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Technical, economic and environmental assessment towards the sustainable goals of photovoltaic systems

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ABSTRACT

Goal 7 of Agenda 2030 is focused on renewable energy. This study proposes a multi-criteria and multi-disciplinary methodology for analysing different incentive scenarios in Italy according to the varying conditions of system installation and the chosen photovoltaic technology (PV). The method is based on three key factors: energy, economic, and life cycle assessment of the photovoltaic system to achieve the improvement of the energy performance through technical and financial solutions that suit the existing buildings and strategies to limit environmental impacts. For the validation of the methodology was chosen the engineering campus of the University of L'Aquila, Italy, was chosen since the energy retrofit of public buildings must be dealt with by considering numerous parameters. These include economic constraints related to the public budget; technical constraints, as not all the solutions on the market, are compatible with the existing building body; and social constraints, as public administrations set an example for their communities and pioneer positive actions inspired by sustainability from every standpoint. The study showed as for defining the optimal scenario a multi-criteria approach is necessary and that a decision based on only technical and economic evaluations can not conduct to an optimal scenario selection. Furthermore, it has shown how subsidies are fundamental for the profitability of PV investments, which, although considered a renewable energy source, can derive non-negligible environmental impacts from these investments. Thus, the methodology adopted, which can be exported to other contexts, allows policy-makers choices to be weighed from many points of view.

1. Introduction

The Sustainable Development Goals of the 2030 Agenda address sustainability from several standpoints by clustering aspects of daily life into key focus areas to achieve the set goals. Of the 17 points, the 7th aims to "ensure access to affordable, reliable, sustainable, and modern energy for all." Based on single targets and their indicators, the main protagonist of this goal is renewable energy, a universally acknowledged substitute for fossil resources that is significant to the mitigation of environmental degradation. For example, the Intergovernmental Panel on Climate Change (IPCC) has highlighted the possibility of reducing energy-related carbon anhydride emissions by 90 % by 2050 and limiting the increase in global temperature to 2 °C by simultaneously enforcing three key strategies: acceleration of renewable energies, deep electrification, and improved energy efficiency [1].

Among renewable energies, solar photovoltaic (PV) energy has a substantial economic and social impact and is expected to continue to grow [2]. However, according to the International Renewable Energy Agency [3], despite more than 60 % of the established goals being reached in 2019, PV has yet to reach the levels obtained during the 2010–2019 decade. If this tendency is re-established, yielding the same growth trend as in the previous decade, the Agency expects PV to increase by approximately 15 %. This would lead to 8.519 installed gigawatts, thus generating 25 % of the global electricity compared to the current value of 3 % as of 2019 [4].

A photovoltaic system's quality and commercial attraction mainly depend on its on-field performance, cost, and durability; photovoltaic modules significantly contribute to each of these factors [2]. Several studies in the scientific community have exhibited an interest in this theme, particularly in the last five years, and the number of publications constituting analyses of the specific aspects has increased from 1.582 in

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Nomenclature

Abbreviations

LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Impact
DALY	Disability adjusted life years

Notations/Symbols and Units

$C_{i,t}$	Insurance cost [€]
$C_{m,t}$	Maintenance cost [€]
$C_{r,t}$	Replacement cost [€]
C_t	Total cost [€]
DPBT	Discounted payback period [years]
dse	% of system efficiency annual decrease
i	Discount rate
inf	Inflation rate
inf^e	Energy inflation rate
I_t	Investment cost [€]
I_u	Unitary investment cost [€/kW]
LCOE	Levelised Cost of Energy [€/kWh]
N	Lifetime of investment [years]
NPV	Net present value [€]
p_t^e	Energy price at time t [€/kWh]
$Perc_{Ci}$	% of insurance cost
FER	Renewable energy source
PV	Photovoltaic
USD2013	US dollars ($) reference year 2013
$Perc_{Cm}$	% of maintenance cost
$Perc_{Cr}$	% of replacement cost
P_{sy}	System power [kW]
$Q_{selfcons}$	% of energy self-consumption
$R_{bonus,t}^{subsidies}$	Revenues by bonus subsidies (FER1) [€]
$R_{FIT,t}^{subsidies}$	Revenues by FIT subsidies (FER1) [€]
$R_t^{electric\ energy}$	Revenues by electric energy [€]
$R_{PV\ recycling,t}$	Revenues by PV recycling [€]
R_t	Total revenue [€]
$Recy_u$	Unitary revenue of PV recycling [€/m[2]]
SOE	System Output energy [kWh/year]
species.yr	Species for year
sqm	Surface of PV module [m^2]
$S_{u,bonus}$	Unitary bonus subsidies [€/MWh]
$S_{u,FIT}$	Unitary FIT subsidies [€/MWh]
T	Time of cash flow

2017 to 3392 in 2022 (source: database Scopus, query "photovoltaic panel" date July 05, 2023). For example, the most recent publications regarding the materials [5–7] discuss integrating photovoltaic systems and phase-change materials. For example Fikri et al. [5] suggest a better utilisation of solar energy through the integration of Concentrated Photovoltaic (CPV) with phase change materials (PCM), for both thermal and electrical production. The most interesting aspect is that the concentration of solar radiation on small areas increases the power produced, which has interesting economic implications. However, such concentration could compromise the durability and performance of the system, as well as requiring an efficient cooling medium. Sharaf et al. [6] analysed the annual performance of a photovoltaic system coupled with a phase change material and aluminium metal foam, employed as a passive cooling technique. It is demonstrated the validity of the system, however, it was found that the effectiveness of PCM for photovoltaics is more evident in summer than in winter. Regarding solutions for production optimization [8–10], there has been a significant focus on the tilt angle. Annibaldi et al. [9] propose methodology to evaluate economic and environmental performance assessed through life cycle cost analysis and avoided CO2 emissions, respectively. The results show that although the case study does not have the optimal roof pitch angle, there are economic and environmental benefits. Regarding intervention compatibility, specific intervention strategies have been elaborated for installation on valuable buildings [11], and limits and obstacles have been observed in two distinct contexts, Italy and Switzerland. Lucchi et al. reconstruct a European legislative and authorisation framework. The results show that thanks also to the introduction of specific targets and economic incentives, policies implemented in all territorial contexts drive the use of solar energy. More specifically, in Italy, due to the complex authorisation process, the implementation of photovoltaics has slowed down over the years. Whereas in Switzerland it has increased, thanks to streamlined and simple procedures. Concerning emerging technologies [12,13], studies have been identified concerning the Passivated Emitter and Rear Cell (PERC) design [14], and the heterojunction technology; concerning environmental conditions, certain studies [15–17] have highlighted decreased productivity owing to dust and wind.

