energies

MDPI

Article

Eco-Innovation Method for Sustainable Development of Energy-Producing Products Considering Quality and Life Cycle Assessment (QLCA)

Dominika Siwiec * and Andrzej Pacana

Faculty of Mechanical Engineering and Aeronautics, Rzeszow University of Technology, 35-959 Rzeszow, Poland; app@prz.edu.pl
* Correspondence: d.siwiec@prz.edu.pl

Abstract: The sustainability of products remains a challenge, mainly due to the lack of consistent approaches for simultaneously taking into account the key criteria of the concept in the process. This research aims to develop an eco-innovative QLCA method to create new product solutions that integrate quality (customer satisfaction) and environmental impact assessment throughout the product life cycle. The QLCA method includes: (i) product prototyping according to quality and environmental criteria; (ii) prospective assessment of the quality of prototypes, taking into account customer requirements; (iii) prospective life cycle assessment of product prototypes using a cradle-to-grave approach in accordance with ISO 14040; and (iv) setting the direction of product development while taking into account the fulfilment of customer expectations and the need to care for the environment throughout the product life cycle. Owing to the lack of previous research in this area, as well as the popularity of photovoltaic (PV) panels in reducing greenhouse gases, an illustration was obtained and test of the method was carried out on the example of silicon photovoltaic panel modules (Crystalline Si PV Module). In accordance with the adopted assumptions, the results of the QLCA method test showed that the modelled PV prototypes will, in most cases, be satisfactory for customers, but they still require improvement actions to reduce carbon dioxide (CO_2) emissions throughout their life cycle. These activities should be consistent so as to achieve quality that satisfies customers. The QLCA method can be used by designers, managers, and decision-makers at the early stages of design, but also during the product maturity phase for its sustainable development.

Keywords: LCA; quality; photovoltaic panels; sustainable development; entropy method; importance–performance analysis; customer requirement; mechanical engineering; production engineering

Citation: Siwiec, D.; Pacana, A. Eco-Innovation Method for Sustainable Development of Energy-Producing Products Considering Quality and Life Cycle Assessment (QLCA). *Energies* **2024**, *17*, 3841. https://doi.org/10.3390/en17153841

Academic Editor: Benjamin McLellan

Received: 18 July 2024
Revised: 28 July 2024
Accepted: 1 August 2024
Published: 4 August 2024

1. Introduction

Activities aimed at achieving the climate goals of the European Union (EU-27) for 2050 [1] mean that heating and cooling technologies, such as photovoltaic (PV) panels, are becoming increasingly important in reducing negative climatic changes by improving air quality and reducing carbon dioxide (CO_2) emissions [2]. They reduce negative climatic changes by having beneficial impacts on improving air quality and reducing carbon dioxide emissions [3]. Despite this, they require the increased use of limited materials, which are increasingly being considered recyclable [4], but also in the form of obtaining high-quality materials [5]. Furthermore, global climate change makes it important to switch to more sustainable electricity production techniques, including ensuring environmental protection throughout the life cycle (LCA) of green energy generation technologies [6]. Among the key ones are photovoltaic systems [7]. In a life-cycle context, they enable the use of fewer resources than conventional electricity sources. However, it is necessary to consider the environmental impact of these products in terms of their entire life cycle, which can also be applied to the acquisition and extraction of materials, the production process, and the mentioned use and recycling [8].

There have been studies covering the life cycle assessment of photovoltaic panels, e.g., [9–11]. However, achieving carbon neutrality in the implementation of PV should not only focus on eliminating the negative impact on the natural environment. It is also necessary to adapt photovoltaic panels to customer requirements [12]. This means taking into account the voice of customers (VoC) [13] during the design and improvement process of these types of products so that they are satisfactory to customers during their use. This is related to the increased public awareness of environmental protection and customer needs regarding functionality [14,15]. Examples of PV improvement that take into account customer requirements are presented in studies of the authors of this article, e.g., [16,17].

The research gap is the lack of a coherent approach and methods supporting the process of making product development decisions from a qualitative and environmental perspective in relation to their life cycle (LCA). At the same time, there is a lack of research that includes the improvement of energy-producing products taking into account their quality (customer satisfaction with the use of the product) and environmental impact throughout the life cycle. Including the environmental dimension in the process of designing and improving photovoltaic panels can support the activities of manufacturing companies towards sustainable development.

Attempting to meet these challenges, this research aims to develop an eco-innovative QLCA method to create new product solutions that integrate quality (customer satisfaction) and environmental impact assessment throughout the product life cycle. The method was developed in a general way so that it could be used for various types of products. However, an illustration was obtained and a test was carried out for photovoltaic panels, which have not yet been improved via the qualitative and environmental approach presented. Therefore, the QLCA method is dedicated to manufacturing companies in the process of designing innovative products, including when improving products in terms of their sustainable development. The results of the QLCA method can support decision-making by designers, managers, and decision-makers regarding the direction of product development in accordance with the expected level of customer satisfaction and taking into account the need to protect the environment.

This study was systematised as follows: Section 2. Review of the subject literature regarding improving the quality of photovoltaic panels and assessing their life cycle; Section 3. Presentation of the QLCA method, general idea, concept, assumptions, algorithm, and description of the procedure; Section 4. Illustration and test of the QLCA method for the example of photovoltaic panels.

2. Literature Review

A literature review was conducted covering the photovoltaic (PV) panels that were selected for the illustration and testing of the proposed QLCA method. A photovoltaic panel review was carried out in the field of work on improving the quality of photovoltaic panels and assessing their life cycle. The works were obtained from the Web of Science (WoS) database, where the search terms for the works were as follows: "quality", "life cycle assessment", and "photovoltaic panels". These works were searched for their title, abstract, and keywords. The time period covered the available time frame in the WoS database, with the literature review carried out in July 2024. Twenty-four works were identified, which were subsequently subjected to preliminary verification based on the title and abstract. Ultimately, 15 works were selected, which, according to the authors, corresponded to the adopted scope of this research. Therefore, they were further verified using bibliometric analysis, frequency analysis, keyword analysis, and synthetic content analysis.

Initially, the type of study was analysed. Thirteen scientific articles and two post-conference studies were selected for analysis. It can be concluded that the area of research is becoming important from a utilitarian point of view and has found little application in practice.

Then, the number of studies published per year was analysed. The purpose of this analysis was to determine the pace of development of the research area, as shown in Figure 1.

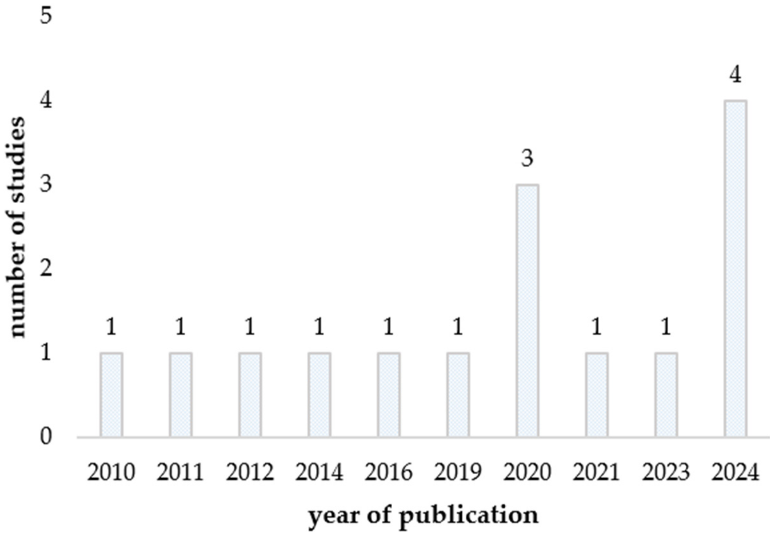

Figure 1. Number of studies published per year. Own chart based on the Web of Science database.

It was observed that the first works from the given research period were created relatively recently, in 2010. In recent years, 2010–2024 (up to July), the number of works has been relatively small, because one work was published per year, excluding 2020 (3) and 2024 up until July (4). Therefore, it can be concluded that the selected research area that covered the improvement of photovoltaics in terms of quality and at the same time limiting their negative impact on the environment in LCA is in the initial development phase. This research topic is not popular and may have numerous research gaps.

Subsequently, the keywords included in all the analysed studies were verified. There were 84 total keywords, which were keywords indicated by the authors of these studies. The keywords most frequently repeated are presented in a word cloud in Figure 2.

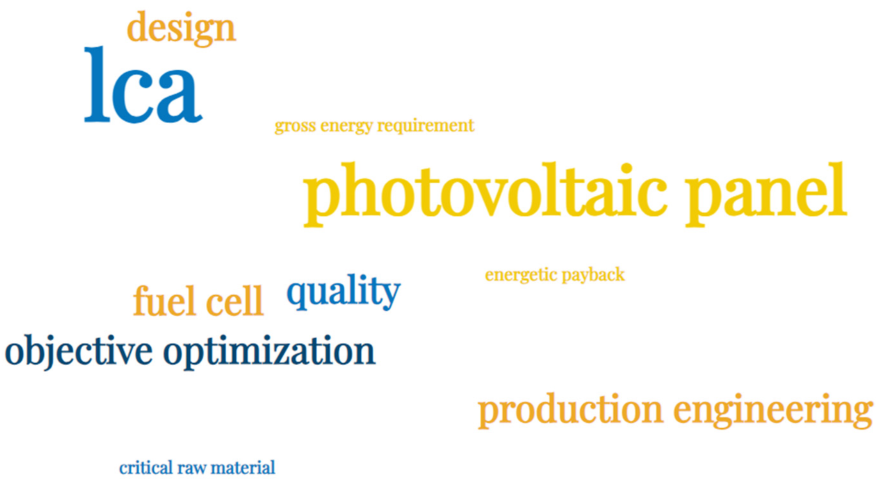

Figure 2. Cloud of the most frequently occurring keywords. Own image based on the Web of Science database and produced using Word Cloud Generator.

The most frequently repeated words were “LCA” (including life-cycle assessment, life-cycle assessment) (12 occurrences) and “photovoltaic panel” (including solar panel (5 occurrences). However, this could have resulted from the given entry when searching for work for verification. Other keywords often appeared: design, quality, objective optimisation, or production engineering. Therefore, it was considered that the main thematic scopes of the selected works included PV life cycle assessments and were focused on PV design and quality, or process optimisation in the context of energy and materials.

Later, the citation of selected works was analysed. Citation of the works was verified on the basis of data from the WoS database, which took into account the number of citations from all databases. The process of this type of verification was designed to select the work that had the greatest impact on the analysed research area. Among those analysed, Ref. [18] had the highest number of citations (113), in which the authors presented the possibilities of recovering precious and crystalline metals from recycling silicon photovoltaic waste. The research was focused on the possibilities of the recovery of these materials from the perspective of the PV life cycle. Various recycling scenarios were applied throughout the life cycle of these products, including a focus on secondary raw materials. The results presented in the mentioned study showed that efficient recycling contributes to the production of high-quality materials, such as silicon, glass, and silver. However, processes aimed at recycling to produce high-quality materials may have greater negative environmental impacts, so environmental burdens should be considered, not only for quality-performing recycled materials, but also for the processes themselves that contribute to producing them.

