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Life Cycle Assessment for Photovoltaic Structures—Comparative Study of Rooftop and Free-Field PV Applications

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Abstract: The European Union has set itself the goal of increasing its share in renewable energy up to 42.5% by 2030 by accelerating the clean energy transition plan. National legislation within the Member States must now adapt the strategic plans to rapidly implement their allocation in renewable energy. Solar photovoltaics are in this context considered to be one of the technologies that could rapidly be rolled out, with both building-integrated as well as free-field photovoltaic systems needed to reach these ambitious goals. There are strong arguments for prioritizing photovoltaics on buildings, as they make use of land that is already sealed, and the environmental impact is considered lower as fewer resources might be needed for the structures holding the panels. However, since there is limited literature available to back this claim with quantitative data, this paper presents a comparative study of the structures needed to implement rooftop versus free-field photovoltaic applications. With a detailed life cycle analysis, several commonly used structures have been analyzed in relation to their environmental impact. The findings show that the impact on resources can be up to 50% lower in rooftop systems compared with free-field applications but that a series of site- and material-related factors need to be considered to prioritize one system over another on a regional scale. This study thus aims at providing fact-based decision support for strategic considerations related to photovoltaic implementation plans.

Keywords: photovoltaic systems; rooftop PV; free-field PV; building-mounted PV; life cycle assessment; renewable energy strategies

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1. Introduction

The recast of the Renewable Energy Directive has defined a renewable energy target of at least 32% for the European Union (EU) for 2030. In 2021, new climate targets have been defined with a proposal to also amend the Renewable Energy Directive to increase the share of renewables to at least 40% by 2030 [1]. Following this amendment, the European Commission published the so-called REPowerEU plan in May 2022, setting out a series of measures to drastically reduce the EU's dependance on fossil fuels with a particular focus to reduce imports from Russia. Based on three pillars, (1) saving energy, (2) producing clean energy and (3) diversifying the EU's energy supplies, the plan foresees to increase the target in the directive to 45% by 2030 [2]. By the end of 2022, a temporary emergency regulation was issued to accelerate granting procedures for renewables, and in March 2023, a provisional agreement was reached between the European Parliament and the European Council for a binding renewable energy target of 42.5% by 2030 [3]. Photovoltaics (PV) are considered one of the technologies that can be more easily scaled up and rolled out among EU countries; thus, the REPowerEU plan foresees, among other technology accelerations, a target of 320 GW of PV by 2025 and of 600 GW by 2030 from 158.9 GW in 2021 [3]. Strategically, the accelerations focus on large-scale partnerships, industrial alliances and the European Solar Rooftops Initiative, which aims at obligations for the installations of solar energy on public, commercial and residential buildings across the EU [3].

Overall, there is a strong argument towards a world with 100% renewables, and there are several studies that suggest that this is possible given the right framework conditions. Breyer et al. argue in their analysis of the history and future of 100% renewables that with wind and PV systems on the rise, this goal becomes achievable [4]. With PVs becoming one of the mayor pillars in the European renewable energy strategies, it is also important not to lose sight of other environmental priorities when implementing these systems. In a paper by Ristic et al., the authors assess the various technologies available for Europe's decarbonization based on a system of systems approach to address factors that combine costs, carbon, water and land footprint [5]. There is an ongoing debate as to where these renewable energy systems should ideally be implemented. Diversification is important, but there also needs to be a discussion on prioritizing certain regions or applications for installations. In addition, several factors, such as material and land use, need to be considered. This is where this paper aims at contributing.

There is also a strong argument in diversifying the application of PVs with different system technologies, such as building-integrated photovoltaics (BIPV), concentrated photovoltaics (CPV) and photovoltaic thermal (PV/T), depending on the requirements for power and/or heat and the land available [6]. This shows that there should be a strong correlation between the energy needed, the resources available and the land that can be used. Integrated spatial and energy planning supports this factor by matching energy demand with the availability of (renewable) energy sources [7]. Overall, the implementation of renewables becomes more decentralized and thus more dependent on local circumstances.

In relation to the increased implementation of PV systems, one can differentiate between roof-mounted and ground-mounted PV systems. The former are systems that are mounted on or integrated in a roof, and the latter are systems that are implemented on the ground, with a substructure holding the panels on place. While the roof-mounted systems are generally incorporated into building structures, the latter are installations on the ground, usually in already sealed surfaces, open fields or agricultural land. While from a structural, architectural and land-use perspective these are completely different approaches, the systems also differ in terms of degradation causes and efficiency [8]. A Review study on urban and building-integrated PV systems has also concluded that in dense urban settings, power production can adversely be affected by up to 20% compared with more favorable locations in more rural environments [9].

To break down the overall task of accelerating PV installations across Europe, one can look at the example of Austria, since the case studies used in this paper also refer to Austrian municipalities. In Austria, the share of renewables for power generation is 72%, which is already relatively high [10], with a large proportion coming from large-scale waterpower. Nevertheless, for the national energy targets, Austria has set itself the goal of achieving a rate of 100% renewable power generation by 2023 [11]. A total of 11 TWh are supposed to come from PV installations. Based on a study by Fechner [12], about 4 TWh could be accomplished with building-integrated PV (BIPV) under the current legislation and considering the technical constraints. BIPV in this context refers to both on-top systems (i.e., on the façade and on the roof) and fully integrated systems (i.e., substituting part of the façade or part of the roof). The remainder would need to be implemented as free-field PV systems, which would need an area of 57 km^2, under the assumption of an already improved efficiency compared with currently installed systems. This would equate to about 0.2% of the current agricultural land use in Austria [12]. In a study undertaken to assess the goals for the large-scale PV implementation in Austria, Mikovits et al. [13] adopted a comprehensive methodology to provide a spatially differentiated allocation of the potential of roof-mounted and ground-mounted PV systems, which provides a basis for decision support related to renewable implementation plans on a local level.