Renewable energy from solar PV systems has been discussed extensively; however, by 2050 [18,19], 78 million tons of photovoltaic waste will be produced. The five top waste-producing countries in 2050 are predicted to be China, the United States, Japan, India, and Germany. According to Wade et al. [18], these photovoltaic wastes can be converted to secondary raw materials to fabricate two billion new panels, which is equivalent to an economic value of 15 billion US dollars (USD). This necessitates the hypothesis of a more sustainable end-life scenario from both an environmental and economic standpoint, considering solutions such as recycling, raw material recovery, and repair [20], as well as the employment and search for materials whose life cycle assessment is associated with lower environmental impact. In this regard, life cycle analysis is recognised as a valid tool for assessing the sustainability of a product and process and recently some LCA studies have been performed to analyse energy systems [21]. Parisi et al. [22] elaborate a life cycle assessment of a real semi-industrial production process of solar modules with third-generation photovoltaic technologies. The findings of the paper demonstrate the good performance of the process and the environmental footprint of the panel. Yang et al. [23] calculated the life cycle water consumption of photovoltaic power generation in China. The findings show that applying recycling technologies to the photovoltaic system should reduce total water consumption by 13 %. Finally, Das and De [24] define a validated life-cycle-oriented technical--economic approach to identify the best hybrid energy system combination in an Indian village. The numerical results are context-specific, also if they are based on a generic methodology.

These considerations show that these 2050 scenarios will affect other SDGs of the 2030 Agenda [25] and must therefore be carefully assessed. Thus, political policies must consider future challenges by adapting frameworks that address each region or country's needs and circumstances [18]. Specifically, in Italy, the FER1 decree promotes the diffusion of renewable energy in Italian public buildings through incentives [26]. Considering this framework, the study proposes a multi-criteria and multi-disciplinary methodology for analysing different incentive scenarios according to the installation and variable conditions of the selected photovoltaic system. This methodology integrates the technical-economic optimization of the photovoltaic system, the environmental assessment through LCA analysis to determine optimal approaches for evaluating the different typologies of impact and the multi-criteria decision-making approach. This in order to identify the most economically and technically efficient solutions with the least impact from an environmental point of view. In detail, the proposed approach constitutes a 3-step process. The first is the photovoltaic system energy evaluation through the analysis of the solar potential, while the second phase is represented by the economic analysis. The outcomes are summarized in a comparative matrix to evaluate the resulting scenarios which will then be subjected to a Life Cycle Assessment, the third and final phase of this approach.

The literature review has shown that although there is availability of studies aimed at developing technical-economic analyzes of energy systems, often, few have a multidisciplinary approach that involves the analysis also of environment one. The results of this research allow to filling this gap and to develop new integrated approches. The methodology developed also provides a support tool to policymakers useful for the choices to be calibrated according to priorities and to manage the public housing stock better to limit its impacts and improve its efficiency. The multi-disciplinary approach adopted is a tool for evaluating different investment scenarios. In addition to adopting technical and economic parameters, it adds evaluations related to the life cycle of photovoltaic systems, a field of study yet to be investigated. Moreover, since this method is correlated with the use of the variables defined in a decree aimed at incentivising renewables, it also makes it possible to show the actual usefulness of economic incentives.

In addition to the research and policy implications, the study contributes to the achievement of SDG 7 as well as others:

- target 7.2 “By 2030, increase substantially the share of renewable energy in the global energy mix”, in particular indicator 7.2.1. “Renewable energy share in the total final energy consumption”;
- target 13.2 “Integrate climate change measures into national policies, strategies and planning”, in particular indicator 13.2.2. “Total greenhouse gas emissions per year”;
- target 12.5 “By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse”, in particular indicator 12.5.1. “National recycling rate, tons of material recycled”.

SGD7 is achieved as the study contributes to the spread of solar photovoltaics and thus to increasing the share of renewables in the total final energy consumption [27]. Target 13.2 is satisfied because, thanks to the LCA analysis, it is possible to exclude the scenarios that determine a greater negative impact, eliminating the design solutions responsible for a huger production of CO_2 [28] Target 12.5 is indirectly achieved because the study, while not resulting in an immediate response in terms of target satisfaction, is able to stimulate and disseminate the adoption of life cycle approaches as well as recycling and reuse [29].

The multidisciplinary research is very innovative as it is able to respond simultaneously to the issues of energy efficiency of public real estate, dissemination of renewables, and verification of the validity of fiscal incentives. Moreover, if compared to previous works [26], it introduces novel elements represented by the LCA evaluation of the most widespread photovoltaic technologies in relation to the best scenarios from a technical-economic point of view.

Finally, the methodology was verified by applying it to a case study in the Abruzzo Region, Italy, represented by the enginnering campus of the University of L’Aquila. The study analysed 153 scenarios from an energy point of view and 306 from an economic point of view. Of these scenarios, the three most advantageous ones were analysed with LCA analysis, taking into account the three photovoltaic technologies researched, for a total of a further 9 scenarios. The methodology developed can be applied to university and non-university contexts simply by setting the corresponding parameters.

Therefore this paper aims to respond simultaneously to the issues of energy efficiency of public real estate, dissemination of renewables, and verification of the validity of fiscal incentives. In detail, it intends to define positive and replicable models for public buildings based on multidisciplinary approaches; analyse different incentive scenarios according to the varying conditions of system installation and the chosen photovoltaic technology (PV); develop technical and financial solutions that suit the existing buildings and strategies to limit environmental impacts; fill the research gap related to the lack of environmental analysis and LCAs in renewable energy studies.

2. FER1 decree: photovoltaic energy support laws in Italy

On June 27, 2018, the European Council set the goal of obtaining 32 % of EU energy from renewable sources by 2030 [30]. Photovoltaic technology is essential as it is expected to increase the proportion of renewable energy by 20 % [18]. On July 4, 2019, a ministerial decree (FER1 Decree) was signed in Italy, following European goals for 2020 and 2030. This decree promotes the diffusion of systems to produce electrical energy from renewable sources by offering financial support, and includes newly built PV systems. Therefore, six years after the fifth Italian “Conto Energia” expiration, the feed-in tariff that came into force in August 2012 was withdrawn on July 6, 2013 [31], supporting the establishment of PV systems through incentives, was resumed. In addition to photovoltaic systems, wind farms, hydroelectric systems, and sewage treatment plants, residual gas systems can receive incentives established by the FER1 decree. In particular, the decree subdivides these systems into three groups (A, B, and C) according to their typology, renewable energy source, and intervention category.

Group A includes onshore wind farms and photovoltaic systems. A-2, a sub-group of group A, is dedicated to newly built photovoltaic systems installed to substitute fibre cement or asbestos roof coverings. Group B constitutes newly built hydroelectric power systems and residual gas systems from sewage treatment plants. Finally, group C includes wind farms and residual gas systems from sewage treatment plants involved in partial or total reconstruction. The FER1 decree applies only to newly built PV systems with newly constructed components whose modules are not located in rural areas. These PV systems can receive incentives based on the net electrical energy produced and fed into the grid for 20 years. Unit incentives vary according to the nominal capacity of the photovoltaic systems:

- 105 €/MWh for systems whose power ranges between 20 kW and 100 kW;
- 90 €/MWh for systems whose power ranges between 100 kW and 1000 kW;
- 70 €/MWh for systems whose power is $\geq$ 1000 kW.

