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Article

Development of a Holistic Evaluation System for BIPV Façades

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Abstract: Façades with building-integrated photovoltaics (BIPV) have the advantage that they can produce renewable electric energy. Compared with conventional façades, BIPV façades have therefore a valuable additional property that can generally contribute to increasing the degree of sustainability of buildings. A holistic assessment system for BIPV façade systems for office and administration buildings was developed in the framework of the project "MULTIELEMENT II" at the Fraunhofer Institute for Wind Energy and Energy System Technology (IWES) in Kassel, Germany. The aim of this research was a comparison of conventional façade systems with BIPV façade systems regarding different technical, economical, sustainability, and design criteria. This paper discusses the basic conditions for a holistic evaluation of BIPV façades in comparison with conventional façades. A method for the execution of a holistic evaluation and characteristic values for a comparison interpretation of results is presented. Façade systems are evaluated regarding both quantifiable and non-quantifiable properties by means of a Microsoft Excel-based evaluation tool. The tool facilitates the comparison and evaluation of planned or built façades with and without BIPV. The detailed evaluation results aim to facilitate the certification of BIPV façade systems in the framework of sustainable building certification systems such as the German DGNB.

Keywords: photovoltaic; building integration; façade systems; sustainability criteria; holistic evaluation; sustainable building certification systems

1. Introduction

To facilitate the holistic assessment and evaluation of BIPV components in comparison with conventional building components an evaluation system is developed in the framework of the research project "MULTIELEMENT II"—enhancement of the building technology and building law specific basic conditions for PV-façade-components—at the Fraunhofer Institute for Wind Energy and Energy System Technology (IWES) in Kassel, Germany [1]. The project runs from 1 March 2013, to 31 October 2015. The MULTIELEMENT II project was funded by the German Federal Ministry for the Environment, Nature Conservation, Building, and Nuclear Safety (BMUB) [2] and is funded by the German Federal Ministry for Economic Affairs and Energy (BMWI) [3].

The integration of photovoltaic construction elements in architectural structures and buildings is referred to as "building-integrated photovoltaic" (BIPV) [4,5]. Globally, about 3/4 of the total BIPV area potential is attributed to roof systems and 1/4 to façade systems. Accordingly, up to ~20% of the total BIPV electricity production may be attributable to BIPV façade systems [6]. In Central Western Europe, for example, it is estimated that the average available area for BIPV façade systems is ~6.5 m^2 per person [6]. The achievable level of solar power production from BIPV is dependent on multiple factors. The major factors are the area, total efficiency of the BIPV system (global conversion efficiency %), and the solar yield. Assuming a global conversion efficiency of 10% and the use of all architecturally suitable building areas with an average solar yield of 40%, the achievable levels of solar power production of BIPV roof and façade systems are in the range between 30% and 120% of total electricity consumption (2002 state) in the IEA member states [6]. Accordingly, BIPV has huge development potential. In Germany, for example, the BIPV market potential is estimated at 3000 km^2. Such a building skin area amounts to an installation peak capacity of ~300 GW [7], representing coverage of ~50% of Germany's electricity demand [8].

Compared with ground-mounted PV systems, BIPV offers many advantages. BIPV components function as both conventional building components and renewable electricity producing PV generators [9–11]. Accordingly, compensation costs for the replacement of conventional building component functions can be considered in the calculation of life cycle costs and economical profitability of BIPV [12,13]. Positive complementary measures are also, for example, own consumption of decentralized produced PV-electricity, decentralized electricity storage, and adjustment of the electricity utilization profile. Furthermore, integration of BIPV in façades in different directions can contribute to a widening of the daily peak of PV-electricity [5]. BIPV can also reduce distribution network management costs. BIPV can contribute to the cost-effectiveness of distribution network services, e.g., by local voltage control. Furthermore, BIPV systems can contribute to improved distribution network stability by integration in higher-level distribution network management systems [14]. Nevertheless, only ~1% of the total distributed cumulative installed PV system capacity was integrated into buildings by 2009 [4]. In the same year in Germany, only 2% of the installed PV capacity was integrated in buildings [15].

Due to the advantages of BIPV compared with ground-mounted PV systems and a worldwide trend towards the construction of zero-energy buildings [16], the demand for BIPV is expected to grow. According to the European "Directive on the Energy Performance of Buildings" [17], new buildings in the EU member states have to be constructed as "nearly zero energy buildings" by 2021. According to the directive, the production of a surplus in renewable energy on-site or in close proximity to a building is greatly encouraged. Similar requirements have to be applied for new buildings according to the South Korean energy road map [18]. To meet these requirements, while addressing the proper integration of PV in buildings, a massive expansion of BIPV capacity must take place [5]. Thus, it is believed that the planning of buildings with multifunctional BIPV systems will, in future, become increasingly an essential and accepted part of the architectural mainstream [19].