Subsequently, the works that were relatively frequently cited were studies [19] (36) and [5] (34). In study [19], an eco-energy analysis of the life cycle of materials and components for photovoltaic power plants was carried out. The analysis covered the entire life cycle of power plants in Poland. The results of the analysis showed that, of all the elements analysed, the photovoltaic panels in their LCA had one of the highest negative environmental impacts. This impact mainly concerned photovoltaic materials that were stored after use, had the highest energy demand, and were characterised by high CO_2 emissions. It has been observed that the most harmful materials concern materials such as silver, nickel, copper, lead, and cadmium. Hence, their recycling is dedicated to eliminating the negative impact of photovoltaic energy throughout their life cycle.

However, in [5], the so-called digital twin for the silicon PV lifecycle was discussed. It was a predictive model that analysed in detail the environmental burden of CO_2 emissions when recycling this type of photovoltaic. The results of these studies identify unit processes that need to be improved across all PV technologies.

The analysis of the most frequently cited works showed that the key studies for the development of the analysed research area focused on the photovoltaic recycling process, mainly silicon panels, including the possibility of improving this process to obtain high-quality materials. Furthermore, these studies included an evaluation of the PV life cycle in terms of the environmental burden criterion, which is carbon dioxide (CO_2). This underscores the importance of considering both environmental impact and customer satisfaction in the sustainable development of photovoltaic panels.

The remaining studies selected for analysis were cited less frequently; therefore, synthetic verification is carried out for them later in this article. The remaining studies selected for analysis are summarised and presented in Table 1.

Based on the literature review on the design and improvement of photovoltaic panels in terms of quality and environmental aspects during the life cycle, it was concluded that the research area:

- Becomes important from a utilitarian point of view and has found little practical application;
- Is in the initial development phase;
- Is not popular and may have numerous research gaps;
- Covers mainly life cycle assessment, and to a small extent, it covers both quality improvement and optimisation of production processes in the context of energy and materials;
- In particular, developed on the basis of research on PV recycling, mainly silicon panels, including the possibility of improving this process to obtain high-quality materials;
- Most often related to the assessment of the life cycle in terms of the environmental burden criterion, which is carbon dioxide emissions (CO_2).

Table 1. Synthetic analysis of studies referring to LCA and quality of PV.

Study	Short Description of Study	Rules, Methods, Tools
[20]	Development of passive solar energy technology integrated with air ventilation attached to the building, where it was shown that integrating PV with ventilation was more beneficial than independently functioning PV, and these benefits were visible in economic aspects and were more environmentally friendly in LCA	CML-2001 method using Sustainability Tool
[21]	A proposal of a method for examining the impact of gross energy demand load profiles for autonomous photovoltaic systems was considered, where various parameters were considered to modify the PV dimensions, showing that minimising the storage capacity with cyclic changes generated a limitation in PV dimensions, including affecting the quality of products, costs, and customer satisfaction	NSGA-II genetic algorithm
[8]	Comparison of changes occurring through the use of solar panels in terms of different prioritisations of the return of environmental costs with traditional consideration of the intensity of solar lighting, where the analyses covered the entire life cycle and the payback period of environmental outlays, including the interpretation of differences in the potential of solar energy, the electric energy basket-tric, and impact categories	Environmental payback period (EPBP), LCA
[22]	Photovoltaic life cycle analysis based on the category of environmental burden of greenhouse gas emissions, including photovoltaic optimisation in terms of the possibility of storing hydrogen in batteries as a more favourable form of energy storage	Hybrid optimisation model for electric renewable program
[23]	Model supporting the PV design process at an early stage of development, where quality criteria (regarding customer satisfaction) and environmental criteria are taken into account, adequate in their applicability to product life cycle assessment	Criteria from LCA databases, Weighted Sum Model (WSM)
[24]	Comparison of alternative energy generation solutions, that is, photovoltaic, wind turbines, fuel cells, and diesel generators, in the context of environmental burdens on human health and ecosystem quality in LCA, where photovoltaic energy was found to be more harmful to the environment than other energy generation products	Eco-Indicator 99
[25]	QCE indicator takes into account aspects of quality (customer satisfaction with use), purchase costs, and environmental impact in the product life cycle, where the indicator is dedicated to the selection of PV	FAHP (fuzzy analytic hierarchy process), cost-effectiveness analysis (CEA), and LCA
[26]	Assessment of environmental indicators, i.e., cumulative energy demand, global warming potential, and ecological deficiencies, where this assessment was carried out in terms of the life cycle according to the "cradle-to-grave" approach, including various scenarios using prefabricated facade elements and PV	LCA
[27]	Aggregation of unit processes in life cycle assessment carried out in the ecoinvet database so that it was possible to carry out analyses at the national level, including regionalising trade and taking into account consumption baskets and product origins in different regions; the analyses were carried out for PV, and it was shown, for example, that there were differences in the effects of climate change when the suppliers of components and energy baskets are from different regions of the country	
[28]	Evaluation of environmental costs related to the flow of silicon used in photovoltaic panels, where, for example, the quality of the wafers was considered, including energy consumption in the two main countries producing solar panels, i.e., the United States and China, and the analyses concerned the life cycle of silicon from production until decommissioning	
[29]	Presentation of cases on the need to integrate scales (spatial and temporal) but also dimensions (social, environmental, and economic) that apply to different scenarios and thus drive innovation in LCA, where tests were carried out for PV	
[4]	Analyses of various solutions regarding the materials used in photovoltaic energy in terms of their life cycle, thus considering the introduced innovative programmes of heating and cooling technologies that influence the improvement activities undertaken within PV	

It was observed that there is a lack of research covering the improvement of energy-generating products while taking into account their quality (customer satisfaction with the use of the product) and environmental impact throughout the life cycle. There is a lack of a coherent approach and methods supporting the process of making development decisions from a qualitative and environmental perspective in relation to the life cycle; hence, it was considered a research gap.

Therefore, the QLCA method was developed to predict new product solutions taking into account their quality (customer satisfaction with use) and environmental impact during the life cycle. The method was illustrated and tested on the example of photovoltaic panels, and its general methodology was presented so that it could also be applied to other types of products as part of their sustainable development.

3. Methodology

The QLCA method was developed to support the sustainable product improvement process. The method is dedicated to product development, taking into account quality and environmental aspects, where quality concerns customer satisfaction with the use of products, while environmental aspects include the product's impact on the environment during its life cycle. Hence, Q—product quality, LCA—life cycle assessment in the offered approach interpreted as an indicator of the environmental burden of the product throughout its life cycle.

The model presented included the different methodology and validation tools, i.e., surveys, the entropy method, life cycle assessment in OpenLCA 2.0.0 program with Ecoinvent database, normalisation and aggregation methods, IPA model (importance–performance analysis), and non-parametric tests to compare two dependent samples (variables) in Statistica 13.3.

This part of the study presents the ideas, conceptual outline, and characteristics of the QLCA method.

3.1. General Idea and Concept of QLCA Method

The idea of developing the QLCA method resulted from the need to support the process of making decisions about the direction of product development in terms of its sustainable development, where these decisions also include customer satisfaction and environmental impact in the product life cycle. The QLCA method is intended to support designers at the product prototyping stage, where various production alternatives (prototypes) are considered.

The concept of the method refers to the creation of prototypes based on a reference product (current, on sale), which will be improved in the future, both in terms of quality (customer satisfaction) and environmental impact in LCA [30]. Product prototypes are characterised according to the main quality criteria, that is, those that have the greatest impact on customer satisfaction with the use of the product [31]. The customer evaluates product quality criteria in terms of importance, but they are also assessed in terms of the state of parameters characterising the product and its prototypes [32,33]. On the basis of the weight assessments and criteria quality assessments, the quality index of the reference product and its prototypes is determined. The quality index (Q) is determined using the entropy method [34].

Then, a life cycle assessment of the reference product is performed, as a well as model of inventory data for a prospective life cycle assessment of prototypes [35,36]. Life cycle assessment is carried out for one environmental load criterion, and the methodology is consistent with the ISO 14040 standard [37]. The dedicated approach is "from the cradle to the grave", that is, taking into account the phases of material extraction and processing, production, use, and end of life [38]. In this way, the life cycle environmental index (LCA) is obtained.

The developed quality and environmental indicators are aggregated into one QLCA decision-making indicator, and its interpretation is carried out according to the pro-environmental approach of the IPA model (importance–performance analysis) [39]. Based on the QLCA indicator, it is possible to determine the direction of product development in terms of its sustainable development.

3.2. Assumptions of QLCA Method

In accordance with the review of the literature on the subject and previous research by the authors of this article, e.g., [19,23,40], assumptions for the QLCA model were made. They are as follows:

- The product to be tested is optional and its selection results from the needs of the entity using the proposed method [41];
- The current product (on sale) is the so-called reference product and its alternative production solutions are prototypes [42];
- The total number of the product and its prototypes should be greater than five in accordance with the principles of decision support [43];
- The quality of the product and its prototypes refers to customer satisfaction with use and is calculated based on the current and modified states of the product's quality criteria, including customer requirements regarding the validity of these criteria in the product [44];
- The number of quality criteria results from the complexity of the product and usually ranges from 10 to 15 main criteria (having a significant impact on customer satisfaction with use) [45];
- The environmental impact of the product and its prototypes is the environmental impact calculated according to the criterion of environmental load in the life cycle of the reference product, including the modelled environmental load of its prototypes [46].

Detailed assumptions for the QLCA method are presented in individual stages of the method, as presented later in this article.

3.3. Algorithm and Description of QLCA Method

The QLCA method was developed in four main stages, i.e., (1) product selection and definition of its prototypes, (2) obtaining customer expectations and estimating the quality index of the product and its prototypes (Q), (3) product life cycle assessment and prospective assessment of its prototypes (LCA), (4) aggregation of indicators in QLCA and interpretation of results. The algorithm of the method is presented in Figure 3.

The characteristics of the stages of the QLCA method are presented later in this article.

3.3.1. Stage 1. Product Selection and Definition of Its Prototypes

The test product can be anything. Its choice depends on the nature of the analysis and the needs of the enterprise, e.g., a product requiring improvement activities, being in the maturity phase or competitive on the market. This product should be described by the main criteria that influence customer satisfaction with its use [47]. The selection of criteria depends on the team of experts and can be carried out as part of team work, including on the product catalogue. The number of main criteria results from the complexity of the product, usually ranging from 10 to 15, which results from the decision support principles presented in [43,45]. The main criteria are characterised by parameters in the current state, which can be expressed as a value, a range of values, or a description. The parameters are obtained from the product catalogue. Then, based on the current product (on sale), prototypes (alternative production solutions) are developed. Prototypes are developed by an expert team, e.g., including a designer [48]. The proposed approach assumes the development of more than five prototypes, as confirmed in [43,45]. The prototypes are created by modifying the state of the current criterion. This modification occurs as a change in the value of the criterion parameter by an assumed value or a range of values greater than or less than the current one. The prototypes offered should be presented in a collective table so that they can be further analysed at subsequent stages of the method.

