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Life Cycle Assessment of Luminescent Solar Concentrators Integrated into a Smart Window

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Abstract: The main goal of this paper is to assess the life cycle environmental impacts of a multifunctional smart window luminescent solar concentrator (SW–LSC) prototype through the application of the Life Cycle Assessment methodology. To the authors' knowledge, this is one of the first studies on the topic. The analysis followed a cradle to gate approach, considering the assembly and maintenance phase as well as the end of life, examined separately through a recycling/landfill scenario. A comparison of the impacts of LSC modules with those of some building-integrated photovoltaic technologies was carried out. Results showed that the global warming potential (100 years) for SW–LSC was 5.91×10^3 kg CO_{2eq} and the manufacturing phase had the greatest impact (about 96%). The recycling/landfill scenario results showed the possibility to reduce impacts by an average of 45%. A dominance analysis of SW–LSC components showed that the aluminum frame was the main hotspot (about 60% contribution), followed by the light-shelf (about 19%). Batteries and motors for the shading system were the biggest contributors in the abiotic depletion potential category (36% and 30%, respectively). An alternative scenario, which involved the use of 75% recycled aluminum for the window frame, highlighted the possibility to reduce environmental impacts from 3% to 46%. Finally, the comparison results showed that the LSC modules' impacts were on average 870% lower than that of various PV technologies when compared on the basis of m^2; on the contrary, LSC modules had the highest impacts in all categories (from 200% to 1900%) when compared with other PV technologies on the basis of 1 kWh of energy generated. The results could be used for the definition of eco-design strategies for the examined device, in order to support the scaling-up process and to put "greener" systems onto the market.

Keywords: life cycle assessment; smart windows; photovoltaic technologies; luminescent solar concentrator

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1. Introduction

The building sector has a key role to play in achieving the objectives recommended by the European Union to reduce greenhouse gas emissions and to increase the use of technologies powered by renewable sources by 2030 [1]. The building sector is responsible for almost 40% of global CO_2 emissions and energy consumption, considering both commercial and residential buildings [2]. The future of this sector involves an evolution towards buildings that are more efficient, smart and self-regulating, allowing it to achieve maximum energy saving and greater comfort for occupants [3]. In this field, the concept of nearly zero-energy buildings (nZEBs) has become a core item in decarbonization policies throughout the EU, providing energy independence and synergy with the grid [4]. The successful design and construction of nZEBs includes energy-efficient measures and the use of renewable energy sources (RES), targeting the minimization of energy needs to obtain the right balance between energy use and generation [5]. Other significant aspects of nZEBs are the integrated design [6] and the use of smart technologies; smart technologies and controls facilitate the operational phase of buildings based on energy control and storage strategies, while the integrated design ensures the exploitation of space, opening to new design and construction scenarios [7].

The current trend in photovoltaics installation in the urban context is their integration with building elements, especially roofs. Even if this solution is always to be considered, sometimes there are problems connected with the spaces available, as well as shading issues, which could compromise or reduce the generation potential of the devices. Furthermore, in the perspective of nZEBs, the energy provided by the roof-photovoltaic is adequate for moderately high buildings, which do not exceed a certain height, and this complicates the achievement of the energy balance; consequently, the use of other solutions and additional renewable technologies is required.

In addition to energy generation, another aspect to consider for buildings is the increase in efficiency and the comfort for occupants. In this perspective, thermal comfort is to be pursued as well as visual comfort while keeping thermal performance of the envelope as high as possible.

Considering these aspects (need of increasing energy generation from renewable sources and the problems connected to glazed elements), the technology of Luminescent Solar Concentrators (LSCs) has suitable features for buildings integration, especially in the urban context. An LSC module consists of a colored plastic/glass panel, impregnated or coated with luminescent species such as organic and inorganic dyes and quantum dots [8]. LSC modules are able to capture sunlight and to concentrate it into photovoltaic cells located on the panel edges, where it is converted into electricity. The main advantage of LSCs lies in their being able to produce electricity even in low light conditions and to be integrated as transparent elements of architectural structures.

The technology of LSCs was originally introduced more than three decades ago. During the energy crisis in the 1970s, Weber and Lambe [9] proposed a technique to concentrate sunlight employing an LSC. A few years later, Batchelder et al. [10,11] provided a detailed theoretical and experimental analysis of LSC technology, as well as characterization techniques of the LSC [12]. Until nowadays, the large-scale diffusion of these solar devices has been inhibited by the low conversion efficiency, caused by several loss mechanisms mainly due to dye properties, which show low absorption or excessive self-absorption of solar radiation. Thanks to the research and development of new dyes, this problem has been largely solved, even if the efficiency of LSC modules is still lower when compared to traditional photovoltaics. Initially, the main attraction of this technology was its low manufacturing cost, about 1/3 [13] that of traditional photovoltaics, which represented a possibility to compete with the more expensive silicon technologies. Today, one of the more interesting aspects regards the possibility of integrating LSC modules in replacements of transparent surfaces where, therefore, it would be impossible to exploit traditional silicon modules

Thanks to its characteristics and adaptability, LSC technology is suitable for building integration. The concept of integrating LSC modules into a window led to the design of a multifunctional smart window-LSC (SW–LSC) prototype, a technology that is part of the Eni Ray Plus® project. Since the SW–LSC represents a novelty from a technological point of view, it is important to analyze the aspects related to product development and eco-design that could lead to the evaluation of new opportunities and improvements for the subsequent phase of market uptake. In this context, the Life Cycle Assessment (LCA) is an effective and recognized methodology to evaluate the environmental sustainability of a new product and to predict the possible burdens connected with its life cycle. In addition, in the eco-design context, LCA helps to identify the best options to minimize the negative impacts of the product.

Through this work, authors want to evaluate the environmental impacts of the SW–LSC and LSC technology, and to compare the impacts with those of similar technologies on the market. To the authors' knowledge, this is one of the first studies on the topic. Thus, the results could support future analyses, especially when the device will be commercialized and more information on both the final product and the large-scale production process will become available.

The structure of the paper is here described: Section 2 concerns a literature review of studies related to SW–LSC technology. Section 3 focuses on a description of the SW–LSC structure and its operation. Section 4 describes the initial steps of the life cycle assessment (goal and scope definition, life cycle inventory). After the evaluation of the life cycle impacts of the device (Section 5), a comparison of the impacts of LSC modules and some integrated photovoltaic technologies is made (Section 6). Finally, conclusions are reported.

2. Literature Review

Several studies regarding LSC modules are available. LSC performance depend on different configuration parameters such as device shape, geometric gain, host material (inorganic, polymer, glass, organic paint thinner, organic silicate), luminescent species (organic dye, nanostructure [14], plasmonic, rare-earth ions) and PV solar cell type and spectral response [15]. All these studies referred to laboratory-scale testing, to LSC dye chemical composition and to possible future applications. Only a few studies evaluated performance for large-scale LSCs.