Systems with power below 100 kW receive an additional premium of 10 €/MWh that can be added to the previous premium based on the share of the net produced energy that is consumed on the site, provided that energy self-consumption exceeds 40 % of the net production of the system.

Moreover, PV systems belonging to subgroup A-2 are granted an additional premium (12 €/MWh) on the entire energy production.

3. Material and methods

The introduction of renewable energy to contribute to the achievement of SDG 7 is complicated, particularly for public buildings, because numerous constraints must be considered. These include economic constraints related to the public budget, technical constraints because market solutions are not always compatible with the existing building structure, and social constraints, as public administrations must set an example for their communities and pioneer positive actions inspired by sustainability from every standpoint. This necessitates addressing energy retrofitting and related refurbishments while considering numerous parameters. In response to this need, this study proposes a multi-criteria and multi-disciplinary approach oriented toward sustainability, similar to other studies [32,33] but going beyond already established methodologies. For example, in the field of photovoltaics, Fuster-Palop et al. [34] conducted a multiple linear regression model to determine the economic payback using dimensionless parameters; Cucchiella, D'Adamo, and Rosa [35] investigated photovoltaic end-of-life but only from a financial point of view; Besharati et al. [36] studied a combined fuzzy best-worst method and geographic information system (GIS) to find the optimal location of a solar power plant site in Guilan province; while Junedi et al. [37] defined an environmental and economic performance assessment of integrated conventional photovoltaic. The proposed method in this study is based on energy, financial, and life cycle assessment of the photovoltaic system to achieve three main goals: the improvement of building energy performance, the identification of technical and financial solutions that suit the existing buildings, and individuation of modalities to limit environmental impact. The proposed approach constitutes a 3-phase process, as shown in Fig. 1. The first phase is energy assessment to evaluate the energy production of the installed photovoltaic system through solar potential analysis. The second phase is applying the Discounted Cash Flow (DCF) to calculate the Net Present Value (NPV), Discounted Payback Period (DPB), and Levelized Cost of Energy (LCOE). Then, energy and economic output are synthesised to generate a comparative matrix, an evaluation tool for each adopted strategy. It helps individuate the best-performing scenarios from both standpoints. These scenarios are then subjected to a Life Cycle Assessment, the third and final phase of this approach. This analysis is indispensable as photovoltaic technology, although considered a renewable energy source, still generates an environmental impact [38]. This proposed method was validated using a case study. Each step of the proposed methodology is discussed in detail in the subsequent sections of this work.

3.1. Energy analyses

This study specifically aims to evaluate the potential production of photovoltaic energy for public buildings belonging to the university, which refers to the available roof coverings suitable for installing photovoltaic systems. Therefore, the estimation of photovoltaic energy system producibility must be carried out through a multi-criteria evaluation, considering all the external and internal factors of the system whose variation considerably affects the output data:

- Incident solar radiation at the installation location;
- Orientation of the photovoltaic panel;
- Tilt of the photovoltaic panels;
- Self-shading between rows of adjacent panels;
- Shading, if present, is caused by nearby or distant objects that do not belong to the system;
- Photovoltaic technology.

Therefore, to evaluate the optimal solution from the energy standpoint following the primary choice of the geographic location and intervention surfaces, the proposed methodology performs a subdivision in typical scenarios organised according to the following input data: orientation, tilt, spacing distance between modules, and technology. Each orientation value selected to maximise the useable surface is associated with various tilt angles of the modules, which are then distinguished by different values of spacing distance between the modules and then differentiated according to their technology.

The correct evaluation of photovoltaic producibility requires, first, elaborate mapping to highlight the covering surfaces with remarkable values of incident solar radiation designed for photovoltaic installation. Then, the productivity, economic savings, and cost values can be calculated for each scenario.

These are the main methodological steps for the energy assessment:

- Solar study of roof covering of the selected buildings and individuation of suitable surfaces[1];
- Parameter selection (orientation, tilt, spacing distance between the modules, and technologies)
- Installation hypotheses for the photovoltaic systems with different values of the chosen parameters (scenario individuation); Calculation of incident solar radiation, module area, and energy production for each scenario.

3.2. Economic assessment

The Discounted Cash Flow (DCF) is an economic methodology for estimating project profitability [39]. This methodology calculates the economic value of a project as the present value of the expected cash flow in future business years. The main outputs of the DCF analysis are the Net Present Value (NPV) and Discounted Payback Period (DPB). NPV is the sum of the present cash flow values a project can generate within a given time period, and is a valuable tool for assessing whether a project will lead to net profit or loss. In financial theory, when choosing between two mutually exclusive alternatives, the one that yields a higher NPV is preferable [40]. Instead, the DPB produces a qualitative idea of the riskiness of investment: the higher the DPB, the higher the risk that an investment will not achieve the expected revenue. However, the DPB has certain operational limits: it does not consider the cash flows that occur after the payback period and provides no information concerning the profitability of the examined project.

In addition to assessing the economic profitability of a PV system, it is essential to study economic measures for evaluating energy generation costs using the Levelized Cost of Energy (LCOE) indicator. LCOE is the ratio between the total cost and total energy production during the life cycle of a PV system; it is calculated as the ratio between the present value of the total costs of the system and the current value of electricity production over the system's life cycle. The LCOE represents the suggested sale price of the energy produced during the system's life cycle to balance all the costs incurred for its construction, management, and dismantling. LCOE has been extensively utilised because of its ease of application and methodological clarity, which are required by the scientific community to compare evaluations of energy policies with a broad technological scope.

The input data for economic assessment focusing on policies supporting renewable energy in Italy can be subdivided into two macro-areas:

- PV system costs;
- Economic benefits associated with a PV system.

The PV system costs are characterised by:

- Investment cost;
- Operation costs.

The initial cost of a PV system constitutes the cost of PV modules, balance-of-system (BoS), and soft costs [41]. PV module costs include raw materials, processing, cell production, and mounting [42]. Four factors influence the BoS cost: mechanical BoS, including all the mechanical parts for the installation of the PV system; electrical BoS, including all the electric components to connect the PV modules; inverter, including the inverter and the monitoring system; and

[1] The quantity of producible electrical energy has been calculated based on the radiometric data from the UNI 10349 and UNI 8477 codes and the calculations from satellite images performed by the Satellite Application Facility on Climate Monitoring (CM SAF).