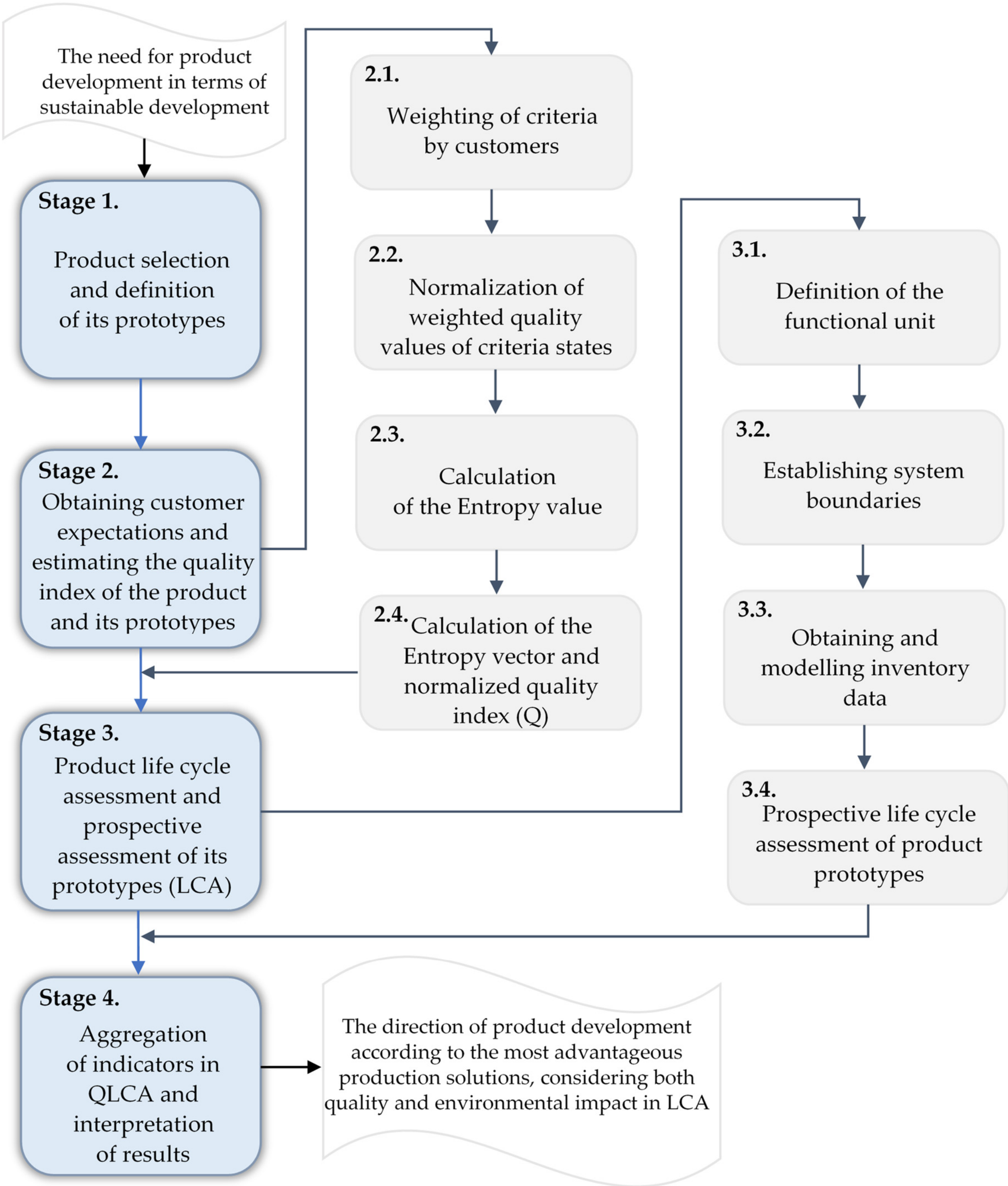

Figure 3. Algorithm of QLCA method.

3.3.2. Stage 2. Obtaining Customer Expectations and Estimating the Quality Index of the Product and Its Prototypes (Q)

In order to take into account the voice of customers (VoC) [13], the proposed method included conducting a survey, questionnaire, or interview [49]. The number of customers participating in the study can be determined on the basis of dedicated methods, e.g., [50–52], including the method offered by the authors of this article, i.e., [53]. Obtaining customer requirements supports the process of sustainable product development, including increasing the likelihood of customer satisfaction with the offered products, which additionally contributes to the company's profit and its competitiveness on the market. It is assumed that customers determine the importance of the product's main criteria, i.e., the weight of these criteria. Obtaining this type of information is the first of the key stages in the process of planning a queue of improvement activities, where the more important the criterion for the client, the higher the priority for its improvement. Therefore, the weights of the product criteria are set on a scale of 0 to 1, where 0—the criterion is not important for the customer, and 1—the criterion is absolutely the most important for the customer [54]. Customers evaluate all the main criteria selected in the first stage of the method. If the number of customers is greater than 1, the arithmetic mean of these weights should be calculated from the weights obtained from the criteria. The weights of the criteria (w) were used to estimate the quality index of the product and its prototypes.

The quality index (Q) was calculated according to the multi-criteria decision support method (MCDM) [55], which is the entropy method [56]. The choice of this method resulted from the possibility of processing various information and decision-making data according to the information entropy [34,57]. Entropy is applicable to the analysis of any criteria; therefore, it was considered appropriate for the proposed method. Within entropy, the input data are the values of the criteria parameters of the product and its prototypes (from stage 1), which are subsequently processed to take into account the importance of the criteria, and then normalised according to Formula (1) [58]:

$$r_{ij} = \frac{w_j q_{ij}}{\sum_{i=1}^{m} q_{ij}} \quad (1)$$

where: w—weight of criteria, q—quality of criteria states, m—number of alternative design solutions, and i, j = 1, 2, . . ., n.

The so-called entropy values are as shown in Formula (2) [34,57]:

$$\begin{cases} e_j = -h\sum_{i=1}^{m} r_{ij} \ln r_{ij}, j = 1, 2, \ldots, n \\ h = \frac{1}{\ln m} \end{cases} \quad (2)$$

where: m—number of alternative design solutions, r—normalised quality value of the criterion state, and i, j, = 1,2, . . ., n.

Then, the entropy vector (O) should be calculated, which is normalised as part of a standardised comparison of the values obtained in further stages of the method. The Q index is a quality index (3) [56,58]:

$$\begin{cases} O_j = \frac{1-e_j}{\sum_{j=1}^{n}(1-e_j)} \\ Q_j = \frac{O_j - \min O_j}{\max O_j - \min O_j} \end{cases} \quad (3)$$

where e—entropy value and j = 1, 2, . . ., n.

The values of the Q indicator should be in the range of 0 to 1. According to the Q values, it is possible to determine the level of customer satisfaction with the quality of products, where the higher the value of this indicator, the more favourable the product is for customers in terms of quality.

3.3.3. Stage 3. Product Life Cycle Assessment and Prospective Assessment of Its Prototypes (LCA)

The concept of the model assumes that the reference product will be evaluated in terms of its environmental impact during its life cycle (LCA). Life cycle assessment is a method for analysing the inputs and outputs of environmental loads that occur during the life of a product and process [38]. It is one of the key methods for assessing environmental impacts, where the basic assessment approach is "from the cradle to the grave", that is, considering the environmental impact in the phase of extraction and processing of materials, production, use, and end of life (EoL) [59]. The LCA method can be carried out in accordance with the ISO 14040 standard, including determining the purpose and scope of the research, inventories, impact assessment, and interpretation [37]. It is assumed that life cycle assessment is carried out for the reference product and subsequently prospectively for its prototypes. The idea of the model includes carrying out a life cycle assessment according to a selected environmental load criterion that is adequate for the subject of research [60]. LCA can be supported by computer programmes.

As part of a life cycle assessment, it is essential to adopt a functional unit. This unit allows the data to be standardised so that they are comparable. The unit is a quantitative description of the product's function; therefore, it can be used to perform calculations for various environmental loads [61]. The unit can be any, but should be selected appropriately based on the subject of research. Additionally, the life cycle assessment method requires defining the boundaries of the system being examined, i.e., a set of criteria that define individual processes, but also the inputs, outputs, and environmental loads according to which the assessment is carried out [62]. As mentioned, in the proposed method, these boundaries should cover LCA phases from the cradle to the grave and may also focus on selected phases of the life cycle with a defined geographical area and time period and inventory data.

Inventory data should be determined for the reference product (current, on sale) [63]. Then, these data should be adequately modelled for the offered product prototypes. This means estimating the inventory data for prototypes prospectively by an expert [64,65]. In this way, the so-called production solution scenarios are subject to life cycle assessment [66]. In this simplified way, the values of the environmental load of product prototypes are predicted, which are marked as EI index values. As part of their standardised analysis with the quality indicator values, the EI values should be normalised to form a life cycle environmental burden indicator (LCA), as shown in Formula (4):

$$\mathrm{LCA_j} = \frac{\mathrm{maxEI_j} - \mathrm{EI_j}}{\mathrm{maxEI_j} - \mathrm{minEI_j}} \tag{4}$$

where: EI—value of the environmental burden of the product in its life cycle, and j = 1, 2, $\cdots$, n.

The higher the value of the LCA indicator, the greater the product environmental burden in the life cycle or its prototype. Accordingly, a product ranking can be created, where the lower the value of the LCA indicator, the less likely the prototype will have a negative impact on the environment during its life cycle.

3.3.4. Stage 4. Aggregation of Indicators in QLCA and Interpretation of Results

The Quality Indicator (Q), relating to customer satisfaction with the use of products, and the Environmental Indicator (LCA), relating to the environmental burden of products during their life cycle, are aggregated into a coherent quality and environmental indicator (QLCA). The purpose of aggregation is to ensure a simultaneous analysis of products and their prototypes in terms of their quality and environmental impact on the life cycle. This is possible because both indicators are normalised on a scale of 0 to 1. The aggregation of the Q indicator with the LCA indicator into one QLCA indicator takes place using the modified IPA (importance–performance analysis) model [67]. IPA is a simple technique that can be applied in the analysis of any area, including those related to product development [68]. In the proposed QLCA method, it is used for simultaneous qualitative and environmental analysis, as shown in Figure 4.

On the basis of the IPA model, product prototypes that are most satisfactory to customers in terms of quality are selected and, at the same time, have the lowest negative environmental impact on the life cycle. These will be prototypes from the "concentrate here" area, i.e., with a high quality index and a low environmental index. Next, one should pay attention to prototypes in the area of "keep up the good work", which have a high quality index, but also have a high environmental index, which means that they will be satisfactory in terms of quality, but have a high environmental burden during their life cycle. Later, one may also be interested in "low-priority" prototypes because they have a small, negative environmental impact during their life cycle. However, these prototypes will not be satisfactory in terms of quality. However, "possible overkill" prototypes should be rejected because they will not be suitable for customers in terms of quality and will have a high environmental impact during the life cycle.

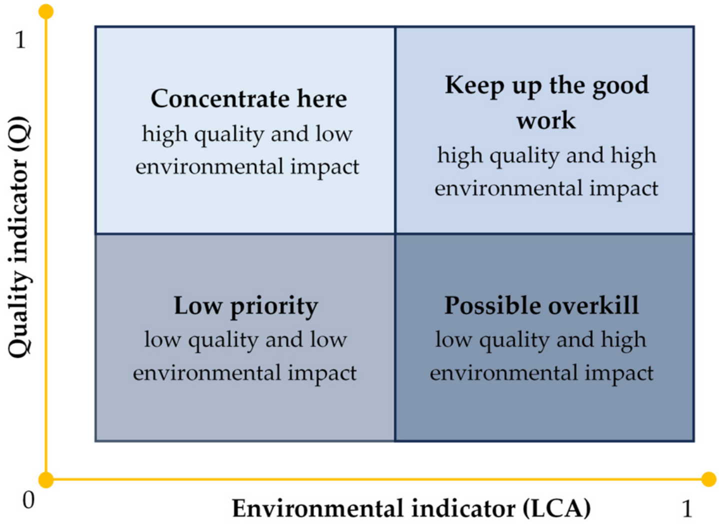

Figure 4. Modified IPA model. Own study based on [69].