However, for broad acceptance and widespread application of BIPV systems, the evaluation, and certification of BIPV products will play an important role [5,19]. It is expected that 63% of the BIPV revenues will be associated with product applications in new buildings [20]. The remaining portion will be applied in the framework of renovation and remodeling projects, based on the exchange of conventional building components.

To facilitate proper decision-making processes regarding the application of BIPV components or conventional building components, a holistic evaluation system is required. Such a system should ideally address applications in both new and existing buildings to facilitate an area-wide evaluation and potentially widespread application of BIPV components. Particularly, the application of BIPV in façades has to be addressed due to the high application potential in building types in offices, administration, and high-rise buildings.

The method, the results and the conclusions of the research on the development of a holistic evaluation system for BIPV façades [21], which has been developed in the framework of the MULTIELEMENT II project at the Fraunhofer IWES [1] are discussed in the subsequent sections of this paper.

2. Methods

The research on the development of a holistic evaluation system (HES) for BIPV façades [21] presented in this paper was executed in the framework of the project MULTIELEMENT II at the Fraunhofer IWES [1]. The aim of the research project is a comparison of conventional façade systems with BIPV façade systems regarding different technical, economical, and design criteria.

The HES methodology for façades is geared to the evaluation methods of existing comprehensive sustainable building assessment and certification systems. The HES for façades can be used independently or in direct combination with existing sustainable building certification systems [21]. The HES is initially developed to function as a planning and optimization tool but can later be integrated in a sustainable building rating and certification systems.

Energy performance is generally considered the most important criterion in sustainable building assessment and certification systems. Energy performance is the only criterion in so-called "cumulative energy demand" (CED) systems and is the most important criterion in all total quality assessment (TQA) systems. CED and TQA systems aim also at assessing ecological, economical, and social aspects of buildings in a balanced manner [22].

The main important sustainable building certification systems, which have been analyzed in the framework of the development of the HES for façades are DGNB (Deutsche Gesellschaft für nachhaltiges Bauen, "German Association for Sustainable Building") [23], LEED (Leadership in Energy & Environmental Design) [24], and BREEAM (Building Research Establishment's Energy Assessment Method) [25]. These three common, comprehensive systems are compared in Table 1 [21].

Table 1. Comparison of the three sustainable building rating and certification systems DGNB, LEED, and BREEAM.

Criteria for the comparison of sustainable rating and certification systems	**Name of sustainable building rating and certification systems (Institution)**		
	DGNB (Deutsche gesellschaft für nachhaltiges bauen)	**LEED (United States green building council)**	**BREEAM (Building research establishment)**
Partner institutes & international application	ÖGNI (Austria) SGNI (Switzerland) DGNBH (Hungary) BGBC (Bulgaria) DGBC (China) TCST (Thailand)	LEED Canada LEED Emirates LEED India LEED Italy LEED Mexico LEED Brazil	BREEAM International BREEAM Gulf BREEAM Europe BREEAM Netherlands BREEAM Spain
Evaluation phases	Planning stage (Pre-certification), Operation (Certificate)	Design stage, Construction stage (Certificate), CS—Core and shell (Pre-certification)	Planning stage (Pre-certification), Operation (Certificate)
Evaluation categories	Ecological Quality Economical Quality Sociocultural and Functional Quality, Technical Quality Process Quality Location Quality	Sustainable Sites, Water Efficiency Energy and Atmosphere, Material and Resources, Indoor Environmental Quality, Innovation & Design, Regional Credits	Management, Health and Wellbeing, Energy, Transport, Water, Materials, Waste, Land Use & Ecology, Pollution
Weighting	Weighting of single evaluation categories and impact factors for criteria	Weighting of impact categories	Weighting of individual evaluation categories
Reference to Standards	DIN EN ISO 14040 [26] DIN EN ISO 14044 [27] DIN EN ISO 14025 [28]	ASHRAE 90.1 [29]	DIN EN ISO 14040 [26] DIN EN ISO 14044 [27] ISO 21930 [30]

The following certifications systems have also been analyzed and considered during the development of the HES for façades but have not been included in the comparative overview of assessment and evaluation criteria in Table 1:

- CASBEE (Comprehensive Assessment System for Building Environmental Efficiency), developed in Japan [31].
- HQE (Haute Qualité Environnemental, "High environmental quality"), developed in Japan [32].
- GBP (Green Building-Program) of the European Commission, did not certify buildings but decorated more than 1000 organizations or building owners with the Green Building Partner Status for outstanding energy efficiency in the period 2006–2014 [33].
- MINERGIE (Mehr Lebensqualität, tiefer Energieverbrauch, "More living quality, low energy consumption"), developed in Switzerland [34].