Zhang et al. tested different-sized LSCs (7.8×7.8 cm^2, 15.6×15.6 cm^2, 31.2×31.2 cm^2 and 61×122 cm^2) and different fluorescent dyes, coupled with commercial c-Si solar cells mounted on the bottom of the luminescent waveguide. Compared to the LSCs with edge-mounted PV cells, the LSCs with bottom-mounted PV cells had a high solar gain. However, the drawback was that the device was not completely transparent due to the PV cells, and this solution might not be ideal for building integration. Aste et al. [16] evaluated the performance of six large LSC modules integrated into an aluminum structure and tested in a building roof. The results showed a better energy performance ratio (from 20 to 40%) for the LSC in comparison with standard PV modules.

Since the technology is currently not fully mature, only a limited number of LCA studies of LSCs are available in the literature. They will be briefly summarized in the following paragraphs.

Lunardi et al. [17] applied LCA to a tandem LSC–Si device and compared the results with those of a single-junction Si module. The dielectric layer consisted of SiO_2 and TiO_2 while the polymeric layer was poly(methyl-methacrylate) and poly(styrene sulfide). Results showed that tandem LSC–Si had lower impacts in all the examined impact categories: Global Warming Potential (GWP) was 22 kg CO_{2eq}, human toxicity potential–cancer effect (HTP–CE) was 1.0×10^{-11} CTU_h/kWh and non-cancer effect (HTP–nCE) was 3.24×10^{-16} CTU_h/kWh, freshwater eutrophication potential was 2.0×10^{-8} kg P_{eq}/kWh, freshwater ecotoxicity potential was 2.2×10^{-5} CTU_e/kWh and abiotic depletion potential (ADP) was 2.5×10^{-7} kg Sb_{eq}/kWh. The use of electricity was the major cause of most of the environmental impacts assessed. Another LCA study of LSCs was carried out by Dijkstra [18]. It focused on GWP, Cumulative Energy Demand (CED) and Energy Pay-Back Time (EPBT). The results were used to compare luminescent solar concentrators with conventional PV. The most efficient LSC module analyzed showed an EPBT as low as 5 years, while CED ranged from 2.16 to 4.88 GJ; the GWP (which ranged from 0.27 to 0.43 kg $CO_{2\text{-}eq}$/kWh) was higher compared to conventional PV.

Since the goal of the study is not limited to LSC modules but is extended to the whole SW–LSC prototype, it is appropriate to consider its dual nature of PV technology and smart window. For this reason, in the next two paragraphs, LCA studies regarding building-integrated solar concentrator technology and LCA of windows and SWs are examined.

2.1. LCA of CPV

Lamnatou and Chemisana [19] made a review of LCA of concentrating solar systems, dividing the analysis into high-concentration PV and low-concentration PV. They found that there are few studies for either category. From the review, it emerged that, in the case of high-concentration systems, CO_{2eq} emissions were less than 50 g/kWh and EPBT was less than 1 year; the tracking system was one of the major contributors to the total impact. In the case of low-concentration systems, the impacts depended on several factors, such as the solar irradiance and the materials of the concentrator. In detail, for a building-integrated concentrator PV (BICPV) with two configurations (with and without reflective film) and integrated into the facade of a building, the EPBT varies from 2.4 years (Barcelona and Madrid) to 3.2–3.5 years (Paris, Exeter and Dublin). The use of the reflective film increased the initial impact of the system by 0.2% but, in the long term, this additional impact was compensated for by a higher electrical output than the CPV without reflective film, allowing a reduction in EPBT and GWP pay-back time (GPBT) values of approximately 11–12% (Lamnatou et al. [20]). The same BICPV system was analyzed by Lamnatou et al. [21], showing that for all the components of the CPV system, climate change/human health, particulate matter formation and human toxicity were the categories with the highest impact.

Menoufi et al. [22] compared a BICPV system with a conventional building-integrated PV (BIPV) systems. The results showed that replacing the BIPV with BICPV led to a 13.5% decrease in environmental impact.

2.2. LCA of Window and SWs

Souviron et al. [23], in their review, analyzed different aspects of window design through an LCA approach. From the literature review, it emerged that in some cases the usual approach followed is to analyze a single element (mostly the frame and rarely the glazing or shading system) and to define the rest of the window with simplified assumptions. In other cases, the window was analyzed in its entirety, including frames and glazing and sometimes the shading system. Most authors considered the entire window as a functional unit, even in cases where the analysis aimed to compare different types of frame or glass. Regarding the boundary systems, it emerged that some studies excluded the use phase: their goal was to provide information on a specific element of the product (frame, glazing). According to other approaches, the use phase was considered in order to highlight the importance of assumption and modelling related to maintenance. The review showed the great variety of analysis methods concerning the life cycle of windows and underlined how it is rather difficult to analyze them using a common approach, since the window is an element connected not only to energy aspects, but also to privacy, acoustic and visual comfort, and daylight. However, it also showed that window studies were quite widespread and this facilitated the possibility of finding similar assumptions and applications and thus having the possibility to compare the results.

Pierucci et al. [24] assessed the life cycle impacts and energy demand of a smart window operating as photovoltaic–chromic window (PVCCs); they compared two commercial buildings with the same characteristics but different glazing technologies: one equipped with PVCCs and one equipped with commercial solar glass panels integrated with PV modules. The results of the analysis showed that the impact of the production of 1 cm^2 of PVCC cell was double that of solar glass, mainly due to high-impact processes, such as depositions, sputtering and sintering of the PVCC cell. The authors extended the analysis to two new functional units: for the first building, the total area of the PVCC windows, and for the second building, the total area of the solar control windows plus the total area of the photovoltaic panels. In this case, the results showed that the overall impact of the PVCC technology was considerably lower than that of traditional technologies with similar performances (from 41 to 44%).

Li et al. [25] assessed the life cycle impacts of a semi-transparent photovoltaic window integrated into a building to generate electricity and improve indoor light and the thermal environment. Results showed that the EPBT of the window was 13.8 years while the GPBT was 10.4 years, both of which were less than the expected life time (25 years). For other impact indices, results showed that respiratory inorganic was 2.38×10^0 kg $PM_{2.5eq}$, water use was 1.24×10^4 kg, ozone depletion potential was 2.58×10^{-5} kg $CFC_{\text{-}11eq}$, acidification potential was 7.73 × 10^0 kg SO_2-eq, photochemical ozone formation potential was 1.81 × 10^0 kg $NMVOC_{eq}$ and eutrophication potential was 6.79 × 10^{-1} kg $PO^{3-}{}_{4eq}$.

From this literature analysis, the innovativeness and peculiarity of the SW–LSC emerged; although it was possible to find LCA studies on solar concentrators, smart windows or photovoltaic windows, there were no life cycle analyses concerning the coupling between LSC modules and smart windows. This lack of studies highlights the novelty of the study presented in this paper, focusing on a window that performs multiple functions in terms of thermal characteristics, optical comfort and renewable energy production, placing itself in an intermediate position between the roles of BIPV and windows.

3. System Description

The SW–LSC is a prototype window developed within the Eni Ray Plus® project. The SW–LSC was assembled and tested at the Eni Research Centre in Novara (Italy).