Product development decisions are made based on the aggregated QLCA indicator of the IPA area. The final decision on the choice of the prototype in which the product should be developed depends on the company, and these decisions may result from the company's production capabilities or available resources.

4. Results

The QLCA method was illustrated and tested for photovoltaic panels, which are photovoltaic modules made of crystalline silicon (Crystalline Si PV Module) [70]. The choice of this research resulted from the relatively low level of research advancement in the area of simultaneous improvement of PV in terms of quality and environmental protection during its life cycle so that their sustainable development is possible, as also confirmed in [28]. Modules of this type are considered the most popular [71] and the most used, which has been confirmed by the significant increase in their installation over the last decade by 90% (from 104 to 1053 GW) [72]. These types of photovoltaic panels are characterised by a multi-layer structure, and each layer has its own specific role, e.g., functional and protective, i.e., frame, front glass, encapsulant, solar cells, encapsulant, backing film, junction box, as discussed in detail in [71,72].

4.1. Product Selection and Definition of Its Prototypes

The product analysed was the above-mentioned photovoltaic (PV) panels, i.e., photovoltaic modules made of crystalline silicon (Crystalline Si PV Module). Based on the PV catalogue presented in [73], as well as on the basis of previous studies by the authors, e.g., [17,25], PV was characterised by seven main criteria: (1) number of cells, width, (2) number of cells, length, (3) cell size (length), (4) factor of cell area, (5) cell efficiency (encapsulated), (6) module width (w/o frame), (7) module length (w/o frame), (8) module area (w/o frame), (9) module perimeter (frame length), (10) number of cells, (11) module power, and (12) module efficiency (glass area, excl. frame). These criteria were characterised according to the parameters in the current state and their modifications (in the future) were proposed. This resulted in 15 production solutions (1 current solution and 14 prototypes), as shown in Table 2.

Table 2. Prototypes of PV according to attributes from (1) to (12).

P1	P2	P3	P4	P5	P6	P7	P0	P8	P9	P10	P11	P12	P13	P14
5.00	3.00	8.00	4.00	7.00	10.00	9.00	6.00	12.00	14.00	11.00	13.00	16.00	15.00	17.00
6.00	8.00	3.00	9.00	4.00	5.00	7.00	10.00	13.00	11.00	15.00	17.00	12.00	14.00	16.00
8.58	6.24	3.90	10.92	13.26	10.92	1.56	15.60	24.96	17.94	29.64	20.28	31.98	27.30	22.62
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
10.08	12.24	3.60	1.44	5.76	7.92	5.76	14.40	20.88	25.20	16.56	25.20	18.72	29.52	27.36
39.44	29.58	69.02	88.74	59.16	78.88	49.30	98.60	138.04	118.32	157.76	128.18	167.62	147.90	108.46
97.20	64.80	32.40	32.40	129.60	64.80	97.20	162.00	226.80	324.00	356.40	194.40	388.80	291.60	259.20
1.36	1.20	1.52	1.12	1.28	1.44	1.04	1.60	1.84	2.00	1.92	2.16	2.08	1.68	1.76
4.95	4.17	3.65	4.69	4.43	3.39	3.91	5.21	6.25	6.51	5.73	7.03	5.47	6.77	5.99
48.00	18.00	36.00	24.00	30.00	42.00	54.00	60.00	66.00	78.00	72.00	90.00	102.00	84.00	96.00
42.00	126.00	84.00	168.00	84.00	168.00	42.00	210.00	420.00	504.00	336.00	462.00	294.00	378.00	252.00
9.90	9.24	12.54	11.22	11.88	10.56	8.58	13.20	15.84	14.52	13.86	15.18	17.82	17.16	16.50

where: P0—current product, P1–P14—prototypes.

4.2. Obtaining Customer Expectations and Estimating the Quality Index of the Product and Its Prototypes (Q)

In the second stage of the method, expectations were obtained from five customers, where the sample was selected as part of pilot and test studies of the method. Customers were people using PV in their homes. They rated the importance of the PV criteria on a scale of 0 to 1, and based on their ratings, the arithmetic mean of these weights was derived, as shown in Table A1. It was observed that the most important criteria for customers were cell efficiency (encapsulated) and the power module. Then, the entropy method was used to determine the prototype quality index (Q). Using Formula (1), the weighted value of the quality of the criteria was calculated and normalised. The result is presented in Table A2. Based on Formula (2), the entropy value was calculated, which in this case depended on 12 criteria, hence the value h = 0.402. The results are presented in Table A3. Finally, using Formula (3), the prototype quality index (Q) was calculated, as shown in Table 3.

Table 3. Preliminary estimation of the total change in the values of prototype criteria parameters relative to the reference PV.

P	P0	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14
O	0.05	0.07	0.06	0.08	0.06	0.07	0.05	0.07	0.08	0.08	0.07	0.08	0.07	0.07	0.06
Q	0.00	0.62	0.31	0.93	0.30	0.60	0.15	0.51	0.84	1.00	0.70	0.87	0.54	0.62	0.37
Rank	14	6	11	2	12	7	14	9	4	1	5	3	8	6	10

where: P0—current product, P1–P14—prototypes, O—entropy vector, and Q—quality indicator.

Prototype P9 was found to have the highest quality index. It could be considered the most advantageous in terms of quality, followed by prototypes P3 and P8. If the company only wanted to increase the quality of PV, it should rely on this ranking. However, the offered approach takes into account further criteria of sustainable development, such as the environmental impact in the life cycle. Therefore, a life-cycle assessment of the reference PV and its prototypes was carried out sequentially.

4.3. Product Life Cycle Assessment and Prospective Assessment of Its Prototypes (LCA)

At this stage, a life cycle assessment of the photovoltaic system and its prototypes was carried out. As adopted, the assessment was carried out according to the "cradle-to-grave" approach. The LCA method was implemented according to the ISO 14040 standard, including the use of the Ecoinvent 3.10 database of the OpenLCA 2.0.0 program [74]. The use of the LCA method in the proposed case was intended to verify the correctness of the QLCA method concept and the assumptions adopted, including the idea of data modelling. Therefore, the LCA method for photovoltaics and its prototypes was implemented in a basic manner, only to obtain a reliable environmental load index according to the approach developed.

Hence, following the authors of studies [75–78], it was assumed that the functional unit was one crystalline silicon photovoltaic module (Crystalline Si PV Module), which produced 1 kWh of electricity. The system boundaries were established taking into account the phases of extraction and processing of materials, production, use, and end-of-life (recycling). Owing to the test nature mentioned for the QLCA method, the geographical data were generalised to Europe, while the time limits included data from 2006 (they were a reference to inventory data [73]), including data from the Ecoinvent 3.10 database used for LCA. A graphical presentation of the system boundaries is shown in Figure 5.

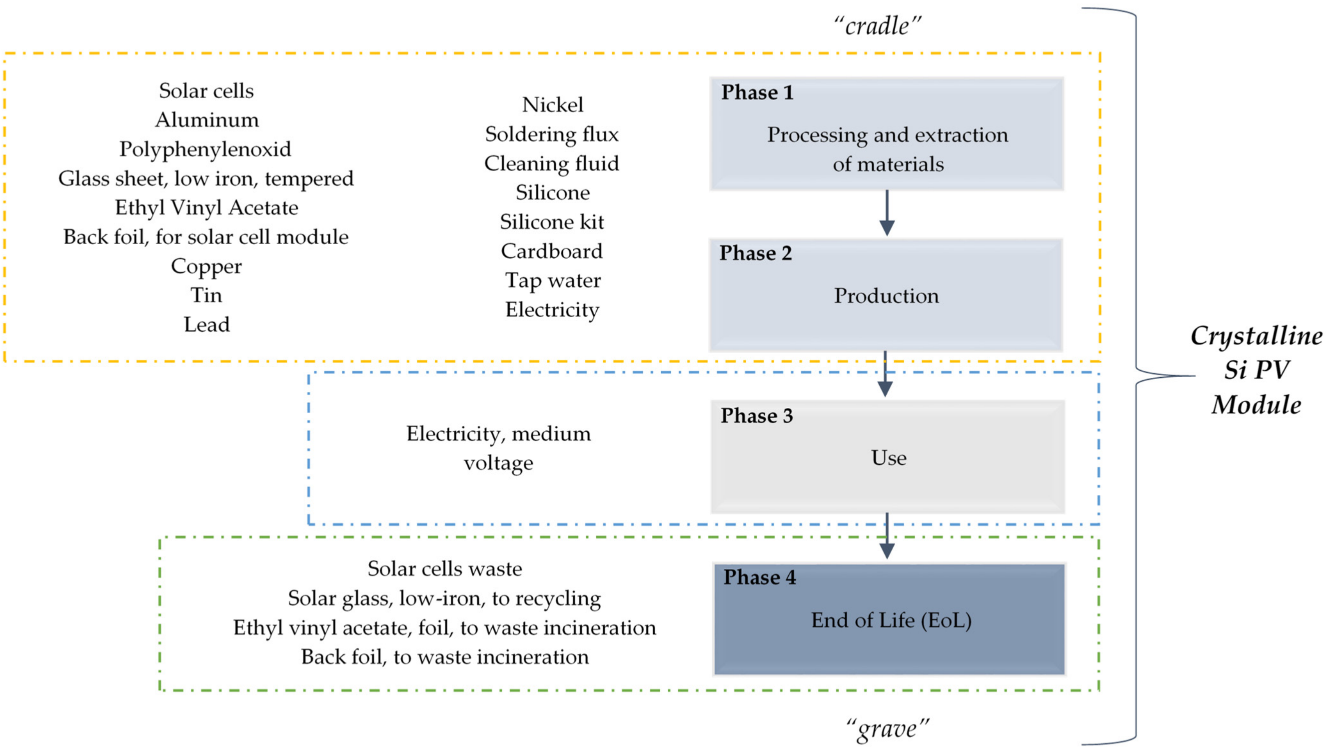

Figure 5. System boundaries. Own creation based on [73].

It was assumed that the boundary of the system would concern the four main phases of the LCA. Individual phases were covered with data on materials, electricity, and waste. The indicated elements in the system, including materials, were used, among others, to connect cells, create and attach PV frames (copper, silicone), rinse glass (water), laminate, test (electricity), etc. Inventory data were specified for the reference PV (current, on sale), and the appointment was accepted after the authors of the study, that is, [73]. On the basis of these data, data for the life cycle assessment of PV prototypes were also modelled, as shown in Table 4.

