greater financial and social benefits at the same time. This approach seems particularly useful when comparing and selecting different technologies. Even though the provided framework aimed to make this whole procedure easier and structured, this method still requires a considerable amount of effort and motivation to be applied.

Due to limited data availability, the weights of selected criteria for the LCSA are based on literature research. Therefore, the conclusions from the study need to be interpreted carefully. The products' assessment results may vary together with different preferences and needs dependent on a case.

The presented research may contribute to develop a systematic assessment of energy renewable technologies from a different viewpoint. The assessment method can facilitate energy decision – making within supported energy policy and further identification of improvements. This research through the authors' paper provides the theoretical and empirical background needed to further develop a complex technology assessment for sustainability relevant to Industry 4.0 and its "designed", future tools [23].

The paper is also to provide industrial plants with a tool aimed at enhancing their commitment to sustainability raising the share of renewable energy into manufacture.

Future research

Measuring sustainability assessment is still subject of many international conferences in terms of the suitability of Industry 4.0. For future works there are additional efforts to be explored to support the achievement as follows:

- Refine the applied assessment method and verify the usefulness of developed indicators for various energy technologies aimed at improving the energy sustainability performance.
- Focus more attention on identifying social indicators to evaluate how technology influences the social dimension of sustainability (social consequences of technological operations).
- The need for comprehensive methods dealing with all relevant uncertainties related to life cycle-based approaches through integrating risk factors in determining economic feasibility of energy technology. Risk can have also possible effects on human health and the environment.
- Provide the three-dimensional extension of sustainability e.g. technical, safety, institutional or other functional considerations (durability, reliability etc.) through establishing standard energy LCA- based data for comparing various technologies. The main important aspect is to provide trade-off and maximize synergies between the three dimensions, and even four concerns according to the OECD recommendations.

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