This overview of sustainable building certification systems does not claim to be complete. Worldwide, many more sustainable building rating systems are available that are one-dimensional and focus, for example, on evaluation of cumulative energy demand, or are multi-dimensional and focus on life cycle assessment, and/or total quality assessment [22]. DGNB can be regarded as a holistic sustainable building evaluation system because it is a multi-dimensional evaluation tool including total quality assessment, life cycle assessment (LCA) and life cycle costing (LCC). Worldwide there is a growing interest in using LCC in combination with other life-cycle methodologies for the evaluation of sustainable buildings. However the state of LCC development as a concept is not clear [35]. LCA facilitates the assessment of potential environmental impacts based on life cycle inventory data, which is available in different databases. Technical, social and/or economical issues are not considered in LCA [36].

2.1. Evaluation Criteria and Interactions

An essential part of the HES is the objective description of the quality of a specific façade. The description refers to both the complete components and single façade elements. Based on such a detailed and objective description, different façade configurations can be compared with each other.

Qualitative and quantitative assessment criteria are determined for the detailed description of façades with and without BIPV. The following six major quality evaluation criteria are defined:

- Design
- Flexibility
- Sustainability, Ecology
- Production
- Economy
- Building physics and construction

Furthermore three to six individual subcriteria (Table 2, column B) are assigned to each of the six main criteria (Table 2, column A). First, the importance of each main criterion (MC) and each individual criterion (IC) is determined in the framework of a specific research. Then, the evaluation of individual criteria is determined with checklists. In the checklists, it is defined how the properties of a façade have to be evaluated, for both quantifiable and non-quantifiable properties. To facilitate the comparison of different façades and/or alternative designs, a specific weighting is assigned to each MC.

Table 2. Matrix with main criteria, assigned individual criteria and assessment of average values (arithmetical mean) for the evaluation of a façade project.

Main criteria & importance (A) from 5 = very high to 1 = very low	Individual criteria IC & importance (B) from 5 = very high to 1 = very low		Valuation IC (from checklist) 5 = very high to 1 = very low	Average value IC D = (A + B + C)/3 5 = very high to 1 = very low	Average value MC E = (D_1 … + …D_n)/n 5 = very high to 1 = very low	Average value project F = (E_1 … + … E_n)/n 5 = very high to 1 = very low
Importance: A	**Importance:**	**B**	**C**	**D**	**E**	**F**
Design	Contemporary design Corporate design Functional design Design reference to build environment Design reference to other building components					
Flexibility	Flexibility of dimensions Flexibility by color variability Flexibility by material variability Flexibility by energy flow variability Flexibility by functional variability					
Ecology & Sustainability	Energy balance Environmental impact Recyclability					
Production	Production for variable variety Standardized production Prefabrication of multifunctional building components Transport- and assembly variability					
Economy	Construction costs Costs for maintenance and replacement Compensation costs Lifetime Lifecycle costs					

Table 2. *Cont.*

Main criteria & importance (A) from 5 = very high to 1 = very low	Individual criteria IC & importance (B) from 5 = very high to 1 = very low		Valuation IC (from checklist) 5 = very high to 1 = very low	Average value IC D = (A + B + C)/3 5 = very high to 1 = very low	Average value MC E = (D_1 … + …D_n)/n 5 = very high to 1 = very low	Average value project F = (E_1 … + … E_n)/n 5 = very high to 1 = very low
Importance: A	**Importance:**	**B**	**C**	**D**	**E**	**F**
Building Physics & Construction	Fire safety					
	Day light quality					
	Weather protection					
	Sound insulation					
	Thermal insulation					
	Structural design					

After determining both MC and IC, interactions between the criteria are identified (Figure 1 [37]). The kind of interaction can be differentiated into parallel interaction (PI) and reverse interaction (RI). In the case of a PI, the positive evaluation of one criterion results also in the positive evaluation of the other criterion. In the case of RI, a positive evaluation of one criterion results in a negative evaluation of the other criterion. An example of a RI is the interdependency of the IC "thermal insulation," assigned to the MC "building physics," and the IC "construction costs," assigned to the MC "Economy." The reason for the RI is that improved thermal insulation results in a positive evaluation of the MC "building physics" but due to the association with generally higher construction costs, it results in a negative evaluation of the MC "Economy".