To compare building-integrated and free-field applications from an environmental perspective, there are several factors that need to be considered. The land used for PV systems in an open space that has previously not been sealed needs to be considered when opting for free-field applications. Fthenakis et al. have already argued in earlier studies that renewable electricity generation is also favorable in terms of land use compared with nonrenewable systems [14]. In this context, societal aspects must also be part of any evaluation. While some studies argue that there is a consensus among society when integrating PV in buildings [15], other societal and socioeconomic issues arise when addressing PV on green-field or agricultural land [16,17].

Agri-PV, which is the dual use of PV installations over agricultural land that yields both power from the PV as well as fruits or crops, has been on the rise in recent years and has thus more widely been researched. There are several studies that address the topic from an economic point of view [18,19], as well as from a market and industry perspective [20]. In earlier studies, the potential for Agri-PV has also been assessed [21], concluding that several crop species would benefit from shaded systems but also arguing that this highly differs depending on the species and the climatic conditions [22]. To evaluate the actual greenhouse gas mitigation effects, both the crop yield and PV output need to be considered, which might necessitate a different type of life cycle assessment [23]. Similarly, greenhouses that provide shading by incorporating PV to support the yield in the harvested plants can provide a dual function and thus need to be evaluated in this context [24]. Specific typologies, such as the "PV-tree", also provide an opportunity to implement PV on green fields while minimizing space and thus relevant land use [25]. Since the distribution of energy demand and supply are highly relevant, as described above, the spatial distribution of Agri-PV systems becomes ever more relevant [26].

While Agri-PV systems are on the rise in rural regions, there is an increasing trend to integrate PV more extensively in urban areas. On the building side, there are more and more applications that combine green roofs and PV systems in one area. While some earlier studies on this topic focus on the performance of these systems [27–30], others take a more holistic view and address the wider environmental, aesthetic and economic factors [31], as well as the important factor of life cycle analysis in this context by comparing different roof types [32]. Sattler et al. have assessed in a more recent study rooftop garden system, thus adding to the dual use of PV and plants on one surface area with the added benefit of shaded, recreational benefits for the occupants, thus creating a triple use [33].

When addressing the environmental impacts of the different applications of PV systems, the land use is undoubtedly one of the key criteria. Other environmental aspects relate to the actual life cycle of the systems. The materials and energy that are needed to produce and implement renewable energy systems strongly affect their overall environmental performance. Thus, the environmental impact due to the emission of pollutants and the consumption of nonrenewable resources becomes highly relevant, as outlined by Sherwani et al. [34], where a comprehensive review of various PV technologies was carried out. When it comes to PV, there are a multitude of studies that address this life cycle perspective. In some earlier studies, various systems have been analyzed based on specific metals and materials used [35–38], as well as on various system types, such as thin film [39] or concentrated solar power [40]. Eco-design perspectives and general co-benefits have also been elaborated by Chatzisideris et al. [39] and Gibon [41] et al., respectively. Similarly, there are a series of publications focusing solely on the life cycle assessment of BIPV [42–45], thus already addressing the important factor of systems that function without additional land use.

Considering the importance of the "cradle to cradle" view, i.e., addressing the component from the perspective of the materials sources, production and operation but also the end-of-life use and the overall energy prediction of the systems, as well as energy, the return on investment is highly relevant in this context [46,47].

While this review shows that there are a series of studies on the life cycle analysis of the actual PV systems, there is rather limited information available on the environmental impact of the actual construction underneath that provides structural support and stability to the PV panels. To assess the overall life cycle of PV systems, all aspects, including the underlying structure, need to be considered. However, the type and amount of structure needed highly depends on the actual application, i.e., if the PV system is integrated into another structure, such as a building, or if the PV needs a separate structure to be elevated from the ground or installed at a specific angle. Since the environmental impact is considered lower in building-integrated PV systems, as it makes use of land that is already sealed, there is also the argument that fewer resources might be needed for the structures holding the panels compared with free-field structures. These seem to be strong arguments to prioritize PV on or integrated in buildings compared with free-field systems. However, since there is limited literature available to back this claim with quantitative data, this paper presents a comparative study of a life cycle assessment for the structures needed to implement rooftop versus free-field photovoltaic applications.

The aim of this paper is to present the findings of the study that analyzed and compared the ecological effects of the structures of rooftop and free-field photovoltaic systems with the following research question: Which structure types that are required to hold photovoltaic panels in place are the most efficient in terms of ecological balance in a direct comparison between rooftop and free-field systems? To answer the research question, the substructure of the photovoltaic systems was analyzed with a detailed life cycle assessment that compared several commonly used structures for both roof-mounted and free-field systems. To allow for an equal comparison, only on-top structures for PV roof-mounted PV systems were analyzed. Fully building-integrated PV (BIPV) was specifically excluded, as this would have required to allow for the substitution of one material with another. To also provide an assessment of the potential areas required to cover the current power demand, an exemplary analysis of rooftop and land-use requirements was examined using two case study examples. The methodology is summarized in Section 2, followed by the results in Section 3 and the subsequent discussion and conclusion.

2. Methodology

The method chosen to address the research question mainly consists of the key part on the life cycle assessment and a case study to apply the findings to an example in smaller towns in a rural area in Austria. Both parts were supported by a literature review with the aim to determine the state of the art on the ecological aspects of PV systems and their substructures, as well as the framework conditions related to rooftop PV systems and free-field PV systems. This review was also essential to determine the qualitative aspects of the results. The main component of the quantitative analysis was a life cycle assessment of the components of PV substructure types. The quantitative analysis includes mathematical and statistical research methods. The results consist of numerical values. The quantitative assessment provides an important aspect to deliver comparative results from different systems and types. The respective case studies consisted of a Geographical Information Systems (GIS) analysis, which gave an example of the potentials for implementations of PV structure in two predetermined areas in Austria for both rooftop systems and free-field PV structures. The overall approach of the study is summarized in Figure 1. It shows that the research question addresses the ecological effects, which are then addressed both by a quantitative analysis as well as a qualitative analysis.