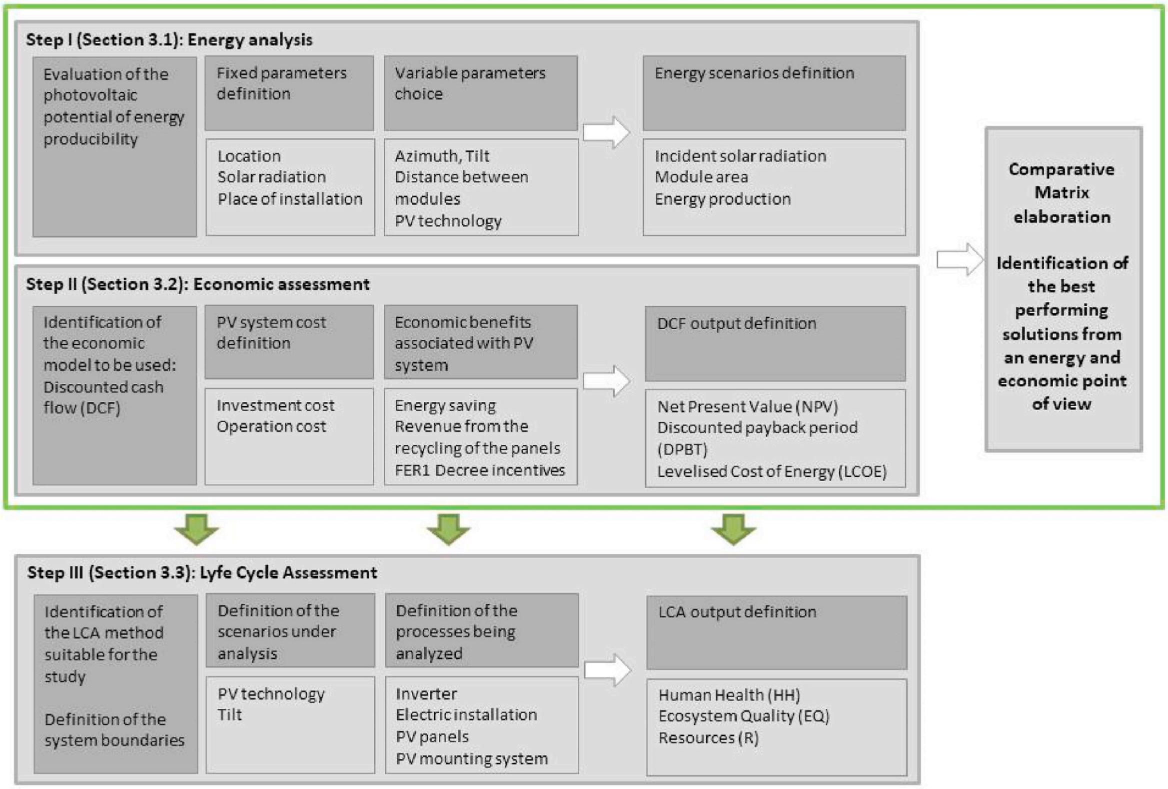


Fig. 1. Methodological approach.

miscellaneous, including all works directly related to the photovoltaic systems, including scaffolding safety equipment [43]. Soft costs comprise authorisation and general costs, including marketing, sale, and administrative costs associated with the system. In Europe, the cost of solar PV panels decreased by approximately 90 % between December 2009 and December 2019 [44].

This reduction was strictly related to the optimization of the production process of the modules, which directly led to a decrease in module and BoS costs. This indicates that optimising the production processes and improving module efficiency are key factors influencing cost reduction. Moreover, the reduction in the costs of modules and inverters led to a 62 % reduction in installation costs from 2010 to 2019. Therefore, the module and BoS costs greatly contribute to the total costs [44]. However, regardless of the decreasing overall cost, the soft costs remain significantly high. O'Shaughnessy et al. [45] demonstrated that soft costs are relatively low for bigger, newly built systems installed by expert installers and in more competitive markets, where authorisation requirements are relatively low. According to the data provided by the International Renewable Energy Agency [44] and market surveys, the investment cost of a PV system is dependent on the technology used. For the polycrystalline system, the investment cost is 960 €/kW, 986 €/kW for the monocrystalline system, and 1147 €/kW for the thin film.

Operational costs are associated with the management of PV systems. They include maintenance, inverter replacement, and insurance costs. According to Gholami and Røstvik [46], the annual maintenance cost of a PV system is 1 % of its investment cost, whereas the cost of inverter replacement is 17 % of the investment cost of the PV system and is incurred every 10 years of system operation. Instead, the yearly insurance cost is considered to be 1 % of the investment cost of the PV system [47].

The second macro-area includes the economic benefits associated with a PV system. The profits of a PV system with self-consumption are produced by the financial savings derived from energy self-consumption and the revenues from the excess electrical energy exported and fed into the grid. These are compounded by the premium for the electrical energy produced by the PV systems according to the FER1 Decree and revenue from recycling photovoltaic modules. Therefore, the benefits can be synthesised using the following items:

- avoided electrical expenses, leading to bill savings;
- the revenue from recycling PV panels;
- obtaining incentives regulated by the FER1 decree.

The first item relates to the economic savings from self-consumption, followed by the avoided acquisition cost of electrical energy. Finally, energy self-consumption is evaluated according to the economic value that would have been paid if the same electrical power had been bought from the grid.

The second item is related to revenue from recycling the photovoltaic panel. According to the research work by Markert et al. [48], the revenue of the c-Si PV module is 1.19 USD per m^2. This value was obtained by subtracting the disposal costs from the positive cash flows derived from the recovery of the materials and energy. The disposal costs of photovoltaic modules are divided into private and external costs. Private costs include all the costs that a PV recycler must pay during the recycling process, such as equipment costs, material costs, electricity costs, and the costs associated with the fuel consumption of trucks for transportation from the installation site of the PV system to the recycling centre. External costs are the environmental damage caused by the pollutants released during the recycling, transport, and incineration processes. These two items cost 12.43 USD per m^2 of the c-Si PV module (6.72 USD/m^2 for private costs and 5.71 USD/m^2 for external costs). Instead, the material and energy recovery was estimated at 13.62 USD per m^2 of the c-Si PV module.

The last item comprises the premium for the electrical energy produced by the PV system according to the FER1 Decree.

The model used for the economic assessment is expressed as follows:

$$NPV = \sum_{t=0}^{N} \frac{(R_t - C_t)}{(1+i)^t} \tag{1}$$

$$\sum_{t=0}^{DPBT} \frac{(R_t - C_t)}{(1+i)^t} = 0 \tag{2}$$

$$LCOE = \frac{\sum_{t=0}^{N} \frac{C_t}{(1+i)^t}}{\sum_{t=0}^{N} \frac{SOE_t}{(1+i)^t}} \tag{3}$$

$$R_t = \begin{cases} 0 & t = 0 \\ R_{FIT,t}^{subsidies} + R_t^{electric\ energy} + R_{bonus,t}^{subsidies} + R_{PV\ recycling,t} & 1 \leq t \leq N \end{cases} \tag{4}$$

$$R_{FIT,t}^{subsidies} = SOE_t \bullet \left(1 - Q_{selfcons}\right) \bullet S_{u,FIT} \tag{5}$$

$$R_t^{electric\ energy} = SOE_t \bullet Q_{selfcons} \bullet p_t^e \tag{6}$$

$$R_{bonus,t}^{subsidies} = SOE_t \bullet Q_{selfcons} \bullet S_{u,bonus} \tag{7}$$