Additionally, data for the life cycle assessment of the reference photovoltaic and its prototypes were subjected to statistical analysis. The aim was to determine whether there were statistically significant differences between the inventory data adopted for the reference photovoltaics and the data modelled suggestively by the expert for the PV prototypes. Statistical analysis was performed in Statistica 13.3. For this purpose, a non-parametric test was performed to compare two dependent samples (variables). It was a sign test applicable in the case of analyses in which it is impossible to clearly assign values to given pairs of variables in an unambiguous way [79]. Therefore, it was applicable to data defined in a model manner. It was assumed that statistically significant differences occurred for p-value < 0.05 [80]. The results obtained are presented in Table 5.

Table 4. Inventory data of reference PV and its prototypes.

P	P0	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14
E1	59.050	67.078	44.395	62.099	53.239	88.173	28.710	61.200	25.357	50.229	66.656	63.691	56.057	63.718	72.659
E2	4.052	4.603	3.047	4.262	3.654	6.051	1.970	4.200	1.740	3.447	4.574	4.371	3.847	4.373	4.986
E3	0.289	0.329	0.218	0.304	0.261	0.432	0.141	0.300	0.124	0.246	0.327	0.312	0.275	0.312	0.356
E4	15.534	17.646	11.679	16.336	14.006	23.196	7.553	16.100	6.671	13.214	17.535	16.755	14.747	16.763	19.115
E5	2.345	2.663	1.763	2.466	2.114	3.501	1.140	2.430	1.007	1.994	2.647	2.529	2.226	2.530	2.885
E6	0.174	0.197	0.131	0.183	0.157	0.259	0.084	0.180	0.075	0.148	0.196	0.187	0.165	0.187	0.214
E7	0.009	0.010	0.007	0.009	0.008	0.013	0.004	0.009	0.004	0.007	0.010	0.009	0.008	0.009	0.011
E8	0.005	0.005	0.004	0.005	0.004	0.007	0.002	0.005	0.002	0.004	0.005	0.005	0.005	0.005	0.006
E9	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
E10	0.013	0.014	0.009	0.013	0.011	0.019	0.006	0.013	0.005	0.011	0.014	0.014	0.012	0.014	0.015
E11	0.020	0.023	0.015	0.021	0.018	0.030	0.010	0.021	0.009	0.017	0.023	0.022	0.019	0.022	0.025
E12	0.188	0.214	0.141	0.198	0.169	0.281	0.091	0.195	0.081	0.160	0.212	0.203	0.178	0.203	0.231
E13	1.689	1.918	1.269	1.776	1.522	2.521	0.821	1.750	0.725	1.436	1.906	1.821	1.603	1.822	2.078
E14	32.806	37.266	24.664	34.499	29.577	48.985	15.950	34.000	14.087	27.905	37.031	35.384	31.143	35.399	40.366
E15	20.610	23.412	15.495	21.674	18.582	30.774	10.020	21.360	8.850	17.531	23.264	22.230	19.565	22.239	25.360
E16	0.012	0.013	0.009	0.012	0.011	0.018	0.006	0.012	0.005	0.010	0.013	0.013	0.011	0.013	0.014
E17	0.154	0.175	0.116	0.162	0.139	0.231	0.075	0.160	0.066	0.131	0.174	0.167	0.147	0.167	0.190
E18	0.116	0.132	0.087	0.122	0.104	0.173	0.056	0.120	0.050	0.098	0.131	0.125	0.110	0.125	0.142

where: P0—current product, P1–P14—prototypes, E1—solar cells, E2—aluminium, E3—polyphenylenoxid, E4—glass sheet, low-iron, tempered, E5—ethyl vinyl acetate, black foil, E6—copper, E7—tin, E8—lead, E9—nickel, E10—soldering flux, E11—cleaning fluid, E12—silicone, silicone kit, E13—cardboard, E14—tap water, E15—electricity, medium voltage, E16—solar cells waste, E17—solar glass, low-iron, for recycling, E18—ethyl vinyl acetate, foil, for waste incineration.

Table 5. Statistical analysis results of modelled data of PV prototypes.

Compared Pair of PV	Number of Unrelated	Z	*p*-Value
P0 and P1	16	3.750	0.00018
P0 and P2	17	3.881	0.00010
P0 and P3	13	3.328	0.00087
P0 and P4	17	3.881	0.00010
P0 and P5	17	3.881	0.00010
P0 and P6	17	3.881	0.00010
P0 and P7	13	3.328	0.00087
P0 and P8	17	3.881	0.00010
P0 and P9	17	3.881	0.00010
P0 and P10	16	3.750	0.00018
P0 and P11	15	3.615	0.00030
P0 and P12	16	3.750	0.00018
P0 and P13	15	3.615	0.00030
P0 and P14	17	3.881	0.00010

The statistical analysis performed showed that there were statistically significant differences between the reference PV and its prototypes. This was confirmed by the *p*-value, which was <0.05 in each of the cases considered. Therefore, it was confirmed that the modelled data of the PV prototypes can constitute a basis as inventory data in the prospective assessment of their life cycle.

Therefore, by sequentially using the Ecoinvent 3.10 database in OpenLCA 2.0.0., a life cycle assessment of the reference PV and its prototypes was carried out. The carbon footprint (CF), which is derived from the ecological footprint, was adopted as a criterion for environmental burden [81]. The carbon footprint is the total amount of CO_2 (carbon dioxide) emissions that are directly and indirectly by a product [82]. In LCA, it is the equivalent of carbon dioxide (eCO_2) [83].

According to the adopted methodology, the environmental load of the reference photovoltaic and its prototypes was estimated for the carbon footprint load category. Then, using Formula (4), these values were normalised and based on them, the PV ranking was developed, as shown in Table 6.

Table 6. LCA indicators of PV prototypes.

P	P0	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14
EI	891.03	859.73	976.60	646.37	904.10	775.12	1283.73	418.00	369.20	731.28	970.48	927.30	816.20	927.64	1057.81
LCA	0.43	0.46	0.34	0.70	0.42	0.56	0.00	0.95	1.00	0.60	0.34	0.39	0.51	0.39	0.25
Rank	8	7	12	3	9	5	13	2	1	4	12	11	6	11	10

It was observed that the lowest environmental burden regarding the creation of a carbon footprint in the PV life cycle could be achieved by the P8 prototype followed by the P7 prototype. However, the highest environmental burden was associated with prototype P6. If PV development decisions were only concerned with environmental aspects, then product development decisions should focus on the P8 prototype. However, in the proposed QLCA method, development decisions include both qualitative and environmental aspects; hence, the next stage of the method is implemented.

4.4. Aggregation of Indicators and Interpretation of Results

The last stage of the method is the aggregation of the quality indicator (Q) and the life cycle environmental indicator (LCA) into one QLCA indicator. The rankings of PV prototypes according to the adopted indicators are presented collectively in Table 7.

Table 7. Ranking of PV prototypes.

	P0	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14
Q	0.00	0.62	0.31	0.93	0.3	0.6	0.15	0.51	0.84	1.00	0.7	0.87	0.54	0.62	0.37
Rank	14	6	11	2	12	7	14	9	4	1	5	3	8	6	10
LCA	0.43	0.46	0.34	0.7	0.42	0.56	0.00	0.95	1.00	0.6	0.34	0.39	0.51	0.39	0.25
Rank	8	7	12	3	9	5	13	2	1	4	12	11	6	11	10

The aggregation of indicators into one QLCA indicator was carried out according to the modified IPA model. As the Q and LCA indicators ranged from 0 to 1, it was assumed that the areas in the IPA model would be distributed according to the value of 0.50, which was half of the numerical range of the values of these indicators. The IPA model for PV prototypes is shown in Figure 6.

The results of the QLCA method made it possible to organise improvement activities within PV. It was observed that none of the photovoltaic prototypes stood out in any particular way, both in terms of quality and the environment, as evidenced by the lack of prototypes in the conventionally called "concentrate here" area. In turn, several prototypes were selected, which constituted relatively advantageous production solutions in terms of quality and environment. They are presented in the "Keep up the good work" area. These prototypes are as follows: P7, P8, P12, P5, P3 and P9. They are characterised by a satisfactory level of quality, but their environmental impact in LCA was also relatively high. Therefore, improvement activities undertaken for the reference PV should be undertaken to achieve any selected prototype from the "Keep up the good work" area, along with possible consideration of taking additional actions to limit their negative environmental impact in LCA. Final development decisions depend on the entity using the offered method, and may depend on, for example, the financial capabilities of the company.

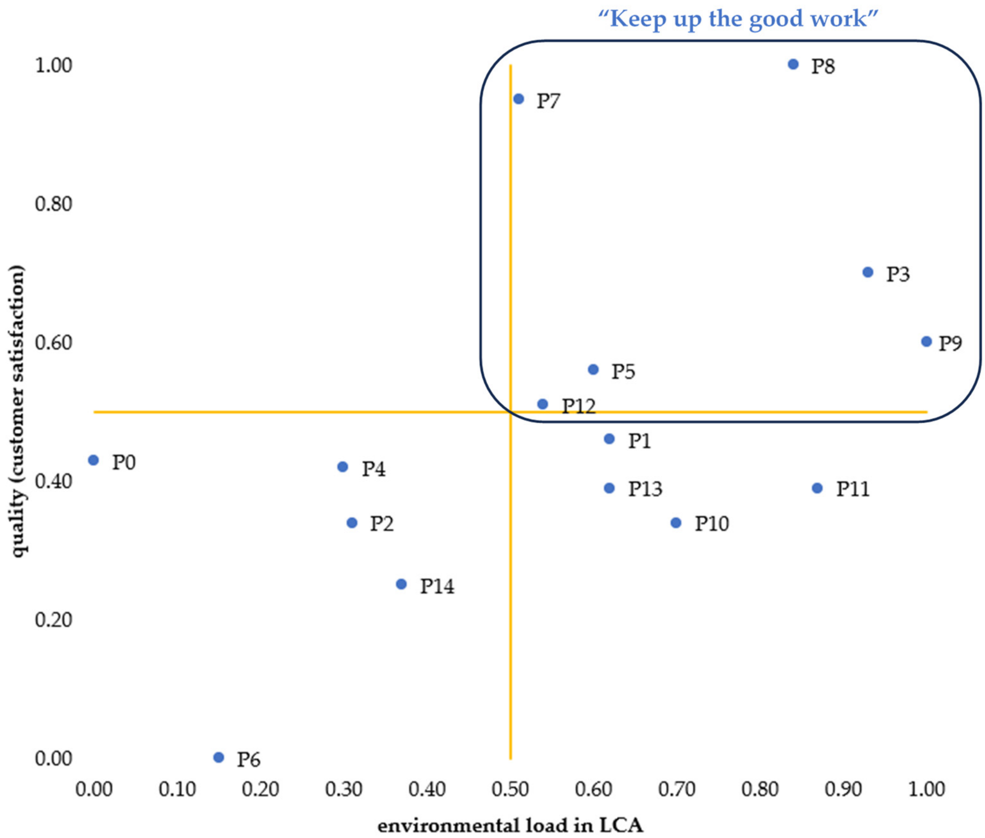

Figure 6. Determining the direction of PV development according to the aggregated QLCA indicator.

5. Discussion

The sustainable development of energy-producing products remains a challenge [84]. One of the key issues is the search for solutions conducive to environmental protection, for example, reducing greenhouse gases [85], but also solutions aimed at meeting customer satisfaction, for example, with product use [86]. Definitely important in this sense is the popularisation of renewable energy sources (RESs) [87], among which photovoltaic (PV) panels appear to be the pioneer in their use in homes and beyond [88,89]. They belong to the so-called green energy-producing products [90]. However, as shown by the literature review, photovoltaics have not yet been designed or improved taking into account the above-mentioned qualitative and environmental aspects.