2.1. LCA Assessment—Methodology

The main section of the quantitative analysis consisted of a life cycle assessment (LCA), which contains a technique for assessing different aspects associated with the development of a product and its potential impact throughout a product's life [34]. The LCA included three steps, as shown Figure 2. The depicted framework for the assessment consists of different steps to define goal and scope and an inventory analysis, as well as an impact assessment that is then interpreted with the use of relevant data. This can then be used for various applications such as product or policy development.

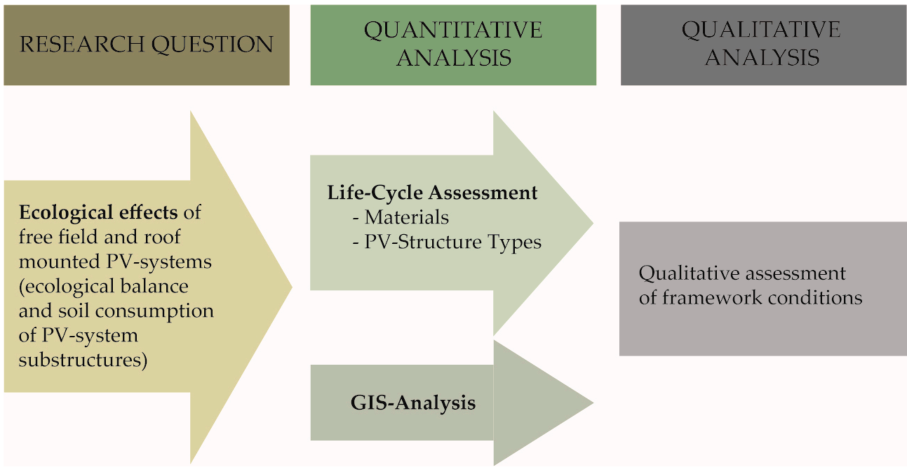

Figure 1. Illustration of the method and its main sections.

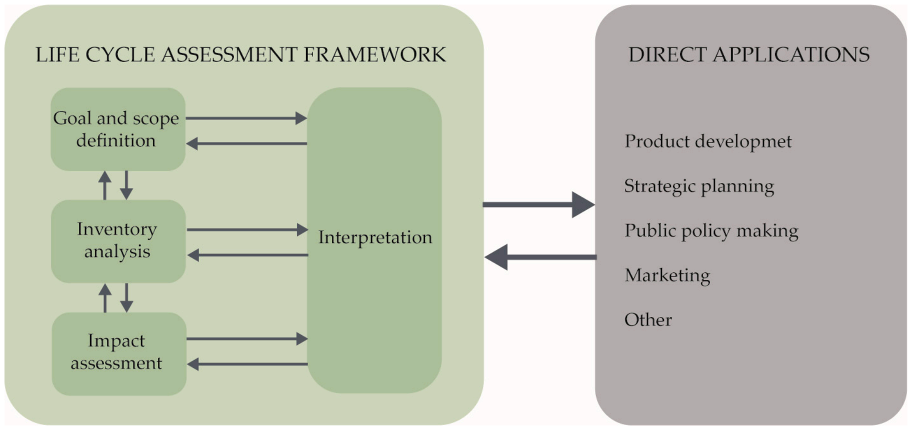

Figure 2. Life cycle assessment framework (based on [48]).

The first step was to define the goal and the scope of the LCA. The goal was to assess the differences between the different types of substructures of PV systems. The attention was on the differences between roof- and ground-mounted PV structures, as well on defining the gap between different types of structures. Therefore, the roof-mounted PV structures were divided in pitched- or slanted- and flat-roof-mounted PV structures. In addition, the ground-mounted PV structures were split into three groups: (1) agricultural PV (Agri-PV), (2) parking roof PV structures and (3) greenfield PV structures. The next step was to define the scope boundaries. Since the main aim was to assess the environmental impact of the structural system, the LCA in the applied method only describes the substructure of the PV systems. Thid means the PV module is not part of the analyses, as the LCA of the actual PV system is independent of the substructure.

The parameter that was chosen in this method was the Global Warming Potential total (GWP-total) specified in “kg CO_2 equivalent per m^2 reference area” per PV module. The GWP is assumed over a period of 100 years (GWP100) and in kg CO_2-Equivalent (kg CO_2 equ.). The reference area of the eco-index (or in German the “Bezugsfläche des Oekoindex-BZFOI”) is the specified gross area together with 50% of the gross area of the buffer zone, when related to buildings [49]. These parameters were calculated in a software called “baubook eco2soft” [49], which is primarily used to calculate the ecological balance for buildings but can be equally applied to all building structures and substructures. The “baubook” is a web portal for building products, components and tools that simplifies the assessment of life cycle data in buildings. The web platform provides validated building material data for the calculation of energy and ecological performance indicators by an independent research institute. The core of the “baubook” is the product database. There, manufacturers declare their building products. Test certificates for the building physical and building ecological characteristic values are stored centrally in the database. After successfully passing "baubook" quality assurance, the declared products are listed in all target group-specific platforms.

The second step of the LCA was an inventory analysis. In this part of the LCA, various materials that are typically used for roof-mounted or free-field PV systems and their respective pollutants were summarized. The selected materials and their Global Warming Potential (GWP) are shown in Table 1. The comparison of the GWP of the various materials highlights the significance of the choice of material and the respective environmental impact.

Table 1. List of Materials and their GWP specified in kg CO_2 equ. per m^2 reference area [49].