$$R_{PV\ recycling,t} = \begin{cases} 0 & t \neq N \\ Recy_u \bullet sqm & t = N \end{cases} \tag{8}$$

$$SOE_{t+1} = SOE_t \bullet (1 - dse) \tag{9}$$

$$p_{t+1}^e = p_t^e \bullet (1 + inf^e) \tag{10}$$

$$C_t = I_t + C_{m,t} + C_{r,t} + C_{i,t} \tag{11}$$

$$I_t = \begin{cases} I_u \bullet P_{sy} & t = 0 \\ 0 & t \neq 0 \end{cases} \tag{12}$$

$$C_{m,t} = \begin{cases} Perc_{Cm} \bullet I_0 \bullet (1 + inf) & t = 1 \\ C_{m,t-1} \bullet (1 + inf) & 2 \leq t \leq N \end{cases} \tag{13}$$

$$C_{r,t} = \begin{cases} Perc_{Cr} \bullet I_0 & t = 10, 20, 30 \text{ V t} < \text{N} \\ 0 & t \neq 10, 20, 30 \end{cases} \tag{14}$$

$$C_{i,t} = \begin{cases} Perc_{Ci} \bullet I_0 \bullet (1 + inf) & t = 1 \\ C_{i,t-1} \bullet (1 + inf) & 2 \leq t \leq N \end{cases} \tag{15}$$

3.3. Life cycle assessment

The collection, analysis, and monitoring of the environmental performance of each photovoltaic technology were performed using SimaPro software [49] version 9.3.0.2. This study complied with international standards ISO 14040 and ISO 14044.

Accordingly, this LCA study was subdivided into four phases as follows: 1) an outline of the goal and scope of the LCA, 2) the life cycle inventory (LCI) analysis, 3) the life cycle impact assessment (LCIA), and finally, 4) the life cycle interpretation.

The scope of an LCA is dependent on the subject and operational purpose of the study. In this phase, the study's goal, functional unit, system boundaries, and categories of data to be collected and analysed are defined. The LCI analysis is the most delicate and arduous phase. It includes quantifying the input and output data related to the studied system. The data required to achieve the study goals were collected and stored in an inventory table. LCI is fundamental for the subsequent phase of LCIA, which aims to determine the potential effects of the system on the environment by connecting inventory data to specific impact categories, providing additional information to support the evaluation of the LCI results of a product system to elucidate environmental implications. Finally, the life cycle interpretation phase summarises all the results and discusses them to draw conclusions and make inferences according to the goal of the analysis.

4. Description of the case study

The case study is the Roio engineering Campus of the University of L'Aquila, situated in L'Aquila, Abruzzo, in the village Monteluco di Roio, atop a homonymous hill approximately 960 m above sea level (geographic coordinates 42°20′13‴’ N and 13°22′43’’″ E). The site is close to a forest area in the North and East and is isolated from urban centres.

This campus comprises three buildings: blocks A, B, and C, with the latter being the site of the auditorium and library (Figs. 2 and 3). It was established by a former fascist mountain colony, which was then transformed into a university campus and was impacted by a devastating earthquake in 2009, which has since led to its condemnation.

In particular, the study was carried out on blocks A and B, whose roof coverings cover a total area of 1400 and 2100 m^2, respectively.

Block A is predominantly oriented along the East-West direction and has four levels, each with a distinct function: the first basement houses the hydraulics, geotechnics, and structural engineering laboratories; the second basement houses classrooms and other laboratories; the ground floor houses the entrance hall, janitor's quarters, the student administration office, and study areas; and the first-floor contains employees' and professors' offices.

Block B mainly stretches along the north-south direction and has three levels. The underground floor primarily houses laboratories for computer science, chemistry, electronics, and administrative offices, while the ground floor and first floor primarily house classrooms and project laboratories.

Both Blocks A and B have rectangular floors and a total height of approximately 21 m, with a spacing of less than 10 m between them, connected by a small walkway. The roof coverings are primarily plain; they are both covered by a meshed Faraday cage and other shading elements. The covering of block A is characterised by exposed beams, while that of block B has semi-cylindrical skylights that provide shading on the surfaces (Fig. 4).

5. Input data definition

5.1. Input parameters for energetic assessment: shading analysis and solar data

First, a shading analysis was performed on the roof covering of the building structures of blocks A and B. Specifically, a solar study was conducted during the solstices (summer and winter) and equinoxes (spring and fall).

The standard primary input for estimating the photovoltaic potential, and consequently the producibility of a PV system, is the measurement of the incident, global, and diffuse solar radiation at a given location, in addition to external temperature values. As a result, this needs the evaluation of incident solar radiation on the two coverings a priori to identify the most suitable surface regions for photovoltaic installation, specifically those characterised with favourable incident solar radiation values, as shown in Fig. 5.

The total net area is 2352.81 m^2, divided into 780.03-m^2 for block A and 1572.78 m^2 for block B.

The primary solar data for the site exported from the PVGIS2 database regarding both the optimal tilt and orientation on the vertical and horizontal axes are reported in Table 1.

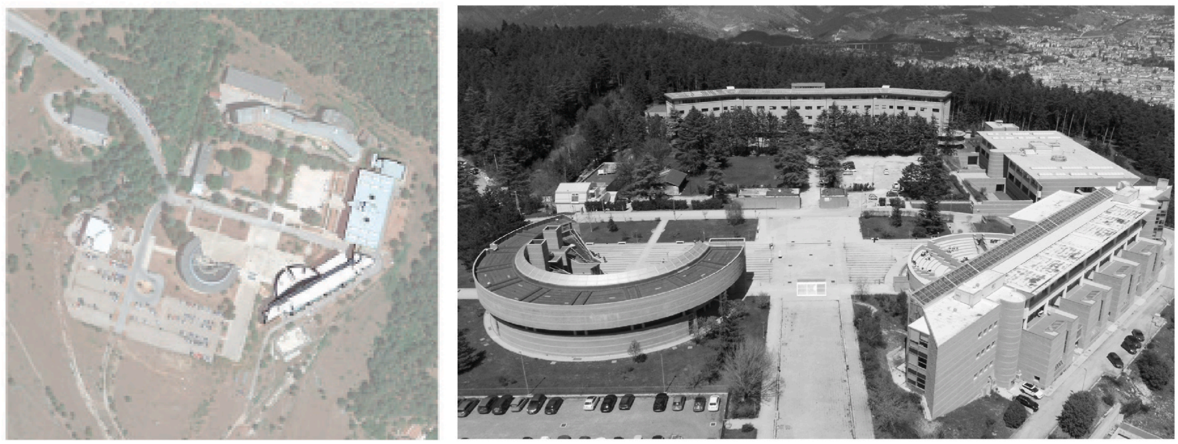


Fig. 2. Aerial view of the intervention site.