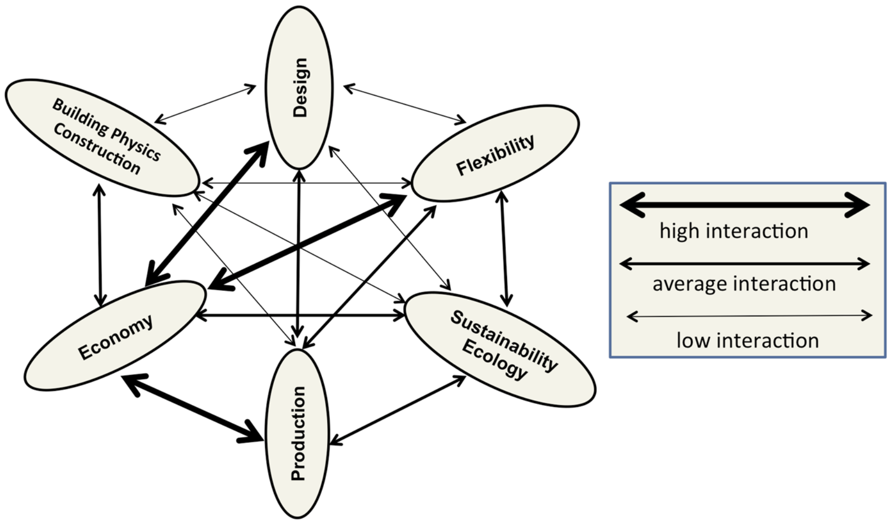

Figure 1. Diagram illustrating interactions between main qualitative and quantitative assessment criteria.

The analysis of examples results in the following methodical approach for the determination of specific interactions (examples have different project-dependent results regarding the interdependencies of criteria):

- Interactions between main criteria can only be determined clearly based on interactions between the associated individual criteria.
- Interactions between criteria generally have qualitative characteristics and can only be quantified in particular cases.
- Within the framework of comparing evaluations of projects or project alternatives, interactions between specific criteria have to be considered and addressed similarly.

2.2. System Description

To facilitate the evaluation of façades according to technical, formal, and economic criteria, both basic conditions limits of the HES have to be defined clearly. Evaluation criteria for different façade concepts and design alternatives have to be comparable. Thus, specific basic conditions have to be distinguished clearly.

Façades to be evaluated during the design and planning phase or after they have been built, have to be clearly and systematically defined: e.g., according to project name, building owner, location, function, planning or realization stage, and basic conditions for the evaluation such as descriptions, calculations and plans. Such a systematic definition is useful for both the evaluation and the definition of requirements during the planning stage.

The coverage of the different evaluation criteria is adapted to the specific properties of each evaluation criteria. Different coverage of a specific façade portions that have to be evaluated are, for example:

- An array of e.g., ~1–2 m^2 with complete required data for the analysis of specific building physical properties, such as the heat transfer in the area of windows.
- An array of e.g., ~10–20 m^2, which covers the complete area of a room behind, calculated by multiplication of room width by room height. Such an array can include smaller façade arrays with different properties and facilitates the evaluation of a complete façade for one room, e.g., regarding daylight and shading.
- A façade array of e.g., ~100–500 m^2 with similar orientation. Such an array can be, for example, a complete south-oriented façade of a building that could be evaluated regarding the energy balance or the relation to other building components.

2.3. Evaluation Method

The concept of a façade is significantly dependent on different influencing factors, which result in a very individual design. The concept is dependent on the specific context in which a building is designed. Accordingly, criteria have to facilitate project-specific evaluations of façades. The criteria have to be determined as a basic condition before an evaluation can take place. The project-specific evaluation of façades for different buildings is therefore possible. However, the evaluation results are not necessarily directly comparable. The definition of strict rules is indispensable to facilitate a directly comparable evaluation of façades for different buildings. Particularly, the context and the external general conditions have to be determined and considered from the beginning of an evaluation.

An evaluation method has been developed to guarantee that evaluations of different projects can be compared and related to each other while also considering project-related differences. The evaluation is executed in a consistent way following a five-step method and documented. The method is explained in the following paragraph and illustrated in Table 2.

The importance of the main criteria to be evaluated has to be entered in column A "Main Criteria & Importance". The specific importance is differentiated into five grades. The following points are assigned depending on the degree of importance of specific criteria for the project:

- 5 points: very high
- 4 points: high
- 3 points: average
- 2 points: low
- 1 point: very low

The specific importance of the individual criteria to be evaluated are entered in column B “Individual Criteria & Importance” (Table 2). The specific importance is differentiated in five grades, according to the same point system.