The term "Smart Window" refers to a technology that can actively or passively participate in the energy performance and energy saving of the building, thanks to dynamic solar control and to the intrinsic characteristics of the device (transmittance of glass and frame). In the case of SW–LSC, which also includes the use of LSCs, it also contributes in terms of energy production and daylight improvement. The functioning of the SW–LSC is based on a passive and motorized shading system exploiting the electrical energy of LSC modules integrated into the frame. The SW–LSC prototype (Figure 1) has dimensions equal to 2.342 × 2.252 m (W × H) and consists of a two-part window: an extra window in the upper part (upper window, UW) and a double-wings window that opens inwards in the lower part (lower window, LW).

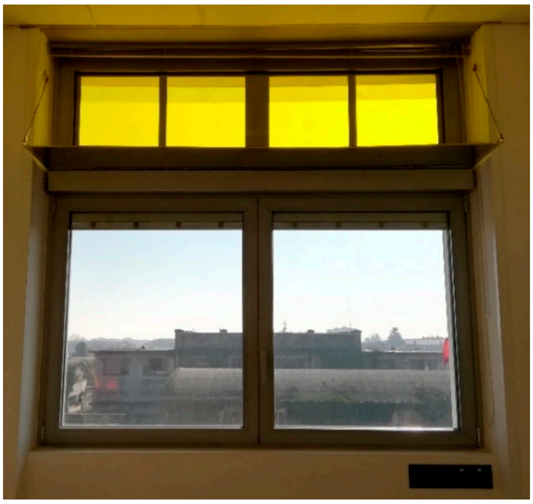

Figure 1. The SW–LSC prototype.

The upper window is semitransparent, since it integrates four LSC modules, 50 × 50 × 0.6 cm each, installed inside a double glazing. The lower window is a normal double-wings window with a double-glazing filled with air. The frame of the whole structure is made with thermal break aluminum profiles. The upper and lower parts of the window are divided by a horizontal, highly reflective, aluminum shelf, which extends from the inside to the outside of the building. The shelf helps to mix the colored light that passes through the LSC panels with the clear light that passes through the neutral glass below, in order to obtain a natural light characterized by a lower color temperature [26]. Solar control is achieved through metal venetian blinds, placed inside the double-glazing of the lower window, adjustable according to the conditions of the sky and the irradiation level. The movement of the blinds is driven by electric motors (DC motors), one for each wing, integrated into the window frame and powered by LSC panels. In order to guarantee electrical conservation and continuity of operation even during days with low solar radiation, the SW is equipped with two batteries, incorporated in the frame. The shutters' movement is guided by an external sensor (a light/radiation meter) connected to a computer with an adaptive control logic, which allows for the best setting in terms of interior comfort and energy saving, without the intervention of the inhabitants. Since the modules produce energy even with diffused radiation thanks to the use of storage batteries, the system guarantees operation even for several cloudy days [26].

The LSC modules are the main hub behind this operation. LSC components (Figure 2) consist of a transparent matrix of polymeric material doped with a luminescent dye (fluorophore). The transparent matrix acts as a waveguide and it is made in the form of a slab. The fluorophore allows the absorbing and re-emitting of incident solar radiation, while the waveguide concentrates it towards the edges of the slab; here, small photovoltaic solar cells convert solar radiation into electrical energy. The photovoltaic cells are glued on the edges of the slab and they are protected by a perimeter frame; they can be connected both in series and in parallel, according to the specific needs of use.

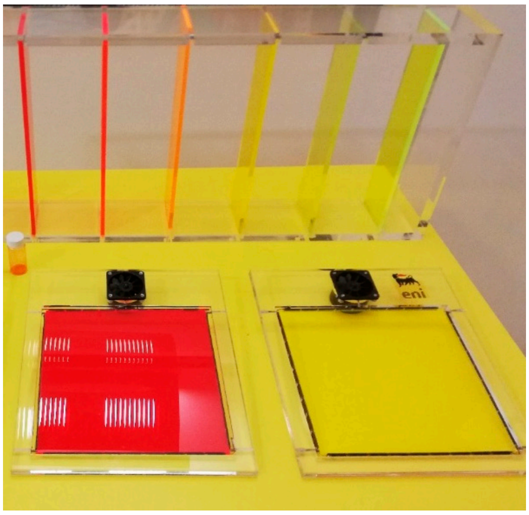

Figure 2. Different LSC modules and dyes.

The fluorophore inside the matrix determines the final color of the slabs and the final performance of the modules. Through different synthesis processes it is possible to obtain a variety of fluorophores and colors (those synthesized by Eni are red, yellow and orange). The color variation obviously also affects the final product, the LSC slab, and consequently the spectrum of the radiation filtered into the environment by the SW. In the case study, the use of the "yellow dye" was analyzed, since it gave the best response from the point of view of efficiency and optical performance when used for the production of the modules [27].

To summarize, the main elements of the SW–LSC prototype are:

- The LSC modules, consisting mainly of three elements: the transparent matrix of polymeric material (polymethylmethacrylate, PMMA); the luminescent dye, called fluorophore, i.e., the element that absorbs and re-emits part of the solar radiation; the solar cells, suitably arranged at the edges of the slab.
- The aluminum structure: the LSC panels are integrated in the upper part of the SW. The lower part consists of a double-glazed window (with air-filled cavity). Both the upper window and the lower part are enclosed by a thermal break aluminum structure, which constitutes the frame of the SW–LSC.
- The accessory elements: the venetian blinds, the two electric motors, the venetian blinds' management and control system, the radiation sensor, the batteries and the horizontal aluminum light shelf. Further details on the prototype, on its daylighting and energy performances during the use phase are explored in [28].

4. Life Cycle Assessment Methodology

LCA is a systematic tool for analyzing the environmental impacts of a product system throughout its life cycle, from the extraction of resources, through the production of materials, parts, and the product itself, to its use and end-of-life (EOL) (reuse, recycling, or final disposal). LCA, based on the standards of the ISO 14040 [29] and ISO 14044 [30], compiles and evaluates the inputs and outputs and the potential environmental impacts associated with the life cycle of the product system [31].

4.1. Goal and Scope Definition

The final goal of the analysis is to assess the environmental impact of the SW–LSC prototype that is currently installed at the ENI research center in Novara. Considering the dual nature of the device (photovoltaic modules + smart window), it is necessary to clarify that the initial focus of the analysis was to calculate the impacts of the LSC modules and, subsequently, to evaluate the impacts related to the whole SW–LSC. This approach allows us to obtain a clear picture of the impacts of the entire SW–LSC and, at the same time, to evaluate the impact of the LSC modules separately, considering also the possibility of using them for other types of applications (direct integration into the building, skylights, etc.).

After the impact evaluation of each phase, a dominance analysis was performed to assess the impact of individual components of the SW–LSC on the main results. In addition, two different scenarios for the SW–LSC frame were explored. The first scenario considered the use of a primary aluminum for the thermal break aluminum frame, and the other involved the use of a thermal break aluminum frame with 75% recycled material.