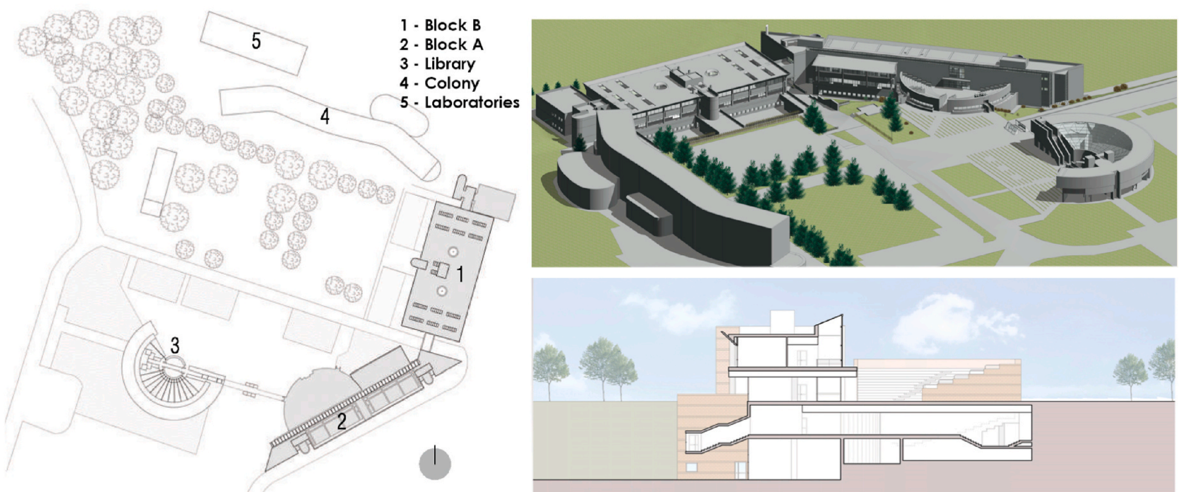


Fig. 3. The roof plan simplified the three-dimensional model and section.

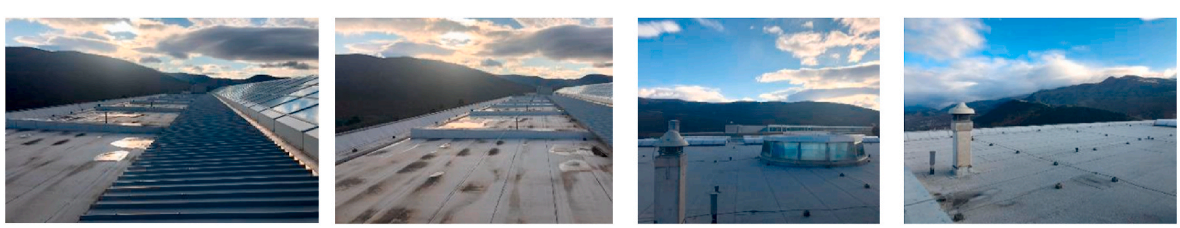


Fig. 4. Photographs of the roof coverings of block A (left) and block B (right).

5.2. Input parameters for economic assessment

Evaluation of the economic feasibility of this case study requires several parameters. The economic parameters are presented in Table 2.

The service life of the PV systems was set at 20 years based on the indications in the FER1 Decree. In the case study, $Q_{selfcons}$ was set to 35 % and 45 %. Therefore, without specific actions and/or investments, the share of self-consumption is 35 % [55]. However, the FER1 Decree states that $Q_{selfcons}$ must be higher than 40 % to achieve an additional 10 €/MWh premium. Therefore, the analysis was performed considering both $Q_{selfcons}$ = 35 % and $Q_{selfcons}$ = 45 %.

6. Results

6.1. Energy results

General solar studies should follow the outline of the intervention scenarios, which aims to maximise the exploitation of the useable area using every combination of variable parameters, such as orientation, tilt, and spacing distance between modules. This has allowed various possibilities for calculating PV energy system products for the most common technological solutions.

The roof coverings are mainly flat, except for part of the covering of block A, which is 10° slanted. This allowed for selecting various values of orientation and tilt for the modules and required a substructure to install the system.

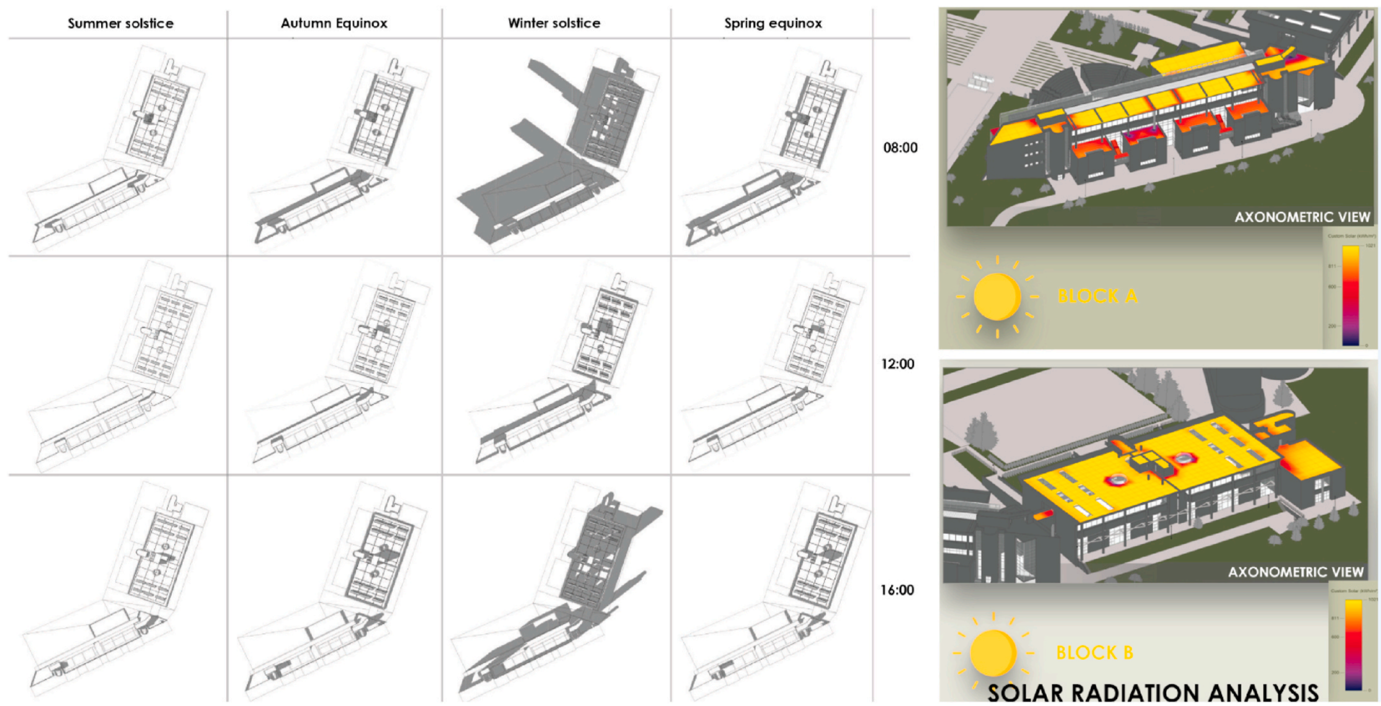


Fig. 5. Analysis of shading and annual incident solar radiation.