Compliance with the requirements for each criterion is entered in column C “Valuation IC” (Table 2). The specific valuations are determined with checklists. Such checklists have been prepared for each IC in the framework of this research. Examples for such checklist are illustrated in Tables 3 and 4. The results of the calculation of average values (arithmetic mean) are entered in column D “Average Value IC” (Table 2), for individual criteria, in column E “Average Value MC” (Table 2) for main criteria, and in Figure 2, column F “Average Value project” (Table 2) for the whole façade.

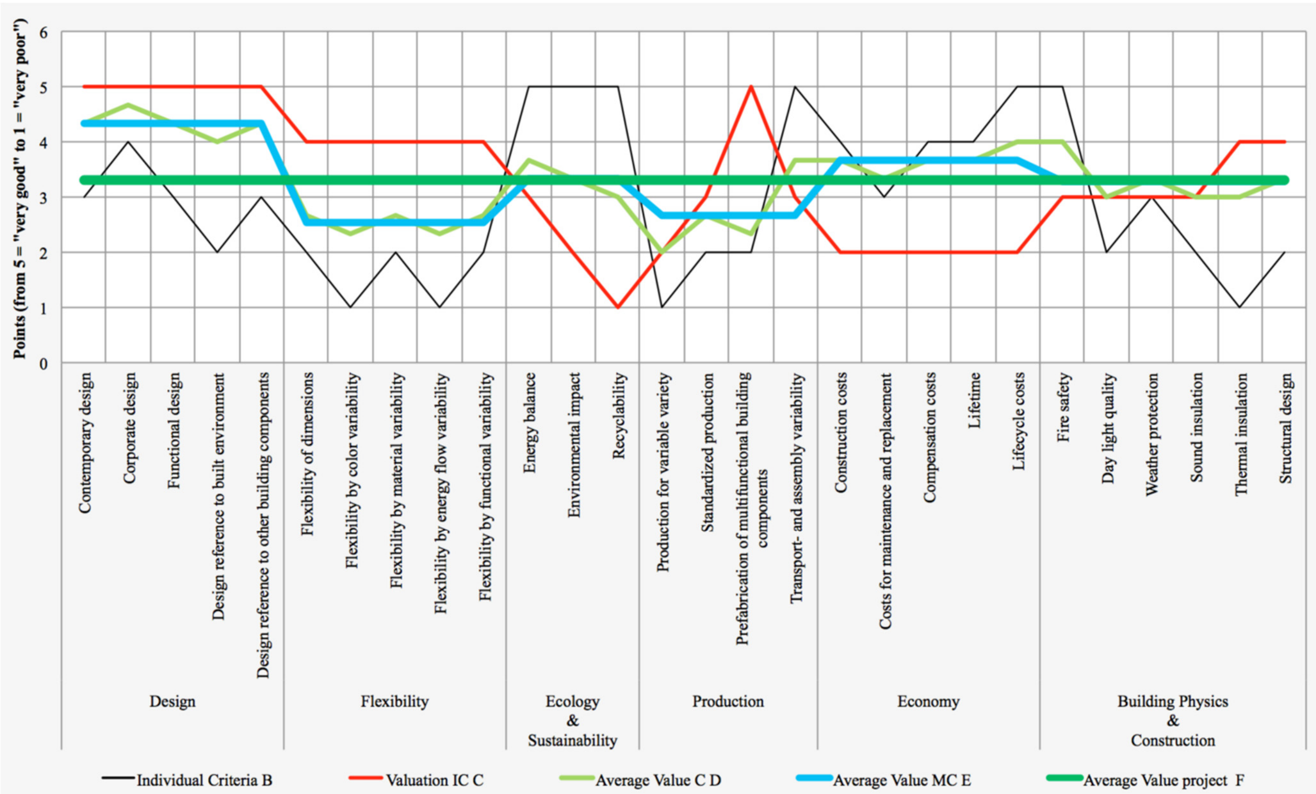

Figure 2. Evaluation Diagram Impacts, evaluations and results of the holistic evaluation of a virtual façade project.

3. Results and Discussion

The differentiation of qualitative and quantitative evaluation criteria results first from different evaluation methods. Qualitative criteria have to describe the properties of an item before it can be evaluated. Such a qualitative evaluation can refer, for example, to terms such as “good *vs.* bad”, “usable *vs.* unusable”, “suitable *vs.* unsuitable”, and “adaptable *vs.* non-adaptable”. Of course, it is also possible to define multiple intermediate stages.

It is assumed that quantitative criteria can be quantified at least partly independently from function. Accordingly, monetary costs can be, for example, specified exactly and compared. However, the main quantitative individual criteria, which cannot be exactly quantified, also have to be specified.