Therefore, the QLCA method was developed, which, although of a general nature, was focused on its applicability to photovoltaic panels. The effectiveness of the offered method was confirmed by an example carried out for silicon photovoltaic modules.

The main benefits of the offered QLCA method include:

- Undertaking preparatory activities as part of product improvement through prototyping, followed by qualitative assessment and life cycle assessment of alternative production solutions;
- Ensuring product development taking into account the voice of customers (VoC) at the stage of assessing the quality of prototypes;
- Supporting the life cycle assessment process of product prototypes in the form of simplified modelling with inventory data of the reference product;
- Creating a ranking of prototypes according to the quality and environmental indicator (QLCA), including the selection of prototypes that are the most advantageous for the customer in terms of quality and the most environmentally friendly.

Additionally, the QLCA method has business benefits, including:

- Supporting decision-making at the early stages of product development and during its improvement, where these decisions can be made by designers, managers, and experts;
- Supporting the company in the production process of a competitive product, where this product will be up to date with the needs of the market, including meeting the idea of sustainable development, mainly in the context of meeting customer requirements and environmental protection regarding the product life cycle;
- Reducing the waste of resources in the form of prospective evaluation of product prototypes in order to direct improvement activities to the most appropriate ones.

However, some limitations of the QLCA method are its effectiveness in the case of the availability of and ability to use programmes dedicated to product life cycle assessment. However, free software is available for this, e.g., OpenLCA or Footprint calculator. Additionally, a certain limitation is the purpose of the QLCA method for life cycle analysis according to an environmental load criterion, which requires a thorough analysis of an important criterion from the point of assessment of the selected research subject. It should also be remembered that product prototypes are subjected to a prospective life cycle assessment, which is based on modelled inventory data. Therefore, these results can be considered as a kind of estimate of the environmental burden.

Therefore, future research will aim to adapt the QLCA method for analysing more environmental burden criteria in LCA. It is also planned to take into account other types of aspects of sustainable development, e.g., financial, on which product development decisions largely depend.

6. Conclusions

A lack of clear techniques and methodologies was observed that would facilitate the identification of beneficial product solutions, taking into account key aspects of sustainable development. Hence, the research gap was the lack of a coherent approach and methods supporting the process of making product development decisions from a qualitative and environmental perspective in relation to their life cycle (LCA). At the same time, there was a lack of research that would include the improvement of energy-producing products taking into account their quality (customer satisfaction with the use of the product) and environmental impact in the life cycle. Including the environmental dimension in the process of designing and improving photovoltaic panels can support the activities of manufacturing companies towards their sustainable development. Therefore, the aim of this research was to develop a QLCA method for predicting new product solutions taking into account their quality (customer satisfaction with use) and environmental impact during the life cycle. The method was created in four main stages: (1) product selection and definition of its prototypes, (2) obtaining customer expectations and estimating the quality index of the product and its prototypes (Q), (3) product life cycle assessment and prospective assessment of its prototypes (LCA), and (4) aggregation of indicators in QLCA and interpretation of results.

The method was tested for photovoltaic modules made of crystalline silicon (Crystalline Si PV Module). As part of the offered method, a qualitative indicator and an environmental burden indicator were determined throughout the life cycle, which were aggregated into one QLCA indicator. Using the IPA method to analyse the value of the QLCA index, several key PV prototypes were selected that may be advantageous in terms of production. These were six prototypes that were characterised by a satisfactory level of quality, but a relatively high environmental burden during their life cycle. Therefore, improvement actions should be taken towards the reference photovoltaic system (PV) in order to achieve a freely selected prototype from among those that are most advantageous in terms of quality and environment, where this decision depends on the company's capabilities.

Therefore, the QLCA method can be used by manufacturing companies in the process of designing innovative products, including when improving products in terms of their sustainable development. The results of the QLCA method can support decision-making by designers, managers, and decision-makers regarding the direction of product development in accordance with the expected level of customer satisfaction and taking into account the need to protect the environment.

Author Contributions: Conceptualisation, D.S. and A.P.; methodology, D.S. and A.P.; software, D.S. and A.P.; validation, D.S. and A.P.; formal analysis, D.S. and A.P.; investigation, D.S. and A.P.; resources, D.S. and A.P.; data curation, D.S. and A.P.; writing—original draft preparation, D.S. and A.P.; writing—review and editing, D.S. and A.P.; visualisation, D.S. and A.P.; supervision, D.S. and A.P.; project administration, D.S. and A.P.; funding acquisition, D.S. and A.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data are available in the article and can be made available upon request.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Weights of PV criteria.

Criteria	Unity	Weights (Importance for Customers)
Number of cells, width	pcs	0.40
Number of cells, length	pcs	0.40
Cell size (length)	cm	0.35
Cell area factor	pcs	0.30
Cell efficiency (encapsulated)	%	0.75
Module width (w/o frame)	cm	0.50
Module length (w/o frame)	cm	0.50
Module area (w/o frame)	m^2	0.55
Module perimeter (frame length)	m	0.60
Number of cells	pcs	0.62
Module power	Wp	0.70
Module efficiency (glass area, excl. frame)	%	0.65

Table A2. Normalised weighted value of quality state criteria of PV prototypes.

P	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
A1	0.01	0.01	0.01	0.02	0.01	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
A2	0.01	0.02	0.02	0.01	0.02	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
A3	0.02	0.02	0.01	0.01	0.02	0.02	0.02	0.00	0.02	0.01	0.02	0.01	0.02	0.02	0.02
A4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A5	0.03	0.05	0.05	0.02	0.01	0.02	0.02	0.03	0.03	0.03	0.02	0.03	0.02	0.04	0.04
A6	0.14	0.13	0.09	0.23	0.21	0.15	0.16	0.16	0.12	0.09	0.14	0.11	0.14	0.12	0.11
P	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
A7	0.23	0.32	0.19	0.11	0.08	0.33	0.13	0.31	0.20	0.24	0.31	0.16	0.32	0.24	0.27
A8	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A9	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
A10	0.11	0.19	0.06	0.15	0.07	0.09	0.11	0.21	0.07	0.07	0.08	0.09	0.11	0.09	0.12
A11	0.42	0.19	0.51	0.39	0.55	0.30	0.49	0.19	0.52	0.52	0.40	0.54	0.34	0.44	0.37
A12	0.02	0.04	0.03	0.05	0.03	0.04	0.03	0.04	0.02	0.01	0.02	0.02	0.02	0.02	0.02

where: P—product and prototypes (0—current product, 1–14—prototypes), A1—number of cells, width, A2—number of cells, length, A3—cell size (length), A4—cell area factor, A5—cell efficiency (encapsulated), A6—module width (w/o frame), A7—module length (w/o frame), A8—module area (w/o frame), A9—module perimeter (frame length), A10—number of cells, A11—module power, and A12—module efficiency (glass area, excl. frame).

Table A3. Entropy values of quality state criteria of PV prototypes.

P	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
A1	−0.03	−0.06	−0.03	−0.08	−0.04	−0.06	−0.07	−0.09	−0.04	−0.04	−0.04	−0.04	−0.05	−0.05	−0.06
A2	−0.05	−0.07	−0.07	−0.04	−0.07	−0.04	−0.04	−0.07	−0.04	−0.03	−0.05	−0.05	−0.04	−0.04	−0.06
A3	−0.06	−0.08	−0.06	−0.04	−0.07	−0.09	−0.07	−0.02	−0.06	−0.04	−0.07	−0.05	−0.07	−0.07	−0.07
A4	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01
A5	−0.11	−0.15	−0.16	−0.07	−0.03	−0.08	−0.09	−0.10	−0.10	−0.10	−0.08	−0.11	−0.09	−0.12	−0.14
A6	−0.28	−0.26	−0.21	−0.34	−0.33	−0.29	−0.30	−0.29	−0.26	−0.21	−0.27	−0.24	−0.27	−0.26	−0.25
P	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
A7	−0.34	−0.36	−0.31	−0.24	−0.20	−0.37	−0.27	−0.36	−0.32	−0.34	−0.36	−0.30	−0.37	−0.34	−0.35
A8	−0.02	−0.03	−0.02	−0.03	−0.02	−0.02	−0.02	−0.02	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01
A9	−0.04	−0.08	−0.06	−0.06	−0.06	−0.06	−0.04	−0.06	−0.03	−0.03	−0.03	−0.04	−0.03	−0.03	−0.04
A10	−0.24	−0.32	−0.18	−0.28	−0.19	−0.22	−0.24	−0.33	−0.19	−0.19	−0.20	−0.22	−0.24	−0.21	−0.26
A11	−0.36	−0.32	−0.34	−0.37	−0.33	−0.36	−0.35	−0.31	−0.34	−0.34	−0.37	−0.33	−0.37	−0.36	−0.37
A12	−0.09	−0.13	−0.12	−0.16	−0.12	−0.13	−0.10	−0.12	−0.07	−0.06	−0.06	−0.07	−0.08	−0.07	−0.09

where: P—product and prototypes (0—current product, 1-14—prototypes), A1—number of cells, width, A2—number of cells, length, A3—cell size (length), A4—cell area factor, A5—cell efficiency (encapsulated), A6—module width (w/o frame), A7—module length (w/o frame), A8—module area (w/o frame), A9—module perimeter (frame length), A10—number of cells, A11—module power, A12—module efficiency (glass area, excl. frame).