Table 1
Technical parameters.

Tilt angle [°]:	34 (opt)	0
Orientation angle [°]:	−19 (opt)	0
PV annual production [kWh/kWp]:	1274.89	1110.01
Global annual solar radiation [kWh/mq]:	1608.51	1413.99
Interannual variation [kWh]:	65.48	45.85
Production variation due to:		
Angle of solar incidence [%]:	−2.82	−3.78
Spectral effects [%]:	1.28	1.15
Low temperature and irradiance [%]:	−6.36	−6.21
Total losses [%]:	−20.74	−21.5

Table 2
Economic parameters.

Parameter	Value	Measurement unit	Reference
dse	0.5	%	[30]
i	3	%	[50]
inf	0.61	%	[51]
inf^e	1.1	%	[52]
I_u	960*-986**-1147***	€/kW	[44]
N	20	years	[53]
p_0^e	0.19	€/kWh	[54]
$Perc_{Ci}$	0.5	%	[47]
$Perc_{Cm}$	1	%	[46]
$Perc_{Cr}$	17	%	[46]
$Q_{selfcons}$	35–45	%	[55]
$Recy_u$	1	€/m²	[48]
$S_{u,bonus}$	$10^{III,i}$-$0^{I,II,ii}$	€/MWh	[53]
$S_{u,FIT}$	70^{I}–90^{II}–105^{III}–0^{IV}	€/MWh	[53]

*Polycrystalline-**Monocrystalline-***Thin film.
i $Q_{selfcons}$ >40%-**ii** $Q_{selfcons}$ <40 %.
I P_{sy} ≥1000 kW -**II** 100 kW < P_{sy} <1000 kW -**III** 20 kW < P_{sy} ≤100 kW -**IV** P_{sy} <20 kW.

The two main orientations of the buildings (north-south and east-west) were retained while considering the tilt angles of the modules. Three values were considered for each direction: 0° (flat), 10° tilt (the height of the panels does not exceed the ridge line of the buildings), and 34° (optimal tilt).

The third variable parameter was the spacing between the panels, and the following values were used: 10, 20, 30, 50, and 60 cm. The various combinations of orientation, tilt, and distance led to different results in incident solar radiation, useable area, and production loss owing to shading and photovoltaic producibility, as shown for one of the scenarios in Fig. 6.

Blocks A and B were analysed, and the panels were hypothesized to be oriented along the longitudinal and transversal directions of the buildings. For the two blocks 153 scenarios were analysed, 78 for the block A and 75 for the block B. For the first one, except for the part of the roof covering that was 10° slanted with SE orientation, there are two main orientations: southeast and southwest, as reported in Table 3. Instead, the main orientations were East and South for Block B (Table 4), whose floor plan is not parallel to Block A. Concerning the tilt and distance hypotheses, the considerations were the same as those for block A.

6.2. Economic results

This section discusses the economic feasibility of PV systems assessed using the model defined in section 3.2 through NPV and DPB.

Likewise, different combinations of orientation, tilt, and distance lead to different results in terms of NPV, DPB, and LCOE. For clarity, the resulting values of NPV, DPB, and LCOE have been grouped into two tables: the first is related to the hypotheses concerning block A (Table 5), while the other is related to the hypotheses formed for block B (Table 6). The scenarios developed are 156 for block A and 150 for block B, i.e. twice as many as those studied from an energy point of view (section 6.1). This is because each scenario in Tables 3 and 4 was analysed considering the percentage of self-consumption to be 35 % and 45 %, since FER 1, as mentioned in section 2.0, sets the percentage of energy self-consumption at 40 % for an additional bonus in the systems with power below 100 kW.

BLOCK A

HYPOTHESIS 1.1-A_SI	
Number of panel rows (n)	48
Square meters (sqm)	724
Distance between panels (m)	0,1
Cumulative insolation (kWh)	958452
Incident solar radiation (kWh/mq)	1325
HYPOTHESIS 1.2-A_SI	
Number of panel rows (n)	42
Square meters (sqm)	824
Distance between panels (m)	0,3
Cumulative insolation (kWh)	1052091
Incident solar radiation (kWh/mq)	1276
HYPOTHESIS 1.3-A_SI	
Number of panel rows (n)	43
Square meters (sqm)	681
Distance between panels (m)	0,3
Cumulative insolation (kWh)	919121
Incident solar radiation (kWh/mq)	1350
HYPOTHESIS 1.4-A_SI	
Number of panel rows (n)	38
Square meters (sqm)	638
Distance between panels (m)	0,5
Cumulative insolation (kWh)	824143
Incident solar radiation (kWh/mq)	1319
HYPOTHESIS 1.5-A_SI	
Number of panel rows (n)	38
Square meters (sqm)	634
Distance between panels (m)	0,6
Cumulative insolation (kWh)	837062
Incident solar radiation (kWh/mq)	1320

	MAXIMUM POWER kWp	ESTIMATED PRODUCTION kWh/year	SPECIFIC PRODUCTION kWh/kWp/year
Monocrystalline silicon	60	71990	1199
Polycrystalline silicon	44	52305	1188
Amorphous silicon	30,8	35377	1148
Monocrystalline silicon	88,8	107856	1211
Polycrystalline silicon	110	132894	1209
Amorphous silicon	38,6	44876	1161
Monocrystalline silicon	60,8	74344	1222
Polycrystalline silicon	42,2	50846	1204
Amorphous silicon	30,5	35439	1162
Monocrystalline silicon	81,2	97953	1201
Polycrystalline silicon	83,6	99855	1194
Amorphous silicon	34,2	39371	1150
Monocrystalline silicon	88,4	105006	1190
Polycrystalline silicon	86	101222	1182
Amorphous silicon	39,4	44840	1139

Fig. 6. Total and specific photovoltaic producibility for the modules with SW orientation and 10° tilt, block A.

Results showed that the profitability of the systemwas always assessed regarding NPV and DPB. In all hypotheses, NPV was always higher than zero, which means that the analysed PV system always produces an economic profit; DPB was also consistently lower than the system's service life.

For block A, NPV values varied between 11,348€ and 127,791€. In particular, the minimum value was associated with hypothesis 2 (A_SE with 35 % energy self-consumption and use of a_Si), where DPB is equal to 9 years and LCOE is 0.0855. The maximum NPV for block A was achieved with hypothesis 3.3-A_SW (45 % share of energy self-consumption using Mono_Si), with a DPB of seven years and LCOE of 0.0777 €/kWh.