Materials	GWP Total kg CO_2 equ. per m^2 Reference Area
Standard concrete with reinforcement 2% (2400 kg/m^3)	0.161
Galvanized steel	2.12
Standard concrete C12/15 (2400 kg/m^3)	0.0866
Timber (525 kg/m^3–ex. larch)–air-dried	−1.69
Aluminum plate	5.97
Cast iron	1.47
Rubber, synthetic material	2.59
Expanded rubber (60 kg/m^3)	2.86

In the third step of the LCA, an impact assessment was carried out. In this stage, conclusions were drawn in an interpretation stage [34]. Accordingly, the data from the LCA were evaluated and applied in charts to show the differences between the various types of PV substructures. Furthermore, conclusions about the materials and the location were gathered. Overall, the comparability of the components between the different PV structure types were highlighted. Based on the results of the LCA, roof-mounted and ground-mounted PV structures can be compared based on the ecological aspects of their substructure.

To further interpretate the data of the LCA, the PV substructures were also analyzed by their Energy Payback Time (EPBT). The EPBT is defined by the period required for a PV module to generate the same amount of energy that was used to produce the system itself [50].

The formula used for the calculation of the EPBT is based on [51]:

$$\text{EBPT} = \text{E input}/\text{E saved} \tag{1}$$

- EPBT = Energy Pay Back Time;
- E input = The energy input during the module life cycle (which includes the energy requirement for manufacturing, installation and energy use during operation, as well as energy needed for decommissioning);
- E saved = The annual energy savings due to electricity generated by the PV module.

The E (electrical energy) input was calculated with the nonrenewable primary energy, which is used to manufacture the components. The respective data were read out of the "baubook" database [49], which was also applied to the LCA. To calculate the EPBT, the same components as in the LCA were used. The primary energy content (PE) is the total requirement for energy resources. The "PENR" lists the primary energy content of all nonrenewable resources (oil, coal, etc.). The "PENRT" contains both the energetically and the materially used resources [49]. Therefore, the PENRT was used for the E input.

The determination of the E saved depends on the performance of the PV module, which is dependent on the location and the efficiency of the panel. To achieve comparable results, for the purpose of this study, an average polycrystalline PV module was used in all cases to determine the EPBT. A typical polycrystalline PV module can reach an average of 1 kWp performance on a surface of 7 to 10 square meters in Austria [52]. Thus, for this study, an average of 8.5 square meters was used and applied to all selected systems. This concludes that a typical PV module with 1.7 square meters has a performance of 0.2 kWp. For the assessment, only the EPBT for the substructure of the PV system was calculated. Therefore, it could be determined how much the substructure affects the EPBT of the whole PV system. After the LCA and the EPBT, an evaluation of the results was carried out and put in a qualitative context.

2.2. GIS Analyis—Methodology

In the second part of the methodology, a GIS analysis is applied on a case study for the LCA to compare the actual application of roof-mounted and free-field PV structures. The question of the ecological impact in a regional context manifests. Therefore, the methodology demonstrates the environmental aspect of rooftop- and ground-mounted PV. In this context, it must be noted that the results of the GIS analysis are limited to the area that was chosen. That implies that the results would be different with other geographical characters. For this, a suitable software (ArcGIS Qgis 3.24.3 [53]) was used to determine areas and subsequent uses. The GIS analysis is an example of the application in two communities that have very different spatial conditions and can therefore serve as an example for other communities. While the LCA shows the ecological effects of the substructures of the PV systems, the GIS analysis gives an example of what is possible in a selected area and what input the PV expansion would have on the open space available in a specific region. The analysis included several steps to obtain an understanding of the spatial impact of roof-mounted and free-field PV structures. The first step was to select suitable case study sites for the GIS analysis. Therefore, it was essential to select a municipality that provided data about potential PV rooftop and land use. In addition, the two chosen municipalities needed to have different requirements in terms of land use and housing structure. Based on these criteria, the two municipalities, Weiz and Thannhausen in Styria, Austria, were chosen as examples for the analysis. Weiz is a denser semiurban are, and Thannhausen is a less dense and more rural area, as shown in the data in Table 2. The second step was to establish the consumption of electrical energy for the two chosen municipalities. To determine how much electrical energy is required, an energy balance compliant representation was used. This means that only electrical energy that was consumed on site was used for the calculation. For that reason, energy data related to mobility were specifically excluded. The key data and the used electrical energy for Weiz and Thannhausen are shown in Table 2. The data for the municipalities were extracted from the database used in Energiemosaik, Austria [54]. The assessment is based on renewable energy data for Austria from 2021, where a stated 72% of electrical energy in Austria is obtained from renewable energy sources and subsequently 28% from nonrenewable energy sources [10].

Table 2. Key energy and land-use data for the two case study municipalities, Weiz and Thannhausen.

	Weiz	**Thannhausen**
Population	11,701	2439
Area	18 km^2	34 km^2
Residential area	586,200 m^2	113,600 m^2
Cultivated area	10 km^2	29 km^2
Power consumption	532,800 MWh per year	58,300 MWh per year
Ratio of electrical energy in an energy balance compliant representation	190,196 MWh/a	11,222 MWh/a
72% of electrical energy in Austria is from renewable energy sources [10]		
Electrical energy that should be covered by PV systems	53,254 MWh/a	3142 MWh/a

The third step was to define the roof space that would potentially be available for PV structures in the two municipalities to determine how much of the electrical energy used could be covered my roof-mounted PV systems. To assess this, the building data were incorporated into the GIS maps to calculate the theoretical roof potential based on roof orientation and solar availability. Regarding how much electrical energy was still needed to supply the municipalities with electricity, the next step was to assess how much PV system area would need to be installed in the open field. Finally, the quantitative results were compared for the two municipalities. For this paper, the GIS analysis merely shows an example of the different potential areas of rooftop and free-field PV systems in Austria based on a detailed assessment, as documented in [55].

At the end of this paper, the results of the LCA and the EPBT analysis, as well and the GIS analysis, are documented in a qualitative section, where the differences between rooftop and free-field PV structures and their environmental impact are discussed.

3. Results

To analyze the impact and ecological effects of the PV structures, the method was applied quantitatively and interpreted in a qualitative analysis. As described in Section 2, the methodology consists of two sections, the LCA and the GIS analyses. The main assessment focuses on the LCA analysis of different roof-mounted and ground-mounted PV structures.