References

1. Kim, M.; Drury, S.; Altermatt, P.; Wang, L.; Zhang, Y.; Chan, C.; Dias, P.; Hallam, B. Identifying Methods to Reduce Emission Intensity of Centralised Photovoltaic Deployment for Net Zero by 2050: Life Cycle Assessment Case Study of a 30 MW PV Plant. *Prog. Photovolt. Res. Appl.* **2023**, *31*, 1493–1502. [CrossRef]
2. Zalamea León, E.; Cuevas Barraza, C. Adaptability of Photovoltaic Mono-Polycrystalline Solar Panels and Photovoltaic Roof Tiles on Dwelling Roofs of Real Estate Developments. *Rev. Constr.* **2019**, *18*, 42–53. [CrossRef]
3. Liantas, G.; Chatzigeorgiou, I.; Ravani, M.; Koukounaras, A.; Ntinas, G.K. Energy Use Efficiency and Carbon Footprint of Greenhouse Hydroponic Cultivation Using Public Grid and PVs as Energy Providers. *Sustainability* **2023**, *15*, 1024. [CrossRef]
4. Lysenko, O.; Yaramenka, K.; Mata, É.; Burgoa Francisco, F.; Gabaldon Moreno, A.; Lidfeldt, M.; Verdugo González, F. Positive Climate and Health Impacts from Upscaled Use of Heat Pumps and Solar Panels in Technology Packages in EU-27 by 2050. *Sustain. Prod. Consum.* **2024**, *44*, 221–233. [CrossRef]
5. Bartie, N.J.; Cobos-Becerra, Y.L.; Fröhling, M.; Schlatmann, R.; Reuter, M.A. The Resources, Exergetic and Environmental Footprint of the Silicon Photovoltaic Circular Economy: Assessment and Opportunities. *Resour. Conserv. Recycl.* **2021**, *169*, 105516. [CrossRef]
6. Holzapfel, P.; Bach, V.; Finkbeiner, M. Electricity Accounting in Life Cycle Assessment: The Challenge of Double Counting. *Int. J. Life Cycle Assess.* **2023**, *28*, 771–787. [CrossRef]
7. Grębosz-Krawczyk, M.; Zakrzewska-Bielawska, A.; Glinka, B.; Glińska-Neweś, A. Why Do Consumers Choose Photovoltaic Panels? Identification of the Factors Influencing Consumers' Choice Behavior Regarding Photovoltaic Panel Installations. *Energies* **2021**, *14*, 2674. [CrossRef]
8. Grant, C.; Garcia, J.; Hicks, A. Environmental Payback Periods of Multi-Crystalline Silicon Photovoltaics in the United States—How Prioritizing Based on Environmental Impact Compares to Solar Intensity. *Sustain. Energy Technol. Assess.* **2020**, *39*, 100723. [CrossRef]
9. Mao, D.; Yang, S.; Ma, L.; Ma, W.; Yu, Z.; Xi, F.; Yu, J. Overview of Life Cycle Assessment of Recycling End-of-Life Photovoltaic Panels: A Case Study of Crystalline Silicon Photovoltaic Panels. *J. Clean. Prod.* **2024**, *434*, 140320. [CrossRef]
10. Yuan, J.; Xu, X.; Huang, B.; Li, Z.; Wang, Y. Regional Planning of Solar Photovoltaic Technology Based on LCA and Multi-Objective Optimization. *Resour. Conserv. Recycl.* **2023**, *195*, 106977. [CrossRef]
11. Costa, D.; De Regel, S.; Espadas-Aldana, G.; Laget, H.; Kishore, R.; Meuret, Y.; Duerinckx, F. Environmental and Economic Impacts of Photovoltaic Integration in Concentrated Solar Power Plants. *Sol. Energy* **2024**, *274*, 112550. [CrossRef]
12. Das Guru, R.R.; Paulssen, M. Customers' Experienced Product Quality: Scale Development and Validation. *Eur. J. Mark.* **2020**, *54*, 645–670. [CrossRef]
13. Shen, Y.; Zhou, J.; Pantelous, A.A.; Liu, Y.; Zhang, Z. A Voice of the Customer Real-Time Strategy: An Integrated Quality Function Deployment Approach. *Comput. Ind. Eng.* **2022**, *169*, 108233. [CrossRef]
14. Ngendahayo, A.; Junyent-Ferré, A.; Rodriguez-Bernuz, J.M.; Nyeko, E.; Ntagwirumugara, E. Sizing Requirements of the Photovoltaic Charging Station for Small Electrical Vehicles. *Int. J. Renew. Energy Dev.* **2024**, *13*, 630–638. [CrossRef]
15. Guirguis, S.E.; Morgan, E.I.; Elguindy, A.; Shehata, O.M. Hybrid Multi-Parametric Optimization for Mobility-Aware Scheduling of Electric Vehicles Charging Station. In Proceedings of the 2023 IEEE 26th International Conference on Intelligent Transportation Systems (ITSC), Bilbao, Spain, 24 September 2023; IEEE: Piscataway, NJ, USA, 2023; pp. 3730–3735.

16. Ostasz, G.; Siwiec, D.; Pacana, A. Model to Determine the Best Modifications of Products with Consideration Customers' Expectations. *Energies* **2022**, *15*, 8102. [CrossRef]
17. Siwiec, D.; Pacana, A. Model of Choice Photovoltaic Panels Considering Customers' Expectations. *Energies* **2021**, *14*, 5977. [CrossRef]
18. Ardente, F.; Latunussa, C.E.L.; Blengini, G.A. Resource Efficient Recovery of Critical and Precious Metals from Waste Silicon PV Panel Recycling. *Waste Manag.* **2019**, *91*, 156–167. [CrossRef] [PubMed]
19. Piasecka, I.; Bałdowska-Witos, P.; Piotrowska, K.; Tomporowski, A. Eco-Energetical Life Cycle Assessment of Materials and Components of Photovoltaic Power Plant. *Energies* **2020**, *13*, 1385. [CrossRef]
20. Sivaram, P.M.; Mande, A.B.; Premalatha, M.; Arunagiri, A. Investigation on a Building-Integrated Passive Solar Energy Technology for Air Ventilation, Clean Water and Power. *Energy Convers. Manag.* **2020**, *211*, 112739. [CrossRef]
21. Thiaux, Y.; Seigneurbieux, J.; Multon, B.; Ben Ahmed, H. Load Profile Impact on the Gross Energy Requirement of Stand-Alone Photovoltaic Systems. *Renew. Energy* **2010**, *35*, 602–613. [CrossRef]
22. Galvez, G.H.; Probst, O.; Lastres, O.; Rodríguez, A.N.; Ugás, A.J.; Durán, E.A.; Sebastian, P.J. Optimization of Autonomous Hybrid Systems with Hydrogen Storage: Life Cycle Assessment. *Int. J. Energy Res.* **2012**, *36*, 749–763. [CrossRef]
23. Pacana, A.; Siwiec, D.; Bednárová, L.; Petrovský, J. Improving the Process of Product Design in a Phase of Life Cycle Assessment (LCA). *Processes* **2023**, *11*, 2579. [CrossRef]
24. Sevencan, S.; Çiftçioglu, G.; Kadirgan, N. A Preliminary Environmental Assessment of Power Generation Systems for a Stand-Alone Mobile House with Cradle to Gate Approach. *Gazi Univ. J. Sci.* **2011**, *24*, 487–494.
25. Gawlik, R.; Siwiec, D.; Pacana, A. Quality–Cost–Environment Assessment of Sustainable Manufacturing of Photovoltaic Panels. *Energies* **2024**, *17*, 1522. [CrossRef]
26. Passer, A.; Ouellet-Plamondon, C.; Keneally, P.; Habert, G. Impact of Building Refurbishment Strategies on the Energetic Payback. *Expand. Boundaries Syst. Think. Built Environ.* **2016**, *1*, 340–344.
27. Peng, S.; Pfister, S. Regionalizing the Supply Chain in Process Life Cycle Inventory with Multiregional Input–Output Data: An Implementation for Ecoinvent with EXIOBASE. *J. Ind. Ecol.* **2024**, *1*, 1–15. [CrossRef]
28. Golroudbary, S.R.; Lundström, M.; Wilson, B.P. Analogical Environmental Cost Assessment of Silicon Flows Used in Solar Panels by the US and China. *Sci. Rep.* **2024**, *14*, 9538. [CrossRef] [PubMed]
29. Mendonca, B.; Eliane, F. Architectural and Urbanistic Quality of Renewable Energy Installations. In Proceedings of the 2014 5th International Renewable Energy Congress (IREC), Hammamet, Tunisia, 25–27 March 2014; IEEE: Piscataway, NJ, USA, 2014.
30. Malindzak, D.; Pacana, A.; Pacaiova, H. An Effective Model for the Quality of Logistics and Improvement of Environmental Protection in a Cement Plant. *Przemysł Chem.* **2017**, *96*, 1958–1962. [CrossRef]
31. Pacana, A.; Siwiec, D. Analysis of the Possibility of Used of the Quality Management Techniques with Non-Destructive Testing. *Teh. Vjesn. Tech. Gaz.* **2021**, *28*, 45–51. [CrossRef]
32. Wang, J.; Ranscombe, C.; Eisenbart, B. Prototyping in Smart Product Design: Investigating Prototyping Tools to Support Communication in the Early Stage Smart Product Development. *Int. J. Des. Creat. Innov.* **2023**, *11*, 159–184. [CrossRef]
33. Elverum, C.W.; Welo, T.; Tronvoll, S. Prototyping in New Product Development: Strategy Considerations. *Procedia CIRP* **2016**, *50*, 117–122. [CrossRef]
34. Qu, W.; Li, J.; Song, W.; Li, X.; Zhao, Y.; Dong, H.; Wang, Y.; Zhao, Q.; Qi, Y. Entropy-Weight-Method-Based Integrated Models for Short-Term Intersection Traffic Flow Prediction. *Entropy* **2022**, *24*, 849. [CrossRef] [PubMed]
35. Nordelöf, A.; Poulikidou, S.; Chordia, M.; Bitencourt de Oliveira, F.; Tivander, J.; Arvidsson, R. Methodological Approaches to End-of-Life Modelling in Life Cycle Assessments of Lithium-Ion Batteries. *Batteries* **2019**, *5*, 51. [CrossRef]
36. Ekvall, T.; Gottfridsson, M.; Nellström, M.; Nilsson, J.; Rydberg, M.; Rydberg, T. Modelling Incineration for More Accurate Comparisons to Recycling in PEF and LCA. *Waste Manag.* **2021**, *136*, 153–161. [CrossRef] [PubMed]
37. Finkbeiner, M.; Inaba, A.; Tan, R.; Christiansen, K.; Klüppel, H.-J. The New International Standards for Life Cycle Assessment: ISO 14040 and ISO 14044. *Int. J. Life Cycle Assess.* **2006**, *11*, 80–85. [CrossRef]
38. Proske, M.; Finkbeiner, M. Obsolescence in LCA–Methodological Challenges and Solution Approaches. *Int. J. Life Cycle Assess.* **2020**, *25*, 495–507. [CrossRef]
39. Kim, B.-Y.; Oh, H. An Extended Application of Importance-Performance Analysis. *J. Hosp. Leis. Mark.* **2001**, *9*, 107–125. [CrossRef]
40. Romli, A.; Prickett, P.; Setchi, R.; Soe, S. Integrated Eco-Design Decision-Making for Sustainable Product Development. *Int. J. Prod. Res.* **2015**, *53*, 549–571. [CrossRef]
41. Diaz, A.; Schöggl, J.-P.; Reyes, T.; Baumgartner, R.J. Sustainable Product Development in a Circular Economy: Implications for Products, Actors, Decision-Making Support and Lifecycle Information Management. *Sustain. Prod. Consum.* **2021**, *26*, 1031–1045. [CrossRef]
42. Bortolini, M.; Gamberi, M.; Mora, C.; Pilati, F.; Regattieri, A. Design, Prototyping, and Assessment of a Wastewater Closed-Loop Recovery and Purification System. *Sustainability* **2017**, *9*, 1938. [CrossRef]
43. Mu, E.; Pereyra-Rojas, M. *Practical Decision Making*, 1st ed.; Springer International Publishing: Cham, Switzerland, 2017; Volume 1, ISBN 978-3-319-33860-6.
44. Wolniak, E.R.; Sędek, A. Using QFD Method for the Ecological Designing of Products and Services. *Qual. Quant.* **2009**, *43*, 695–701. [CrossRef]
45. Kolman, R. *Quality Engineering*; PWE: Warsaw, Poland, 1992. (In Polish)