Another goal of the analysis was to compare LSC modules with other photovoltaic technologies that can be integrated into the building. The comparison of LSC modules with other PV technologies was carried out using two different functional units; 1 m^2 of module surface and 1 kWh of generated energy. The use of two functional units allowed us to evaluate different aspects: on the one hand, the burden linked to the production of the module surface (which is useful in comparing technologies that can be integrated in the building facades or glazed buildings) and, on the other hand, the production of electricity (which takes into account PV performance and yield).

The function of the SW–LSC is to guarantee lighting and contribute to thermal/visual comfort in internal environments through the motorized venetian blind system powered by LSC modules and the thermal and optic characteristics of the whole SW–LSC. In addition, the function of renewable energy generation through the surplus power output must be considered. According to these functions, the functional unit (FU) chosen was a 5.27 m^2 automated shading system window (thermal transmittance U_w = 1.6–1.8 W/m^2K), equipped with colored LSC fanlight (visible transmission t_{vis} = 77% and solar factor g = 85%) [32–34] and which can produce 1.5 kWh/year [28]. Electricity generation was calculated through the analysis of monitored data; these data refer to the city of Novara (Italy) and depend to the local climatic conditions.

The approach used was "from cradle to gate with options" [35], considering also the maintenance of SW–LSC. A simplified flowchart showing the analyzed system elements is shown in Figure S1 of Supplementary Materials.

Loads and credits deriving from energy and materials recovery at the end of life were analyzed separately, since it was not possible to collect data on this phase (because the SW–LSC is a prototype); in addition, there was a lack of data and information about the possible recovery of LSC modules, since the technology is relatively new. The study of this phase was mainly based on assumptions/predictions that will be shown in the next paragraphs.

Authors did not consider the transport of the materials and the packaging. This choice was motivated by the fact that the SW–LSC is a prototype not commercially available, thus the transport of the materials and the packaging of the chemical elements that make up the dye could vary significantly in the future, especially considering a large-scale production of the device, both geographically and quantitatively. Additionally, for this reason, the results of the analysis must be considered as the "worst case", or laboratory case, as they refer to the specific object of the study. In addition, large-scale production generally leads to improved process efficiency and material use.

The datasets used to model materials and processes were derived from the Ecoinvent database [36]. No allocation or cut-off procedures were performed in the analysis.

The life cycle impact assessment was conducted using the SimaPro 8.1 tool and the CML-IA baseline method, updated from the CML2001. CML-IA is one of the most frequently used models not only in PV LCA analysis but also for window-related LCA [32–34,37,38]. It considers a broad set of eleven impact categories which are shown in Table 1:

Table 1. CML-IA impact indicators.

Categories	Unit
Global warming potential (GWP)	kg CO_{2eq}
Abiotic depletion potential (ADP)	kg Sb_{eq}
Abiotic depletion potential fossil fuel (ADff)	MJ
Photochemical oxidation potential (PO)	kg C_2H_{4eq}
Human toxicity (HT)	kg 1.4-DB_{eq}
Acidification Potential (AP)	kg SO_{2eq}
Eutrophication Potential (EP)	kg $PO_4{}^{3-}{}_{eq}$
Ozone layer depletion Potential (ODP)	kg CFC-11_{eq}
Fresh water ecotoxicity (FWE)	kg 1.4-DB_{eq}
Marine aquatic ecotoxicity (MAE)	kg 1.4-DB_{eq}
Terrestrial ecotoxicity (TE)	kg 1.4-DB_{eq}

In conclusion, the main objectives of this work can be summarized as:

- Assessment of the environmental impacts of the SW–LSC prototype; furthermore, identification of the most impactful components of the device through a dominance analysis;
- Assessment of the impacts related to LSC modules;
- Comparison of the environmental impacts of LSC modules with other photovoltaic (PV) technologies that can be used for building integration (functional units: 1 m^2 and 1 kWh).

4.2. Life Cycle Inventory

This section describes the activities carried out for the collection of information and the processing of data relating to the SW–LSC system and its components. Thanks to the collaboration and involvement of ENI, it was possible to find information about the SW–LSC, through data collection campaigns and questionnaires. The company assembled in loco the SW–LSC components manufactured in different places; for this reason, it was necessary to define the different production paths of the main components required for the final product.

In order to simplify the data collection of the SW–LSC elements, three macro-components were identified:

- LSC module, which included the luminescent dye (fluorophore), the PMMA matrix and the photovoltaic cells;
- Aluminum structure (frame);
- Auxiliary components, which included light shelf, DC motors, cables and connections, batteries, venetian blind.

A detailed description of data on the production step of the above macro-components can be found in the section "Data collection in the inventory analysis" of the Supplementary Materials.

Focusing on the assembly step, using the information collected in the company, it takes an estimated total time of about 3 h to assemble the SW by hand. During this phase, the environmental impacts were only related to electricity consumption (medium voltage) due to the use of machinery and tools, such as a drill (0.036 kWh) and a welding machine (0.075 kWh) for aluminum parts.

The maintenance step was modelled considering a life span of 15 years for LSC modules in the SW–LSC, since good protection is offered by both the aluminum mask and glass encapsulation. The life span of the SW–LSC in its entirety can be estimated at around 30 years. The replacement of LSC modules is always possible in the event of a malfunction, since the upper window is equipped with an easy opening system and LSC modules are not welded but only housed in the cavity. It is hypothesized that SW–LSC maintenance should not require any special precautions, other than cleaning the glass covering LSC modules in order to ensure optimal functioning. For all these reasons, in this work, a single replacement of LSC modules after 15 years was considered in all scenarios.

Regarding the EOL phase, although it has not been evaluated for all the elements of SW–LSC due to the lack of information, it is possible to hypothesize the material recycling or the energy recovery after the disassembly of the prototype, as detailed in the following:

- Recycling of 62% of glass from SW–LSC; the remaining percentage goes to landfills;
- Recycling of 80% of aluminum from frame, mask and box; the remaining percentage goes to landfills;
- Energy recovery from PMMA incineration.

Different considerations need to be made regarding window glass recycling. Generally, the glass container is easily recycled while post-consumer float glass (including flat window glass) is rarely recycled due to the contaminants it may contain. The Waste Framework Directive sets a 70% target for the reuse and recycling of construction waste materials, including glass. The main problem is that individual targets are not set on specific types of waste. Furthermore, in the case of window glass, the type of glass used must be considered, which may require several additional treatments. In the present case, since SW–LSC is equipped with an insulated glass, the removal of the spacer bars and edge seals would be required, but no particular limitations would be implemented. In addition, techniques to separate the glass from other window components (window frames, hinges, sealants, insulation materials, etc.) are currently available, but need to be improved and become more widespread. The recycling percentage of 62% was therefore chosen according to a window EPD [39] (same U_g and glass type of SW–LSC). The recycling benefit and costs were allocated to the production of the recycled glass: virgin glass (100 kg) was used as the avoided product.