The evaluation is executed with a Microsoft Excel tool. The importance values of the individual criteria are the basis for the calculation of the mean values of the main criteria. These values are used for the calculation of the mean value of the complete façade. The result can first be presented in the form of an evaluation matrix (Table 2), which is an appropriate starting basis for the final presentation of the evaluation results of a façade project in the form of an evaluation diagram (Figure 2).

3.1. Determination of Main Criteria Impacts

The importance of specific main criteria can vary significantly depending on the specific function of a building. A different number of individual criteria have been assigned to each MC to facilitate its detailed description as the basis for its holistic evaluation (Table 2). The importance and quality of each MC and IC is recorded with a checklist and is objectified. The point-based evaluation method that has been described in Section 2.3 is used consistently in the evaluation process. The maximum value representing the best possible result is always 5 points. Values referring to multiple evaluation criteria are averaged (Table 2, column D—Average Value IC, column E—Average Value MC, and column F—Average Value project). Accordingly, the results of average values are also in the range of a minimum 1 and a maximum 5 points. To facilitate a more detailed value description, average value points include two decimal places.

The importance of the individual criteria (Table 2, column B) for the main criteria (Table 2, column A) Design, Flexibility, Ecology/Sustainability, Production, Economy, and Building Physics/Construction) is generally determined at the beginning of the planning stage in coordination with the building owner. Depending on the project priorities, the importance can differ for each MC and each IC. Generally, importance points have to be determined for each MC and each IC, considering a balanced proportion to other major criteria. Only in exceptional cases, specific main and individual criteria may be excluded from the importance determination. In such a case, the reduced numbers of main criteria and individual criteria (see also the subsequent section) have to be considered in the average determination.

3.2. Determination and Weighting of Individual Criteria Impacts

Individual criteria valuation in column C "Valuation IC" (Table 2) is executed after completion of the determination of main criteria and individual criteria importance in columns A and B (Table 2). The number of assigned points can vary again from 5 for a very high valuation to 1 for a very low valuation. Definitions for the different IC specific valuation points are provided in IC-specific checklists that have been developed in the described research [21]. The checklists, which have been developed for each IC, determine how many points (from 5 to 1) can be allocated for a specific degree of requirement fulfillment. An example for such a checklist for the IC "Design reference to other building components" with allocation of valuation points is provided in Table 3.

Table 3. Checklist for the IC "Design reference to other building components" with allocation of valuation points from 1–5 to specific definitions and degrees of requirement fulfillment.

Individual Criterion (IC) "Design reference to other building components" Fulfillment of requirements		Valuation
Very good solution	The façade design forms a harmonic ensemble together with other building components regarding design properties such as proportion, material, and color.	5
Good solution	The façade design creates a distinct reference to other building components.	4
Satisfactory solution	The façade design creates a distinguishable reference to other building components.	3
Poor solution	The façade design is disturbing and creates a poorly recognizable reference to other building components.	2
Very poor solution	The façade design is inappropriate and has no reference to other building components.	1

A checklist for the valuation of an IC can also be more complex if an IC has multiple subcriteria. The IC "Flexibility by functional variability" has, for example, three subcriteria, which are included in the checklist (Table 4). The row with fulfillment of all criteria and the highest number of points (between 5 and 1) determines the number of valuation points that are transferred to the evaluation matrix of the specific façade project (Table 2).

Table 4. Checklist for the IC "Flexibility by functional variability" with allocation of valuation points from 1–5 to each three specific definitions and degrees of requirement fulfillment.

Individual Criterion (IC) "Flexibility by functional variability" Fulfillment of requirements			
Multifunctional application of façade elements (breasts, sun blinds, roof, or similar)	**Different mode of actions of façade elements (opaque, translucent, transparent, sound absorbing, or similar)**	**Supplementary variability**	**Valuation**
Often possible: >5 options	Often possible: >5 options	Always good possible	**5**
Often possible: >5 options	Often possible: >5 options	Mostly possible	**4**
Partly possible: 2–3 options	Partly possible: 2–3 options	Partly possible	**3**
Almost impossible: expensive multifunctional option	Almost impossible: expensive multifunctional option	Only costly possible	**2**
Impossible: no multifunctional options	Impossible: no multifunctional options	Impossible no supplementary adaptation options	**1**

The valuation of individual criteria in column C "Valuation IC" (Table 2) is assigned independently from the importance of the particular IC and MC. However, if the particular MC is excluded from the evaluation, the assigned individual criteria will also not be evaluated.

3.3. Calculation of Evaluation Results

The point values from columns A, B, and C (Table 2) are added per row and are divided by the number of columns (3) to calculate the average (arithmetic mean) value that is displayed in the same row in column D "Average impact IC" (Table 2). The calculation is executed according to the following formula: D = (A + B + C)/3.