46. Casamayor, J.L.; Su, D.Z. Environmental Impact Assessment of Lighting Products. *Key Eng. Mater.* **2011**, *486*, 171–174. [CrossRef]
47. Li, Y.; Tang, J.; Luo, X.; Xu, J. An Integrated Method of Rough Set, Kano's Model and AHP for Rating Customer Requirements' Final Importance. *Expert Syst. Appl.* **2009**, *36*, 7045–7053. [CrossRef]
48. Halvorsen, K. Team Decision Making in the Workplace. *J. Appl. Linguist. Prof. Pract.* **2013**, *7*, 273–296. [CrossRef]
49. Ponto, J. Understanding and Evaluating Survey Research. *J. Adv. Pract. Oncol.* **2015**, *6*, 168–171. [PubMed]
50. Memon, M.A.; Ting, H.; Cheah, J.-H.; Thurasamy, R.; Chuah, F.; Cham, T.H. Sample Size for Survey Research: Review and Recommendations. *J. Appl. Struct. Equ. Model.* **2020**, *4*, 1–20. [CrossRef] [PubMed]
51. Hyman, M.; Sierra, J. Selecting a Sample Size for Your Customer Survey. *Bus. Outlook* **2016**, *14*, 1–5.
52. Kelley, K.; Clark, B.; Brown, V.; Sitzia, J. Good Practice in the Conduct and Reporting of Survey Research. *Int. J. Qual. Health Care* **2003**, *15*, 261–266. [CrossRef] [PubMed]
53. Siwiec, D.; Pacana, A. A Pro-Environmental Method of Sample Size Determination to Predict the Quality Level of Products Considering Current Customers' Expectations. *Sustainability* **2021**, *13*, 5542. [CrossRef]
54. Sullivan, G.M.; Artino, A.R. Analyzing and Interpreting Data From Likert-Type Scales. *J. Grad. Med. Educ.* **2013**, *5*, 541–542. [CrossRef]
55. Xu, S.; Nupur, R.; Kannan, D.; Sharma, R.; Sharma, P.; Kumar, S.; Jha, P.C.; Bai, C. An Integrated Fuzzy MCDM Approach for Manufacturing Process Improvement in MSMEs. *Ann. Oper. Res.* **2023**, *322*, 1037–1073. [CrossRef]
56. Shanmugapriya, P.; Selvakumari, K.; Kavitha, S. Entropy Method of Multi-Attribute Decision-Making Problems. *E3S Web Conf.* **2024**, *491*, 02001. [CrossRef]
57. Manjate, E.P.A.; Saadat, M.; Toriya, H.; Inagaki, F.; Kawamura, Y. Application of Entropy Method for Estimating Factor Weights in Mining-Method Selection for Development of Novel Mining-Method Selection System. *J. Sustain. Min.* **2022**, *20*, 296. [CrossRef]
58. Zhu, Y.; Tian, D.; Yan, F. Effectiveness of Entropy Weight Method in Decision-Making. *Math. Probl. Eng.* **2020**, *2020*, 3564835. [CrossRef]
59. Raugei, M.; Winfield, P. Prospective LCA of the Production and EoL Recycling of a Novel Type of Li-Ion Battery for Electric Vehicles. *J. Clean. Prod.* **2019**, *213*, 926–932. [CrossRef]
60. Čuček, L.; Klemeš, J.J.; Kravanja, Z. Overview of Environmental Footprints. In *Assessing and Measuring Environmental Impact and Sustainability*; Elsevier: Amsterdam, The Netherlands, 2015; pp. 131–193.
61. McAuliffe, G.A.; Takahashi, T.; Beal, T.; Huppertz, T.; Leroy, F.; Buttriss, J.; Collins, A.L.; Drewnowski, A.; McLaren, S.J.; Ortenzi, F.; et al. Protein Quality as a Complementary Functional Unit in Life Cycle Assessment (LCA). *Int. J. Life Cycle Assess.* **2023**, *28*, 146–155. [CrossRef] [PubMed]
62. Li, T.; Zhang, H.; Liu, Z.; Ke, Q.; Alting, L. A System Boundary Identification Method for Life Cycle Assessment. *Int. J. Life Cycle Assess.* **2014**, *19*, 646–660. [CrossRef]
63. Khoo, H.H.; Isoni, V.; Sharratt, P.N. LCI Data Selection Criteria for a Multidisciplinary Research Team: LCA Applied to Solvents and Chemicals. *Sustain. Prod. Consum.* **2018**, *16*, 68–87. [CrossRef]
64. Khanam, T.; Rahman, A.; Xu, X.; Mola-Yudego, B.; Moula, M.M.E.; Pelkonen, P. Assessing the Awareness and Willingness of European Experts to Reduce Their Carbon Footprint in Everyday Consumption. *Environ. Impact Assess. Rev.* **2022**, *97*, 106889. [CrossRef]
65. Meijer, S.; Toxopeus, M.; Bruns, F. Integrating LCA Data and Expertise into Sustainable Product Development. *Procedia CIRP* **2024**, *122*, 825–830. [CrossRef]
66. Gajdzik, B.; Gawlik, R.; Skoczypiec, S. Forecasting-Scenario-Heuristic Method Proposal for Assessment of Feasibility of Steel Production Scenarios in Poland—Managerial Implications for Production Engineering. *Arch. Civil. Mech. Eng.* **2018**, *18*, 1651–1660. [CrossRef]
67. Abalo, J.; Varela, J.; Manzano, V. Importance Values for Importance–Performance Analysis: A Formula for Spreading out Values Derived from Preference Rankings. *J. Bus. Res.* **2007**, *60*, 115–121. [CrossRef]
68. Sever, I. Importance-Performance Analysis: A Valid Management Tool? *Tour. Manag.* **2015**, *48*, 43–53. [CrossRef]
69. Midilli Sarı, R.; Bekar, İ. Evaluation on Spatial Quality in Retail Stores through Importance-Performance Analysis (IPA). *ICONARP Int. J. Archit. Plan.* **2023**. [CrossRef]
70. Wang, X.; Tian, X.; Chen, X.; Ren, L.; Geng, C. A Review of End-of-Life Crystalline Silicon Solar Photovoltaic Panel Recycling Technology. *Sol. Energy Mater. Sol. Cells* **2022**, *248*, 111976. [CrossRef]
71. Heath, G.A.; Silverman, T.J.; Kempe, M.; Deceglie, M.; Ravikumar, D.; Remo, T.; Cui, H.; Sinha, P.; Libby, C.; Shaw, S.; et al. Research and Development Priorities for Silicon Photovoltaic Module Recycling to Support a Circular Economy. *Nat. Energy* **2020**, *5*, 502–510. [CrossRef]
72. Chen, P.-H.; Chen, W.-S.; Lee, C.-H.; Wu, J.-Y. Comprehensive Review of Crystalline Silicon Solar Panel Recycling: From Historical Context to Advanced Techniques. *Sustainability* **2023**, *16*, 60. [CrossRef]
73. Fthenakis, V.; Kim, H.; Frischknecht, R.; Raugei, M.; Sinha, P.; Stucki, M. *Life Cycle Inventories and Life Cycle Assessment of Photovoltaic System*; IEA PVPS Task 12, Report T12-02; International Energy Agency (IEA): Paris, France, 2011; pp. 1–63.
74. Ciroth, A. ICT for Environment in Life Cycle Applications OpenLCA—A New Open Source Software for Life Cycle Assessment. *Int. J. Life Cycle Assess.* **2007**, *12*, 209–210. [CrossRef]
75. Pacca, S.; Sivaraman, D.; Keoleian, G.A. Parameters Affecting the Life Cycle Performance of PV Technologies and Systems. *Energy Policy* **2007**, *35*, 3316–3326. [CrossRef]

76. Reich, N.H.; Alsema, E.A.; van Sark, W.G.J.H.M.; Turkenburg, W.C.; Sinke, W.C. Greenhouse Gas Emissions Associated with Photovoltaic Electricity from Crystalline Silicon Modules under Various Energy Supply Options. *Progress. Photovolt. Res. Appl.* **2011**, *19*, 603–613. [CrossRef]
77. Perpiñan, O.; Lorenzo, E.; Castro, M.A.; Eyras, R. Energy Payback Time of Grid Connected PV Systems: Comparison between Tracking and Fixed Systems. *Progress. Photovolt. Res. Appl.* **2009**, *17*, 137–147. [CrossRef]
78. Gerbinet, S.; Belboom, S.; Léonard, A. Life Cycle Analysis (LCA) of Photovoltaic Panels: A Review. *Renew. Sustain. Energy Rev.* **2014**, *38*, 747–753. [CrossRef]
79. Mishra, P.; Pandey, C.; Singh, U.; Keshri, A.; Sabaretnam, M. Selection of Appropriate Statistical Methods for Data Analysis. *Ann. Card. Anaesth.* **2019**, *22*, 297. [CrossRef] [PubMed]
80. Kim, M. Application of Functional ANOVA and Functional MANOVA. *Korean J. Appl. Stat.* **2022**, *35*, 579–591. [CrossRef]
81. Kazemzadeh, E.; Fuinhas, J.A.; Salehnia, N.; Koengkan, M.; Silva, N. Assessing Influential Factors for Ecological Footprints: A Complex Solution Approach. *J. Clean. Prod.* **2023**, *414*, 137574. [CrossRef]
82. García, A.; Monsalve-Serrano, J.; Martinez-Boggio, S.; Soria Alcaide, R. Carbon Footprint of Battery Electric Vehicles Considering Average and Marginal Electricity Mix. *Energy* **2023**, *268*, 126691. [CrossRef]
83. Han, J.; Tan, Z.; Chen, M.; Zhao, L.; Yang, L.; Chen, S. Carbon Footprint Research Based on Input–Output Model—A Global Scientometric Visualization Analysis. *Int. J. Environ. Res. Public. Health* **2022**, *19*, 11343. [CrossRef] [PubMed]
84. Karimu, A.; Bali Swain, R. Implication of Electricity Taxes and Levies on Sustainable Development Goals in the European Union. *Energy Policy* **2023**, *177*, 113553. [CrossRef]
85. Kocak, E.; Ulug, E.E.; Oralhan, B. The Impact of Electricity from Renewable and Non-Renewable Sources on Energy Poverty and Greenhouse Gas Emissions (GHGs): Empirical Evidence and Policy Implications. *Energy* **2023**, *272*, 127125. [CrossRef]
86. Jamali, M.-B.; Khosroshahi, H. Pricing and Long-Term Decisions of Manufacturers and Electricity Suppliers toward Sustainable Development under Eco-Innovation and Renewable Electricity Generation: A Real Case Study. *Environ. Dev. Sustain.* **2023**, *26*, 13097–13116. [CrossRef]
87. Hemeida, M.G.; Hemeida, A.M.; Senjyu, T.; Osheba, D. Renewable Energy Resources Technologies and Life Cycle Assessment: Review. *Energies* **2022**, *15*, 9417. [CrossRef]
88. Konstantzos, G.E.; Malamis, D.; Sotiropoulos, A.; Loizidou, M. Environmental Profile of an Innovative Household Biowaste Dryer System Based on Life Cycle Assessment. *Waste Manag. Res.* **2019**, *37*, 48–58. [CrossRef] [PubMed]
89. Stopochkin, A.; Sytnik, I. Algorithm for Rapid Estimation of the Performance of Small Rooftop Solar PV Use by Households. *Energies* **2022**, *15*, 3910. [CrossRef]
90. Ncube, A.; Mtetwa, S.; Bukhari, M.; Fiorentino, G.; Passaro, R. Circular Economy and Green Chemistry: The Need for Radical Innovative Approaches in the Design for New Products. *Energies* **2023**, *16*, 1752. [CrossRef]