A percentage of aluminum of 80% was taken considering that the material is easily recyclable without loss of quality, even from windows. The recycling benefit and costs were allocated to the production of the recycled aluminum: aluminum, primary, ingot (210 kg) was used as the avoided product.

Finally, the incineration route was chosen for PMMA, since recycling should be evaluated on the basis of the presence of the dye. The scenario was modelled through Ecoinvent [36] as waste incineration of plastics (PMMA) (7.14 kg).

This EOL analysis aims to quantify the credits deriving from the recycling of glass and aluminum, directly avoiding the use of raw materials. This means that the modelling of the EOL does not consider the costs due to recycling operations itself. The remaining percentage of materials not counted in recycling is destined for landfill (in the case of glass) or sanitary treatment and landfill (in the case of aluminum). As regards PMMA, the incineration operation considers both the energy recovery and its costs.

5. Results

The main results of the LCA study (excluding EOL phase) are showed in Table 2.

Table 2. Environmental impacts of SW–LSC.

Impact Categories	Unit	Total	Production	Assembly	Maintenance
ADP	kg Sb_{eq}	3.08×10^{-2}	3.04×10^{-2}	3.00×10^{-7}	3.82×10^{-4}
ADff	MJ	5.63×10^{4}	5.42×10^{4}	3.59×10^{0}	2.11×10^{3}
GWP	kg CO_{2eq}	5.91×10^{3}	5.76×10^{3}	4.02×10^{-1}	1.45×10^{2}
ODP	kg $CFC_{\text{-}11eq}$	2.20×10^{-4}	2.10×10^{-4}	1.55×10^{-8}	1.01×10^{-5}
HT	kg 1.4-DB_{eq}	5.28×10^{3}	5.26×10^{3}	3.51×10^{-1}	2.03×10^{1}
FWE	kg 1.4-DB_{eq}	3.57×10^{3}	3.56×10^{3}	2.21×10^{-1}	1.56×10^{1}
MAE	kg 1.4-DB_{eq}	4.67×10^{7}	4.67×10^{7}	3.31×10^{3}	4.85×10^{4}
TE	kg 1.4-DB_{eq}	1.21×10^{1}	1.19×10^{1}	1.36×10^{-3}	1.60×10^{-1}
PO	kg C_2H_{4eq}	2.01×10^{0}	1.98×10^{0}	1.39×10^{-4}	3.00×10^{-2}
AP	kg SO_{2eq}	3.26×10^{1}	3.20×10^{1}	2.31×10^{-3}	5.57×10^{-1}
EP	kg ${PO_4}^{3-}{}_{eq}$	8.39×10^{0}	8.30×10^{0}	5.60×10^{-4}	8.89×10^{-2}

Results show that the production phase contributed more than 96% in all categories, as might be expected from a hand-assembled prototype which is not mass produced. The assembly phase and maintenance phase were about 0.01% and 2% of total impacts, respectively.

Considering the production phase, the SW–LSC components' contribution to the impact categories is shown in Figure 3.

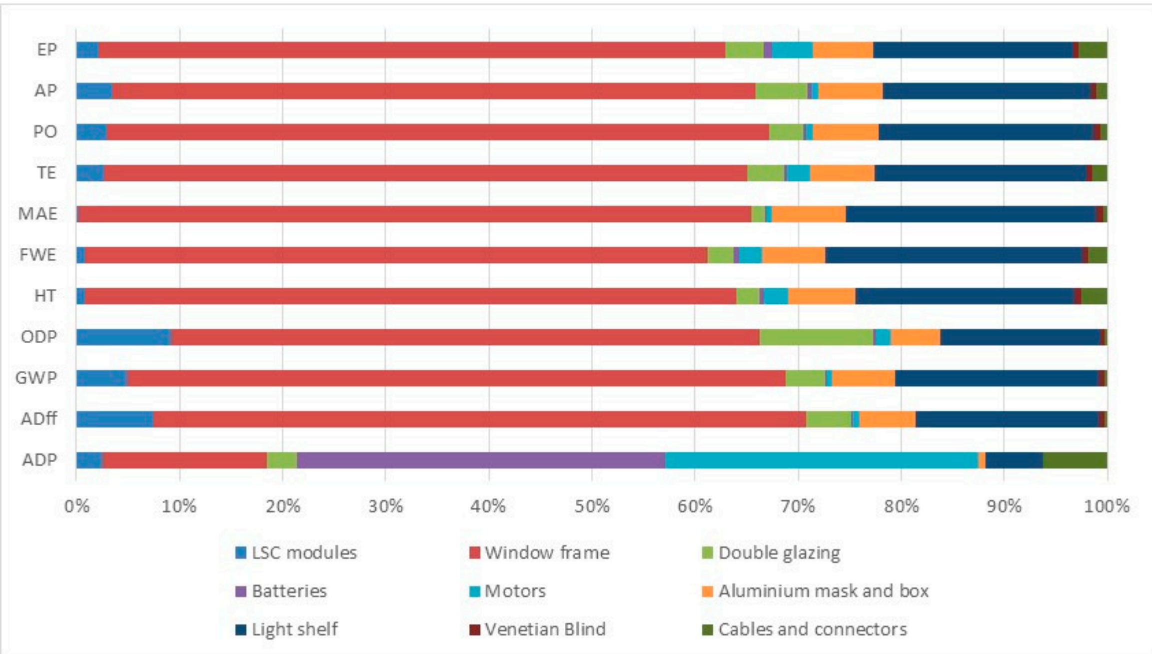

Figure 3. Contribution of SW–LSC elements to the total impact.

The most impactful components of SW–LSC system in the base scenario are:

- Window frame: the contribution of this component to the environmental impact was above 60% in all categories, from 59.78% (ODP) to 65.80% (ADP fossil fuel)), except for ADP where the contribution was 16.22%.

- Light shelf: the contribution of this component ranged from 16.29% (ODP) to 25.02% (FE) in all categories, except ADP where the contribution was only 2%.
- DC motors and batteries: these components had a great contribution (30.74% and 36.26%, respectively) in ADP but a low contribution (less than 4% for DC motors and 1% for batteries) in all other categories.

Aluminum box and mask had a mean contribution of 6% in all categories, from 4.96% (OPD) to 7.24% (ME), except for ADP where it was less than 1%. The other components of the system had an impact lower than 5% in all categories; the only exception is the window glazing which was the third contributor to ODP (11.52%).

The above results show that the aluminum frame is one of the most impactful elements in the life cycle of a window. This is due both to the higher percentage of the material in the total structure and to the fact that its processing requires extremely energy-intensive processes. The impact of batteries and motors is limited to the ADP category, since these elements involve a greater use of raw materials or specific materials characterized by limited availability and high-quality value, compared to other SW–LSC elements.

It should be noted that the LSC modules, which represent one of the main elements of the system, provide a low contribution in all categories, from 0.39% (HT) to 4.82% (ODP). However, it is useful to report the relative impact of the various components of LSC modules, which is shown in Figure 4.