3.1. Categorization of PV Structures

Based on the structure of LCA assessments by Rebitzer et al. [48] (see Figure 2), in a first step, the goal and scope have to be set. For the quantitative analysis, the different construction types for the PV structures were defined. Furthermore, the materials of the different structures, as well as the sizes and standard dimensions, were essential to assess the structures. For an initial categorization, the structures were divided and described in roof-mounted and ground-mounted (free-field) PV structures.

3.1.1. Roof-Mounted PV Structures

The structure needed for roof-mounted PV systems mostly depends on the orientation, inclination and shape of the roof. If the roof is flat, the PV panels are usually applied at an angle in either full south orientation or east–west orientation. In either case, a substructure is needed to provide the ideal angle for the PV panels. For a pitched or slanted roof, PV panels can either be implemented at the angle of the roof, which requires only hooks or fasteners to connect the roof to the PV panels, or a construction similar to a flat roof if a higher angle is required. Therefore, the substructures are divided as follows:

- Pitched or slanted roof:
  - Roof hook;
  - Profiled roof hook.
- Flat roof:
  - Adjustable basic structure;
  - Adjustable basic module with floor connectors;
  - Rooftop structure with east–west orientation.

The detailed LCA assessment of these structures related to their respective GWP and EBPT was carried out using the database for materials with the software "baubook eco2soft" [49], as outlined in Section 2.

Table 3 shows the differences between the chosen types of PV substructures for roof-mounted PV systems. The roof hooks have the lowest GWP and the lowest EPBT for the case study, which is due both to the type of material used and the relative limited quantity of material used compared with other structures.

Table 3. GWP and EPBT for selected roof-mounted PV structures.

Type	Roof-Mounted PV Structures	GWP Total kg CO_2 equ. per m^2 Reference Area	EPBT (Years)
Pitched or slanted roof	Roof hook	27	0.5
	Profiled roof hook	71	1.3
Flat roof	Adjustable basic structure	58	1.2
	Adjustable basic module with floor connectors	83	1.5
	Rooftop structure with east–west orientation	71	1.3

3.1.2. Ground-Mounted PV Structures

The most significant difference between roof-mounted and ground-mounted (free-field) PV structures is the anchoring options in the ground. In the context of the roof-mounted PV structures, the anchoring does not have a significant impact on the LCA, as the structure is connected to the roof and does not need an additional foundation. However, the ground-mounted PV structures must have some sort of foundation in the free field. Thus, to accurately compare the different ground-mounted PV structures, the foundations must be considered in addition to the above-ground structures. The results for the GWP total for the various foundation types are shown in Table 4.

Table 4. GWP for selected foundations for ground-mounted PV structures.

Foundation	GWP Total kg CO_2 equ. per m^2 Reference Area
Concrete foot	5
Ramming profile	32
Screw anchor	166
Deep foundation 30 × 30 × 80 cm	122
Deep foundation 40 × 40 × 80 cm	199
Strip foundation	466
Concrete-free foundation with 6 metal threads	47
Concrete-free foundation with 12 metal threads	48

A comparative overview of the different foundation types is shown in Figure 3.

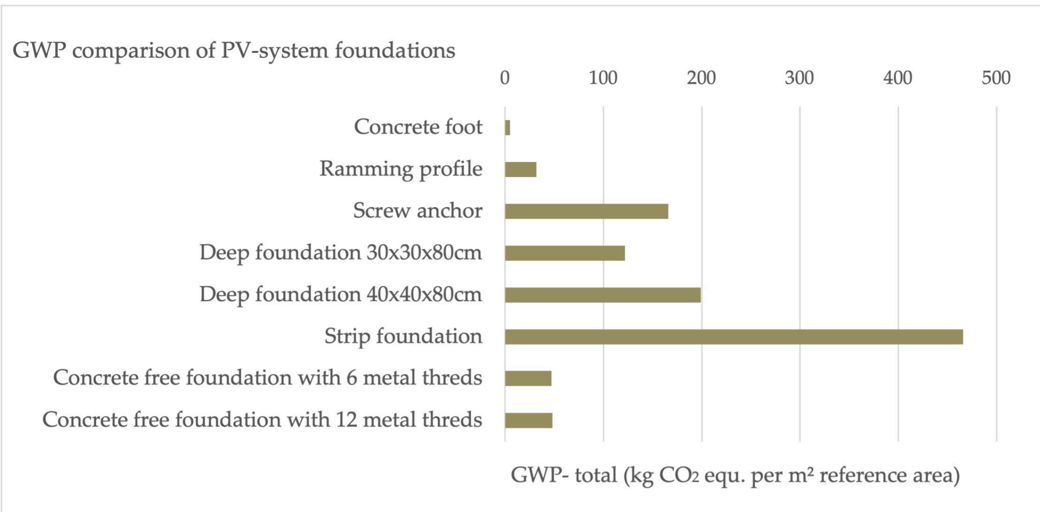

Figure 3. GWP comparison for selected foundations for ground-mounted PV structures.

The results, as depicted in Figure 3, show that the choice of foundation has a significant impact on the overall GWP for the structure. For an equal comparison, a foundation was selected that could potentially be used for all ground-mounted structure types. For the overall assessment of the ground-mounted PV structures the "concrete-free foundation with 6 threads" was used for all ground-mounted structures to provide an equal assessment of the above ground structure. This foundation was chosen because it can be used for different types of ground conditions, and it can cater to various sizes of PV systems. For the application of the chosen method, it was relevant to compare the different ground-mounted PV structures.