The values are calculated to two decimal places and can be compared regarding their impact on the overall evaluation of the project. The values are calculated according to the previously used scale:

- 5 (4.50–5.00) points: very good value of the IC
- 4 (3.50–4.49) points: good value of the IC
- 3 (2.50–3.49) points: satisfactory value of the IC
- 2 (1.50–2.49) points: poor value of the IC
- 1 (0.50–1.49) points: very poor value of the IC

The assigned values can be compared directly with each other regarding their impact on the evaluation of the complete façade project.

After completion of calculation and average determinations in column D, the value of the main criteria is calculated in column E "Average Value MC" (Table 2) by averaging the assigned individual criteria by application of the following formula: $E = (D_1 + \ldots + D_n)/n$. Accordingly the calculated values are again between 5 points and 1 point, and have two decimal places. Also these values can be compared directly regarding their impact on the overall evaluation of the project.

Finally, the value for the whole façade project is calculated by averaging the values of the main criteria in column F "Average impact project", by application of the following formula: $F = (E_1 + \ldots + E_n)/n$. The values are calculated with two decimal places. The results between 5 points and 1 point describe the result of the holistic façade project evaluation according to the interpretation similar to the scale above.

The holistic evaluation of a façade project is completed with the final determination of the average value of all addressed criteria. For a better understanding and illustration of the evaluation results of a façade project, data from a completed Evaluation Matrix are used for the preparation of an Evaluation Diagram. An example for such a diagram, which is prepared with points for importance, valuation and value from a virtual façade project evaluation, is illustrated in Figure 2.

3.4. Aspects for the Evaluation of Conventional Façades and BIPV Façades

The HES was developed for the detailed evaluation of both conventional façades and BIPV façades. Both façade types can achieve many importance points in the majority of the main criteria and individual criteria. However, BIPV façades can receive, by nature, more importance points for specific individual criteria. The specific properties of BIPV façades are addressed in subsequently discussed criteria, which may therefore significantly influence a higher number of importance points and the positive evaluation of BIPV façades.

3.4.1. MC "Flexibility"—IC "Flexibility by Functional Variability"

In contrast to conventional façade elements, BIPV façade elements can fulfill multiple functions, based on the specific properties of PV generators. BIPV façades can, for example, take on the following functions:

- Weather protection
- Heat insulation
- Fire prevention
- Sound insulation
- Electric energy generation
- Radiation protection from electromagnetic radiation
- Electromagnetic communication by using a BIPV façade as planar antenna
- Natural light management for interior by shadowing light control

If these functions are not taken into consideration in the technical integration process, additional components would usually be needed [5,9]. As part of installation technology, BIPV façades have a positive influence on the entire energy efficiency of a building because they can lower the primary energy requirements and contribute substantially to future-oriented town planning development [5,38].

3.4.2. MC "Ecology & Sustainability," IC "Energy Balance," and IC "Environmental Impact"

The environmental impact and the energy balance of façade elements result from summarizing and balancing the total or environmental costs and the energy consumption that occurs during the lifecycle of a façade element, and the total profits that can be generated during the same period. While conventional façade elements generate only environmental costs and only consume energy during their entire lifecycle, BIPV façade elements produce during the same period also gains in form of renewable electric energy. Accordingly, both the energy balance and the environmental impact of BIPV façade elements can be, by nature, significantly better than for conventional façade elements.

3.4.3. MC "Economy," IC "Compensation Costs," and IC "Lifecycle Costs"

The compensation costs for conventional façade elements replaced by BIPV façade elements can be investigated by estimation of conventional building component costs. According to exemplary calculations, minimal compensation costs for the replacement of conventional façade functions are in the range from 15.00 €/m^2 (e.g., for thermal insulation) to 35.00 €/m^2 (e.g., for esthetics/design). By consideration of multiple functions, the creditable compensation costs for the use of BIPV façade elements instead of conventional façade elements can be increased accordingly.

The lifecycle costs of façade elements result from summarizing and balancing the total costs that occur during the lifecycle of a façade element, and the total profits that can be generated during the same period. While conventional façade elements generate only costs during their entire lifecycle, BIPV façade elements produce, during the same period, gains in the form of renewable electric energy. Accordingly, the lifecycle costs of BIPV façade elements can be, by nature, significantly lower than for conventional façade elements.