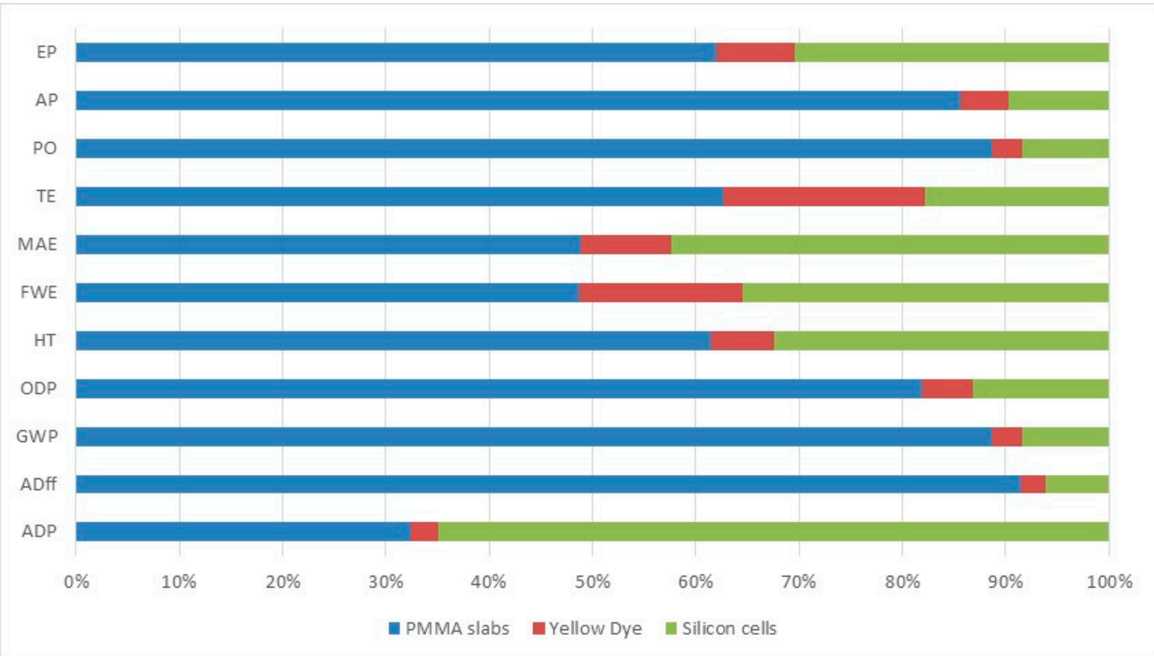

Figure 4. Environmental impacts of LSC module (1 m^2).

Considering the LSC module, the major contributors in all categories (except ADP) were PMMA slabs (from 32% (ADP) to 91% (ADP fossil fuel), followed by the photovoltaic cells (from 6% (ADP fossil fuel) to 65% (ADP)). The contribution of the dye was lower than 8% in all categories, except fresh water ecotoxicity (16%) and terrestrial ecotoxicity (20%).

Considering the EOL phase, the impacts connected with the landfill phase were analyzed together with the credits deriving from the recycling (aluminum and glass) and the energy obtained from the PMMA incineration. The total life cycle impacts could be reduced by a percentage that ranges from 14% (marine aquatic ecotoxicity) to 80% (ADP) (Table 3).

Table 3. Total impacts and credits of the EOL.

Impact Categories	Units	Total	Landfill	Credits from Recycling	Reduction (%)
ADP	kg Sb_{eq}	2.73×10^{-2}	1.81×10^{-5}	-2.17×10^{-2}	80%
ADff	MJ	5.33×10^{4}	4.40×10^{1}	-1.79×10^{4}	36%
GWP	kg CO_{2eq}	5.67×10^{3}	2.85×10^{0}	-4.36×10^{3}	79%
ODP	kg $CFC_{\text{-}11eq}$	2.06×10^{-4}	3.72×10^{-7}	-1.13×10^{-4}	60%
HT	kg 1.4-DB_{eq}	5.04×10^{3}	1.48×10^{0}	-1.20×10^{3}	25%
FWE	kg 1.4-DB_{eq}	3.26×10^{3}	1.98×10^{0}	-1.68×10^{3}	52%
MAE	kg 1.4-DB_{eq}	4.53×10^{7}	2.77×10^{3}	-6.01×10^{6}	14%
TE	kg 1.4-DB_{eq}	1.15×10^{1}	5.68×10^{-3}	-3.56×10^{0}	32%
PO	kg C_2H_{4eq}	1.94×10^{0}	1.05×10^{-3}	-7.40×10^{-1}	40%
AP	kg SO_{2eq}	3.13×10^{1}	1.76×10^{-2}	-1.18×10^{1}	40%
EP	kg ${PO_4}^{3-}{}_{eq}$	7.94×10^{0}	5.01×10^{-3}	-3.10×10^{0}	41%

Alternative Scenario

As already mentioned, the alternative scenario (recycling scenario) involves the use of 75% recycled aluminum during the manufacturing of the window frame. The recovery of the aluminum comes from remelting, shredding, sorting and decoating of post-consumer scrap; the remaining percentage of aluminum in the final product comes from process scrap (10%) and primary ingots (15%). Compared to the base scenario, the presence of recycled aluminum is the only difference in the inventory of the SW–LSC. The results of the comparison between the base scenario and the recycling scenario is shown in Figure 5.