For the ground-mounted (free-field) structures, there are several types that are currently being used. The types depend mostly on the ground, where the structure is implemented and the potential additional use other than that for energy generation. For agricultural land use, several types have emerged in recent years, as already documented in Section 1. For agricultural use, mostly vertical PV systems and canopy PV structures are implemented. These systems are summarized under the category "Agri-PV". Shading or protection for cars are categorized under "Parking roof PV structures". As a last category, the "Greenfield PV structure" was defined, with the main difference from the "Agri-PV" systems being that no additional agricultural use is applied in combination with these systems. Thus, the structures were categorized as follows:

- Agri-PV:
  - Vertical PV system;
  - Canopy PV structure.
- Parking roof PV structure:
  - Steel parking roof structure;
  - Wood parking roof structure.
- Greenfield PV structure:
  - High pole PV structure;
  - South-orientated PV structure with one pole;
  - South-oriented PV structure with two poles;
  - Wood south-orientated PV structure;
  - Free-field structure with east–west orientation.

As before with the roof-mounted PV structures, all systems were analyzed based on their respective quantity and type of material use. The results from the LCA analysis are summarized in Table 5.

Table 5. GWP and EPBT for selected ground-mounted PV structures.

Type	Ground-Mounted PV Structures	GWP Total kg CO_2 equ. per m^2 Reference Area	EPBT (Years)
Agri PV	Vertical PV system	85	1.1
	Canopy PV structure	125	1.7
Parking roof PV structures	Steel parking roof structure	192	2.4
	Wood parking roof structure	3	0.4
Greenfield PV structures	High pole PV structure	120	2.2
	South-orientated PV structure with one pole	137	1.6
	South-orientated PV structure with two poles	102	1.1
	Wood south-orientated PV structure	2	0.3
	Free-field structure with east–west orientation	131	1.6

This shows that both the GWP as well as the EPBT for the case study vary depending on the type of structure, as this influences the type as well as the quantity of the materials used. The more elaborate the structure, for example, with canopy systems, the more material is used and the higher the impact. The choice of material, for example, wood compared with steel, similarly highly influences the results. The following subchapter provides a comparison of the two main types of analyzed structures.

3.2. LCA Assessment—Results

The results of the GWP of roof-mounted and ground-mounted PV structures are compared in Figure 4, where the gray bars represent the roof structures and the green bars represent the structures used for free-field applications. It becomes evident that except for constructions based on wood, in general, roof-mounted structures have a lower GWP than ground-mounted structures.

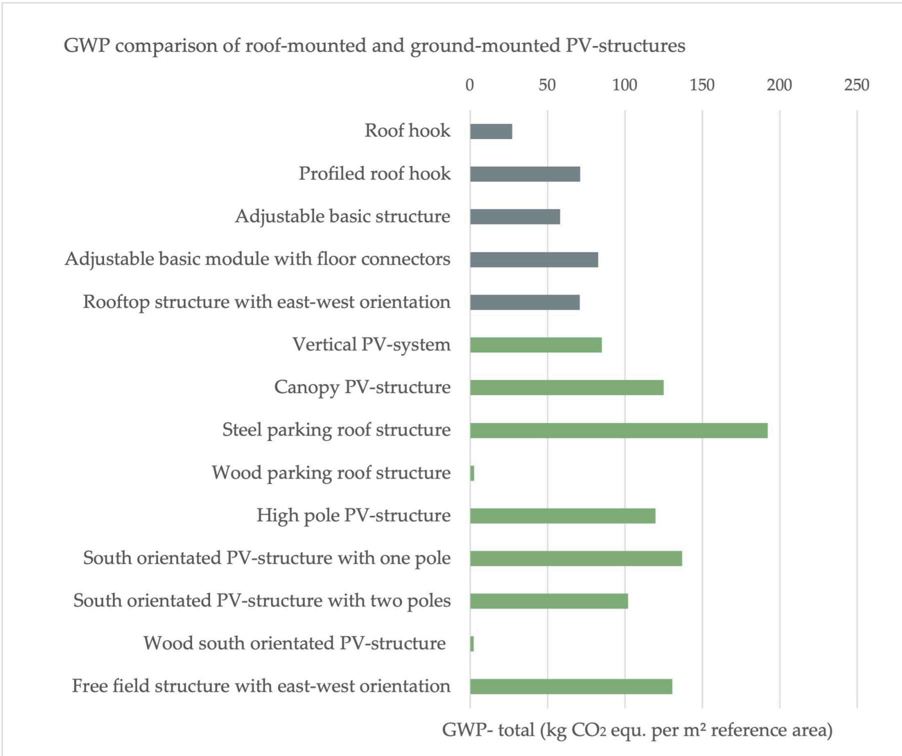

Figure 4. GWP comparison for selected roof-mounted and ground-mounted PV structures.

This shows that the choice of materials and their quantity needed for the respective structures are decisive for the impact of the GWP. Especially, the foundations of the ground-mounted PV structures are not to be dismissed. The wooden substructures in the free-field structures are noteworthy. Because wood has a negative GWP (see Table 1), the GWP for these structures is very low and thus almost neglectable. Thus, except for wood structures, free-field PV structures, which are used for comparison in this paper, have a GWP that is almost 50% higher than that of roof-mounted PV systems. This shows the significance of the amount of material used in different construction types, as free-field PV needs a more complex substructure to withstand wind and other forces than roof-mounted PV. The impact of the material on the GWP is shown in the difference in GWP between steel and wood parking roof structures. For parking roof structures, the construction is more extensive and requires more material than in other structures, because cars have to park beneath it. However, the wood parking roof structure has the second lowest GWP of the chosen structures due to the inherently low GWP of wood.

In Figure 5, the EBPT comparison for selected roof-mounted and ground-mounted PV structures is shown, with the gray bars representing the roof structures and the green bars representing the structures used for free-field applications.