The life cycle costs of two similarly constructed exterior walls but with two different claddings, one with high value tiles (1) and the other with crystalline BIPV panels (2), have been calculated and compared with each other. The results illustrate that the cumulative costs per m^2 for the marble façade are lower (Figure 3: balance cumulative without PV) than the cumulative costs per m^2 for the BIPV façade (Figure 3: cost cumulative). However, due to the estimated profit of 15 €/m^2 × a generated by renewable electricity production (Figure 3: gain cumulative), the cumulative balance of the BIPV façade element (Figure 3: balance cumulative with PV) is only 65% of the cumulative balance of the conventional façade (Figure 3: balance cumulative without PV) [12,13]. The costs for maintenance, financing and depreciation are included in the calculation. The specific recycling costs and the compensation for the external costs related with conventional electric energy have not been considered [39].

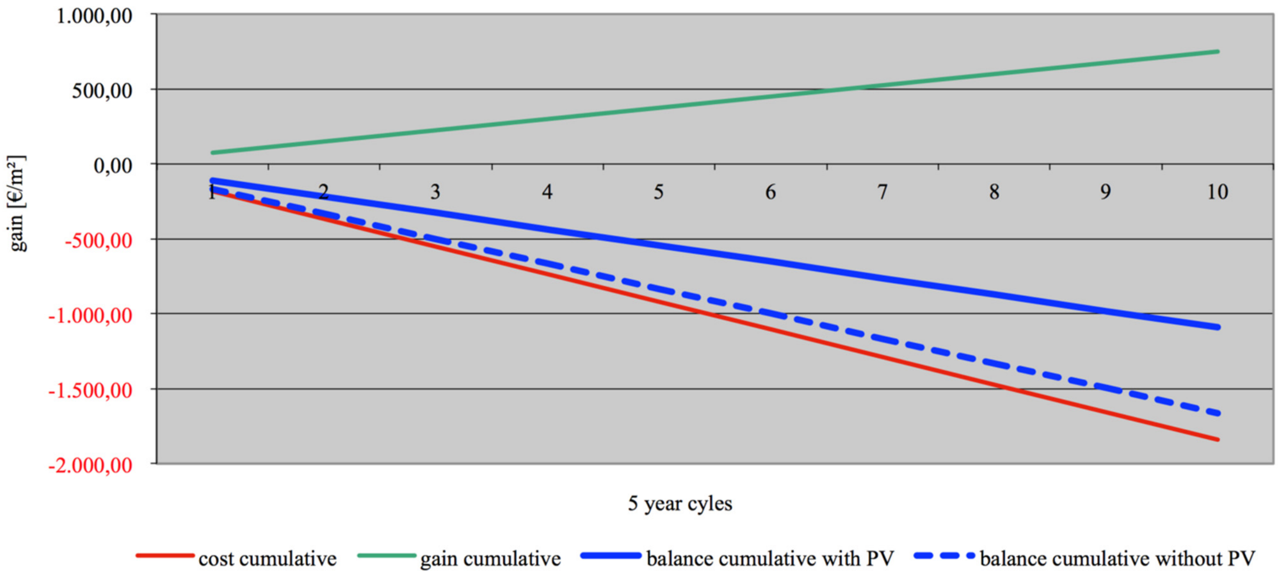

Figure 3. Lifecycle costs of a conventional façade with high value cladding and a BIPV façade over a period of 50 years divided in 5-year cycles.

4. Conclusions

A holistic evaluation system (HES) for façades with and without BIPV was developed within the framework of the MULTIELEMENT II research project. The system can be applied on façades that are in the planning stage or on façades that have already been built. Different façades can be evaluated and compared with each other regarding multiple individual criteria (three to six) which are assigned to the six main criteria "Design", "Flexibility", "Ecology & Sustainability", "Production", "Economy", and "Building Physics & Construction". This HES method aims for the utilization of the evaluation results in different sustainable building assessment and certification systems, such as DGNB [23], LEED [24], and BREEAM [25]. This HES consists of checklists and Microsoft Excel-based calculation tools, such as the "Evaluation Matrix" and the assigned "Evaluation Diagram". Based on the HES, a "Decision Tool" is developed for the practical application and rough estimation of façade planning alternatives. A brief "Guideline" for the planning praxis is also developed on the basis of the checklists for each IC. Both systems have to be tested, optimized, and standardized carefully in a next research step before they are generally applicable.

The HES discussed in this paper needs therefore to be tested in the framework of concrete projects, based on detailed building documentation of realized façades or sufficiently described façades in the planning stage. Also the "Guideline" needs to be optimized, facilitating decision-making about specific planning options already during the planning phase of a building, by estimation of design, technical, and economic consequences of specific options. Furthermore, digital planning software for the holistic evaluation of façades during the planning stage, particularly considering multifunctional BIPV components, will be developed on the basis of HES.

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Author Contributions

The authors contributed equally to this work.

Conflicts of Interest

The authors declare no conflict of interest.

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