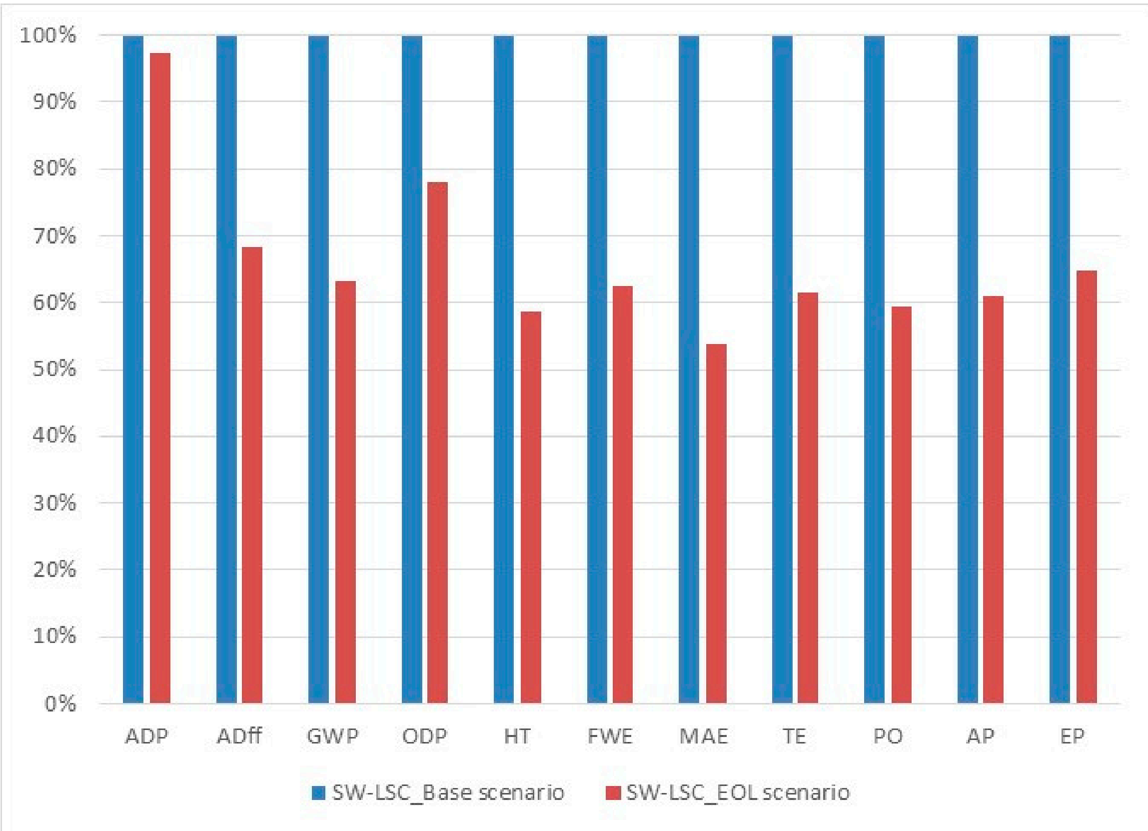

Figure 5. Comparison between Base scenario and Recycling (EOL) scenario for the SW–LSC.

The use of aluminum with a recycled content of 75% in the window frame allows a reduction in impacts in all categories, from 3% (ADP) to 46.6% (ME). The reduction in the ADP category was mainly due to aluminum; however, this reduction is low due to the processes connected with recycling itself and the presence of substances such as zinc and copper, which are always present in aluminum scraps. The reduction in the ADP (fossil fuel) category is mainly due to less energy-intensive processes than those related to the production of primary aluminum, and the consequent reduction in the use of energy carriers such as coal, gas and crude oil. The reduction for AP and EP categories was related to lower emissions into air of ammonia (−16%), nitrogen oxides (−39%) and sulfur dioxide (−39%) for AP, and to water emission of phosphate (−35%) and nitrate (−29%) for EP. The reduction for the FE category was mainly related to lower beryllium (−21%), copper (−28%), nickel (−36%) and vanadium (−46%) emissions on water. HT and ME categories were related to the reduction in hydrogen fluoride (−49%), TE to the reduction in mercury (−42%) while for PO to the reduction in sulfur dioxide (−40%) and carbon monoxide (−46%). The reduction in ODP was mainly related to methane (−29%).

6. Comparisons of LCA Results

Moreover, the environmental impacts of the LSC modules were compared with other photovoltaic technologies on the basis of two different functional units: the m^2 of the module and the kWh of electricity produced. Input data of the other photovoltaic modules were from the Ecoinvent database [36]. Firstly, the results were compared using 1 m^2 of module surface as FU, using the CML-IA method. The choice of m^2 lies in the final application foreseen for LSC modules, which is that of integration into buildings. The comparison aims to quantify the impact of LSC modules and the other modules on the market (Ribbon-Si, Multi-Si, a-Si, CIS) considering only their surface and excluding the inverter or any supporting structures for the final application. On the other hand, the analysis based on 1 kWh of energy generated as FU, considers the final purpose of the products, which is to generate electricity. In addition, all the technologies used for the comparison (single-Si, multi-Si, CdTe, a-Si, ribbon-Si) were integrated in the building (roof or façade) and the use of an inverter (200 W) was considered.

The results referring to m^2 (Table 4) showed that the LSC module had the lowest impacts in most categories (ADP, EP, HT, FAE, MAE, TE); in some categories (GWP100a, ODP and PO) the LSC module performed worse than a-Si and CIS technologies. When compared with multi-Si and ribbon-Si, the LSC showed a low impact in all categories.

Table 4. Environmental impacts comparison between different PV modules (1 m^2).

Impact Categories	Units	LSC	Multi-Si	Ribbon-Si	a-Si	CIS
ADP	kg Sb_{eq}	3.82×10^{-4}	2.76×10^{-2}	2.68×10^{-2}	1.50×10^{-2}	3.19×10^{-2}
ADff	MJ	2.11×10^{3}	2.35×10^{3}	1.80×10^{3}	8.84×10^{2}	1.37×10^{3}
GWP	kg CO_{2eq}	1.45×10^{2}	2.03×10^{2}	1.65×10^{2}	7.74×10^{1}	1.25×10^{2}
ODP	kg CFC_{-11eq}	1.01×10^{-5}	2.56×10^{-5}	2.16×10^{-5}	3.38×10^{-6}	6.81×10^{-6}
HT	kg 1.4-DB_{eq}	2.03×10^{1}	2.62×10^{2}	2.23×10^{2}	1.27×10^{2}	3.28×10^{2}
FWE	kg 1.4-DB_{eq}	1.56×10^{1}	2.69×10^{2}	2.47×10^{2}	1.62×10^{2}	2.75×10^{2}
MAE	kg 1.4-DB_{eq}	4.85×10^{4}	4.91×10^{5}	4.31×10^{5}	2.21×10^{5}	4.19×10^{5}
TE	kg 1.4-DB_{eq}	1.60×10^{-1}	4.69×10^{-1}	3.62×10^{-1}	2.72×10^{-1}	3.02×10^{-1}
PO	kg C_2H_{4eq}	3.00×10^{-2}	4.70×10^{-2}	3.66×10^{-2}	2.15×10^{-2}	2.48×10^{-2}
AP	kg SO_{2eq}	5.57×10^{-1}	9.72×10^{-1}	8.11×10^{-1}	3.96×10^{-1}	5.98×10^{-1}
EP	kg ${PO_4}^{3-}{}_{eq}$	8.89×10^{-2}	4.41×10^{-1}	3.77×10^{-1}	1.55×10^{-1}	3.81×10^{-1}

The results referring to the generation of 1 kWh of energy showed an opposite trend, as the environmental impacts connected to the LSC modules were the highest in all categories when compared with other photovoltaic technologies as shown in Table 5.

Table 5. Environmental impacts comparison between different PV modules (1 kWh).