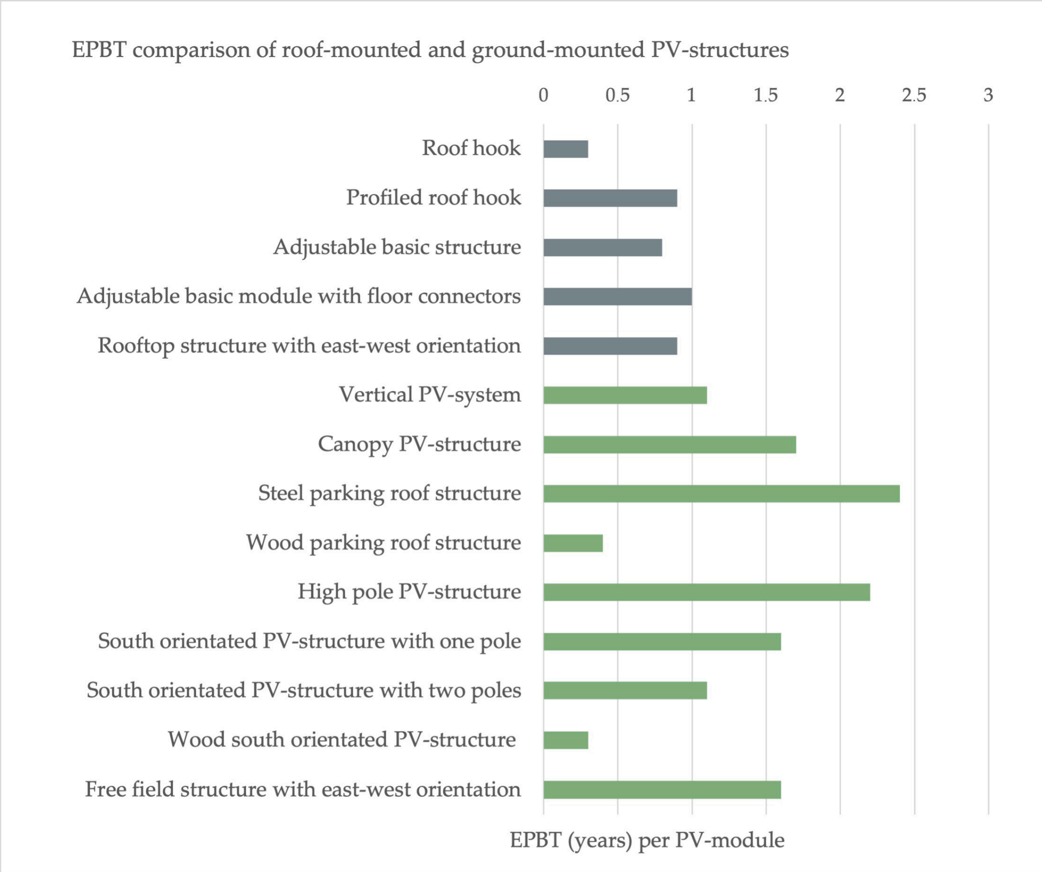

Figure 5. EBPT comparison for selected roof-mounted and ground-mounted PV structures.

This shows that GWP and EPBT increase and decrease similarly, as structures with a high GWP also have a high EPBT, as the same data for the PV panel efficiency and location are used for the calculation of the EPBT. This is because both the GWP and the EPBT depend on the amount and choice of material used. However, when it comes to the EPBT, it should be noted that is also influenced by the performance and choice of the PV module. This is why it should be considered that free-field PV systems can usually be positioned in an optimal orientation and angle towards the direction of the sun, while roof-mounted PV structures mostly depend on the orientation and angle of the roof. However, irrespective of the type of PV used and the exact location, the choice of the PV substructure can influence the EPBT of the overall PV system. On average, the PV substructure of roof-mounted PV systems can extend the EPBT for up to half a year. Free-field structures, except for the wooden structures, can increase the EPBT for up to two years.

Overall, the results of the GWP and the EPBT are purely quantitative and focused on the structure only. In addition to the results of the GWP and the EPBT, land use should be included in the discussion, as the availability and distribution of different land-use types in specific regions can be a decisive factor in the choice of applications. Therefore, as outlined in Section 2, the next step was to address this issue with the application of a case study.

3.3. GIS Analysis—Results

The GIS analysis showed, on the one hand, the difference in size, energy demand and potentially available area between the two municipalities, Weiz and Thannhausen (Table 2). On the other hand, it broke down the importance of spatial questions in the planning of PV systems and the challenges of the increased implementation of renewable energy sources. The results shown in Table 6 are an example of the distribution possibilities of roof-mounted PV systems.

Table 6. Results of the GIS analysis for Weiz and Thannhausen based on the potential PV coverage.

	Weiz	**Thannhausen**
Electrical energy that should be covered by PV systems	53.254 MWh/a	3.142 MWh/a
Potential areas for roof-mounted PV systems	22.115 kWp	5.361 kWp
Coverage of electrical energy with roof-mounted PV systems	41%	100%
Necessary coverage of the electrical energy with free-field PV systems	31.419 kWp is to be installed in the open field	0 kWp

For the purpose of this study, an average irradiation value for Austria was applied with the assumption that 1 kWp of installed power results in approximately 1 MWh/yr in energy yield. The exemplary results show that the municipality of Weiz could potentially cover 41% of the electrical energy that is required in the area by roof-mounted PV systems. This would mean that a remaining 31.419 kWp would need to be installed in the open field. This equals around 31 ha (3%) of the cultivated area in Weiz. Since the municipality Thannhausen has a lower demand for electrical energy, the local requirements could be covered solely by roof-mounted PV systems. In addition, there is a surplus of 2.219 kWp when all roofs are used for PV installations. This also relates to the previously described study by Mikovits et al. [13], where it is concluded that in theory, the requirements for PV in Austria could potentially be covered solely by the rooftop potential for PV systems. However, they also conclude that for future power demands, both free-field and building-integrated options must be pursued.

The exemplary GIS analysis showed the importance of roof-mounted PV systems, but furthermore, it set an example for the need to analyze the combination of free-field and roof-mounted PV systems on a case-by-case basis. Nonetheless, it should be noted that this GIS analysis represents the technical potential of PV systems in the two case study municipalities of Weiz and Thannhausen to give a rough indication for the required sizes. The technical potential indicates only the theoretical potential for the municipalities. For a more accurate estimate, the realizable potential must be calculated, as this would also include ecological, social and economic aspects. However, for a rough estimate of roof-mounted PV systems, the technical potential can be used to state an example of the possibilities of the distribution of PV structures.