Impact Categories	Units	LSC	Single-Si (Roof)	a-Si (Roof)	Multi-Si (Facade)	Single-Si (Facade)	Ribbon (Roof)	CdTe (Roof)	Multi-Si (Roof)
ADP	kg Sb_{eq}	3.23×10^{-5}	7.96×10^{-6}	6.02×10^{-6}	1.19×10^{-5}	1.15×10^{-5}	8.52×10^{-6}	6.12×10^{-6}	8.23×10^{-6}
ADff	MJ	1.47×10^{1}	8.78×10^{-1}	6.08×10^{-1}	1.14×10^{0}	1.33×10^{0}	6.57×10^{-1}	4.43×10^{-1}	7.50×10^{-1}
GWP	kg CO_{2eq}	1.06×10^{0}	7.64×10^{-2}	5.23×10^{-2}	9.98×10^{-2}	1.18×10^{-1}	5.90×10^{-2}	3.96×10^{-2}	6.43×10^{-2}
ODP	kg $CFC_{\text{-}11eq}$	7.36×10^{-8}	7.53×10^{-9}	2.61×10^{-9}	1.10×10^{-8}	1.12×10^{-8}	6.89×10^{-9}	2.65×10^{-9}	7.37×10^{-9}
HT	kg 1.4-DB_{eq}	1.15×10^{0}	3.31×10^{-1}	3.19×10^{-1}	4.94×10^{-1}	4.97×10^{-1}	3.24×10^{-1}	3.97×10^{-1}	3.29×10^{-1}
FWE	kg 1.4-DB_{eq}	6.54×10^{-1}	3.28×10^{-1}	3.19×10^{-1}	4.92×10^{-1}	4.96×10^{-1}	3.26×10^{-1}	3.61×10^{-1}	3.26×10^{-1}
MAE	kg 1.4-DB_{eq}	1.93×10^{3}	3.64×10^{2}	3.38×10^{2}	5.38×10^{2}	5.59×10^{2}	3.47×10^{2}	3.63×10^{2}	3.50×10^{2}
TE	kg 1.4-DB_{eq}	2.60×10^{-3}	2.83×10^{-4}	2.44×10^{-4}	3.95×10^{-4}	4.27×10^{-4}	2.44×10^{-4}	2.41×10^{-4}	2.61×10^{-4}
PO	kg C_2H_{4eq}	3.63×10^{-4}	2.55×10^{-5}	2.25×10^{-5}	3.70×10^{-5}	3.95×10^{-5}	2.22×10^{-5}	2.07×10^{-5}	2.38×10^{-5}
AP	kg SO_{2eq}	6.02×10^{-3}	5.16×10^{-4}	4.27×10^{-4}	7.25×10^{-4}	7.95×10^{-4}	4.50×10^{-4}	4.28×10^{-4}	4.68×10^{-4}
EP	kg ${PO_4}^{3-}{}_{eq}$	2.60×10^{-3}	2.37×10^{-4}	1.82×10^{-4}	3.22×10^{-4}	3.53×10^{-4}	2.10×10^{-4}	2.00×10^{-4}	2.16×10^{-4}

In detail, the LSC module impact per 1 kWh generated were higher than ten times in some categories such as ADP (fossil fuel), GWP, PO, AP and EP. The smallest difference was recorded for impact categories such as ADP, HT, and TE with an increase of 200%.

This result, which is mainly due to the low annual yield and efficiency of the LSC modules (1–1.3%), must however be interpreted on the basis of the geographical conditions (location and irradiation) and the geometry of the configuration (inclination of the modules and series/parallel connections of the cells) during data monitoring, on which the assumptions relating to the production of electricity during the useful life of the modules are based.

Since LSC modules have a lower efficiency than the photovoltaic technologies analyzed, the choice to use LSC modules lies in the advantages possessed by the technology: the possibility of application in glazed buildings, the possibility of integration with non-optimal angles for facades and balconies, and the generation of energy also under conditions of diffuse radiation. LSC modules could be a good solution for some applications, but they proved to be a poor solution from an environmental point of view if compared to other technologies for energy generation. In conclusion, LSC technology will need improvements in efficiency and annual yield in the future to compete as substitute of other PV technologies (the research on this challenge is ongoing), but they could actually have niche applications thanks to some peculiar characteristics, such as transparency.

7. Conclusions

This paper presented the LCA of the SW prototype equipped with LSC modules which is currently installed and monitored at the Eni research center in Italy.

The system is a novelty in the field of smart windows (as regards the functioning of the device) and incorporates a photovoltaic technology (luminescent solar concentrators) which is not yet fully widespread on the market. The possibility of incorporating LSC modules inside a window, thanks to their characteristic of being semi-transparent, guarantees the production of electricity where the use of conventional PV technologies would not. Although the electrical performance of the LSC modules is currently not comparable with traditional PV, in terms of efficiency, this solution could still facilitate the achievement of a balanced budget between production and consumption inside buildings, especially considering the thermal characteristics of the SW–LSC device equipped with a thermal break aluminum frame and coated double glazing filled with air. LSC modules also have the characteristic of producing electricity even with diffused radiation and do not require tracking systems like most solar concentrators. LCA results show that, considering the SW–LSC prototype, the aluminum frame is the most impactful element in most of the categories (with an average contribution of about 60%). Additionally, considering the other aluminum elements that complete the structure (the perimeter frame which protect slab edges and photovoltaic cells, the box where the storage batteries are located, and the light shelf) this contribution reaches about 80%. DC motors and storage batteries are the major contributors to the abiotic depletion potential category (above 34% and 40%, respectively), but their contribution is lower than 4% in the other categories. The light shelf is a controversial element in the SW–LSC; although it allows it to avoid excessive lighting phenomena near the window and achieve a better distribution of light in the rooms, this is the second largest contributor in most categories (about 16%). Consequently, the idea of replacing it with other solutions that have a lower environmental impact or the removal of this element should be evaluated.

LSC modules contribute less than 5% in all impact categories. A comparison of the environmental impacts of LSC modules with those of other photovoltaic technologies shows that, for 1 m^2 of the module's surface, the environmental impact of LSC modules is lower than multi-Si and ribbon Si technologies in all the impact categories, while when compared with CIS and a-Si higher or lower environmental impacts are found depending on the examined impact category. Results for 1 kWh of energy generated show that the LSC module has the highest impact in all categories (from 200% to 1900%) when compared with other PV technologies. Considering these results, the application of LSC modules could be justified where a large application surface is available and the presence of transparent elements is required. In this case, the power generation could be maximized and exploited in an optimal way. Furthermore, future studies should focus on increasing the LSC efficiency to compete with other technologies, e.g., the use of another type of coupled photovoltaic cells (CIS or GaAs), could lead to an increase in efficiency without affecting the overall environmental burden (since the solar cells occupy only the edges of the module, and therefore a small surface).

In conclusion, the LCA of the SW–LSC prototype made it possible to quantify the environmental burdens of the device and to highlight the critical elements of the system. Although further studies regarding this technology are required, especially considering large-scale production processes and the consequent use of raw materials with greater efficiency, the device represents a promising alternative to exploit a different type of installation into buildings in urban contexts. In the future, this technology could find a place inside near-zero-energy buildings, alongside other photovoltaic and renewable technologies, contributing to the achievement of good results in terms of energy generation, thermal insulation and management of solar gains.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en16041869/s1, Figure S1. Flowchart of the analyzed system; Figure S2. Synthesis process of the "yellow" dye; Table S1. Composition of the final dye referred to 1 m^2 of LSC modules; Table S2. Photovoltaic cells profile; Table S3. Aluminum frame profile; Table S4. Aluminum mask and box profile (1 m^2); Table S5. Light-shelf profile (1 m^2); Table S6. Double glazing profile (1 m^2); Table S7. Venetian blind profile (1 m^2).

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