Overall, the LCA and the GIS analyses state a quantitative framework for the decision-making progress concerning the choice and location of a PV system.

4. Discussion

In the evaluation of photovoltaic systems, qualitative, organizational and economic aspects must be considered in addition to technical parameters, such as GWP and EPBT, to be able to present an evaluation as well as the application possibilities and limitations of the different types of photovoltaic systems.

The demand for building-integrated solutions, which could be favored from an ecological point of view, is faced with the great interest of system installers in the implementation of ground-mounted PV systems. A main driver of the strong growth of ground-mounted PV systems is their better cost efficiency. By building large plants, proportional transaction costs for planning, permits, construction and coordination are significantly lower, thus reducing the cost per installation capacity. In addition, a higher yield can usually be achieved with ground-mounted systems, as the modules can be more optimally aligned.

The Implementation of building-integrated systems or systems that are placed on top of existing structures, especially in existing buildings, is further complicated by increased planning and coordination efforts. In addition to the technical effort, such as the structural ability of the roofs and the routing of the cables, as well as the integration into the building services, an increased planning and approval effort is required due to building regulations, local image and heritage protection, as well as an often more complex set of stakeholders (number of owners, neighbors, etc.). Thus, it is often difficult to reconcile the interests and goals of building owners and system builders. The refinancing periods of plants and the planning horizons of businesses can differ greatly and can subsequently represent an obstacle to implementation.

The economic and organizational disadvantages of building-integrated systems are offset by ecological advantages. On the one hand, the substructures have a lower GWP, as was demonstrated with this study. On the other hand, no additional land use, sealing of additional land or the use of foundation in greenfield applications is needed.

The aesthetics of the systems on buildings and in the landscape as well as the intervention in the landscape are important factors for the acceptance of PV systems. On intensively managed agricultural land or parking lots ("agricultural and asphalt deserts"), the view on aesthetics and acceptance of changed aesthetics can greatly differ.

Optimal orientation can produce a higher yield, and the choice of material can lower the environmental impact. While wood is a good choice for canopies, metal can be costly but necessary for Agri-PV if increased stability or longevity is required. In addition, it must be considered that the EPBT for the actual PV systems can decrease over time with improved efficiency and better production for the panels; so, wood construction for canopies may not be necessary given the need and vast capacity. Looking ahead, the integrated design and implementation of PV systems on buildings is becoming more relevant. When systems are planned and implemented not only as add-ons but as structural components, another ecological and economic advantage is created: PV as a roofing material or an inherent component in a façade system.

In view of the need to expand the use of renewable energy sources, the question from an ecological point of view is not one of implementing either one system or another but rather one of implementing both systems, however, with consideration of site-related factors. Both building-integrated and ground-mounted solutions will be important components of the energy transition. The results of this study should provide quantitative data on the choice of material and type of structure used in this context.

To achieve this, it is necessary to build planning know-how in dealing with integrated systems and to provide certified products from manufacturers. It is also important that planners and builders develop an understanding of this type of construction method and are aware that such planning and implementation of PV systems on buildings can provide additional added value for the buildings, such as the yield from the systems and additional shading and weather protection, as well as a building culture learning effect that considers technical facts as well as cultural and architectural ones for planners and building owners.

Given the environmental benefits of building-integrated PV solutions, legal and organizational measures should be put in place to support the implementation of such systems. As already implemented in some provinces in Austria (e.g., Vienna and Styria), an obligation for the mandatory use of such systems can be helpful. In this context, minimum requirements for the installed solar power should be defined according to the type of use and the usable area. If such regulations are not possible, at least regulations for the obligatory preparation or consideration of building-integrated systems can be made. To promote a building culture orientated towards solar energy, an integrated planning culture and specific training tracks should be developed in the academic and planning fields, as well as in the practical ones. This should lead to better planning as well as technical and physical integration of the system in buildings.

5. Conclusions

Recent legislation on the European and national level aiming at raising the share of renewables will accelerate the implementation of photovoltaics. Both rooftop as well as free-field implementations will have to be substantially increased to meet the ambitious climate goals. The type of installation depends on a series of framework conditions, such as land use and location, as well as technical and economic feasibility. Among these aspects, the life cycle assessment of the actual structures holding up the panels in a ground-mounted or roof-mounted application differs significantly, as ground-mounted systems need more resources, as they cannot build on other structures such as roofs or existing canopies. The assessment undertaken in this study, which compared the structures needed to fasten PV panels on roofs with erecting specific structures to hold PV panels on the open field provides quantitative data on the two different systems. It shows that constructions for free-field PV systems, which are ground-mounted and need structural foundations, can have a GWP of more than 50% higher than roof-mounted systems for the same PV reference area. Based on a typical PV module efficiency and an application in central Europe, the simplest systems on slanted roofs thus can have an EPBT of 0.5 years compared with a typical free-field streel structure with an EPBT of 1.1 and 2.4 years, depending on the complexity of the construction type. However, construction on roofs that hold up the panels at a certain angle, which is usually the case for flat roofs, can have an EBPT of 1.1 years, which is comparable to the simplest systems on the free field. The lowest impact can be achieved by using wood structures with a GWP close to zero, compared with metal structures with a GWP over 120, which highlights that the choice of material is a critical factor in the total life cycle impact. Overall, one can conclude that even though the rooftop systems generally have a lower GWP and EPBT, the differences are relatively small, given that PV systems yield renewable energy for at least 30 years or more. Thus, the life cycle approach is one of many factors that would need to be considered in PV implementation strategies, but other factors such as site, location and economics of scale are equally relevant and might be, on a local scale, more decisive. Future work in this context should focus on developing strategies can that provide comparative data on a local scale in order to prioritize adequate system types for different regions.

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