The DPB indicator takes values between seven and 15 years, while the maximum value of LCOE is 0.1162€/kWh in hypothesis 2.1-A_SE. Similar considerations concerning Block B were elaborated. The maximum value of NPV (258,873€) is associated with hypothesis 2.2-B_E, with 45 % energy self-consumption and poli_Si as the employed material. In contrast, the minimum value (47,311 €) is produced in hypothesis 1.1-B_S, with 35 % energy self-consumption and employment of a_Si. For block A, in block B, the minimum value of DPB is seven years, while the maximum value is 13 years. LCOE had lower values in block B than in block A. The maximum value of LCOE for block B is 0.0955 €/kWh, whereas that for block A is 0.1011 €/kWh.

7. LCA

As detailed in Section 3.3, the LCA is divided into four phases: definition of the goal and scope of the LCA, LCI, LCIA, and life cycle interpretation phase.

7.1. Definition of the goal and scope of analysis

This study aims to systematically compare and evaluate the environmental impacts produced by three different technologies for photovoltaic systems: polycrystalline, monocrystalline, and thin film. In particular, LCA was performed for the three optimal intervention scenarios (1.2-A_SW, 2-A_SE, and 1.1-B_E) based on the results obtained from the solar studies.

LCA is patterned after the "from cradle to gate" paradigm and considers the following three types of photovoltaic technologies: mono-Si, multi-Si, and a-Si, using the ReCiPe method [49,56], considering its more recent and advanced version [57].

Based on other studies [1,58], the service life of photovoltaic systems is assumed to be 30 years. Therefore, the functional reference unit for the results of the LCA is peak power, measured in kWp.

7.2. Life cycle inventory

The study's second phase is the LCI, which quantifies the input and output data of the three technologies of photovoltaic systems. The input data were mainly obtained from the internationally acknowledged Ecoinvent v3 database [59,60], which has the broadest available database of LCI data.

Table 7 presents a synthetic list of the product quantities for each scenario.

7.3. Life cycle impact assessment

Following the LCI, the three scenarios and the nine solutions related to the various photovoltaic technologies, each with a different kWp, were subjected to a LCIA. The environmental impact was evaluated using the ReCiPe 2016 endpoint (H) method; this is considered the most recent and advanced method that combines the midpoint-based approach of CML-IA and the endpoint-based approach of Eco-indicator 99, which are internationally acknowledged [61].

The ReCiPe method outlines five phases in LCIA: characterisation, damage assessment, normalisation, weighting, and single-score. The ISO standards only mandate the characterisation phase, while the remaining phases are optional (BS EN ISO 14040:2006 + A1:2020).

Table 8 reports the results of the characterisation phase, which is

Table 3
Synthetic table – block A.

Orientation	Block	Tilt (°)	Distance (m)	Hypothesis (code)	Incident solar radiation (kWh/year)	Power (kWp)	Techn.	Total estimated production (kWh/year)	Specific production (kWh/kWp year)
South-East	A	10°	0,1	1.1-A_SE	716,687	65	mono_Si	77,887	1206
						60	poli_Si	71,896	1196
						39	a-Si	44,222	1147
			0,2	1.2-A_SE	679,847	60	mono_Si	72,899	1214
						69	poli_Si	83,107	1211
						37	a-Si	42,565	1164
			0,3	1.3-A_SE	625,616	72	mono_Si	88,115	1220
						66	poli_Si	79,736	1211
						37	a-Si	42,565	1164
			0,5	1.4-A_SE	596,366	61	mono_Si	73,417	1207
						48	poli_Si	57,631	1192
						33	a-Si	37,374	1149
			0,6	1.5-A_SE	591,051	65	mono_Si	77,572	1200
						42	poli_Si	50,327	1191
						31	a-Si	34,907	1142
		34°	**0**	**2-A_SE**	**241,765**	**24**	**mono_Si**	**30,440**	**1258**
						21	**poli_Si**	**26,380**	**1249**
						11	**a-Si**	**14,090**	**1254**
			0,1	2.1-A_SE	766,964	86	mono_Si	85,344	994
						69	poli_Si	68,123	992
						37	a-Si	34,900	954
			0,2	2.2-A_SE	710,976	61	mono_Si	64,964	1061
						66	poli_Si	69,155	1052
						38	a-Si	37,882	1007
			0,3	2.3-A_SE	738,321	72	mono_Si	78,845	1095
						66	poli_Si	72,149	1093
						34	a-Si	35,907	1050
			0,5	2.4-A_SE	726,909	71	mono_Si	81,332	1139
						71	poli_Si	80,203	1128
						36	a-Si	39,147	1088
			0,6	2.5-A_SE	721,715	68	mono_Si	78,567	1148
						69	poli_Si	77,957	1135
						35	a-Si	37,932	1093
South-West	A	0°	0,5	1.1-A_SO	698,370	86	mono_Si	100,962	1168
						76	poli_Si	87,962	1158
						41	a-Si	46,735	1137
			0,1	**1.2-A_SO**	**870,370**	**109**	**mono_Si**	**124,129**	**1140**
						95	**poli_Si**	**108,044**	**1141**
						51	**a-Si**	**59,477**	**1156**
			0,3	1.3-A_SO	779,148	100	mono_Si	115,892	1162
						85	poli_Si	98,609	1161
						46	a-Si	51,609	1116
			0,6	1.4-A_SO	676,625	85	mono_Si	96,700	1138
						74	poli_Si	85,618	1158
						40	a-Si	46,435	1160
			0,2	1.5-A_SO	805,506	102	mono_Si	118,896	1166
						84	poli_Si	98,257	1163
						48	a-Si	53,062	1117
		10°	0,5	2.1-A_SO	619,509	72	mono_Si	88,229	1225
						63	poli_Si	77,274	1220
						35	a-Si	41,208	1189
			0,1	2.2-A_SO	747,948	91	mono_Si	111,299	1220
						79	poli_Si	96,083	1213
						43	a-Si	51,506	1204
			0,3	2.3-A_SO	658,393	80	mono_Si	97,423	1221
						69	poli_Si	83,383	1214
						37	a-Si	44,367	1213
			0,6	2.4-A_SO	632,818	76	mono_Si	93,091	1225
						66	poli_Si	80,112	1218
						36	a-Si	43,488	1210
			0,2	2.5-A_SO	752,299	91	mono_Si	111,183	1219
						79	poli_Si	95,982	1211
						43	a-Si	51,050	1193
		34°	0,5	3.1-A_SO	653,632	86	mono_Si	106,900	1237
						74	poli_Si	90,777	1228
						41	a-Si	49,937	1228
			0,1	3.2-A_SO	758,505	112	mono_Si	129,059	1150
						97	poli_Si	110,698	1144
						53	a-Si	61,975	1173
			0,3	3.3-A_SO	682,634	93	mono_Si	112,791	1215
						81	poli_Si	97,844	1208
						44	a-Si	52,590	1205
			0,6	3.4-A_SO	655,755	85	mono_Si	105,825	1245

(continued on next page)

Table 3 (*continued*)

Orientation	Block	Tilt (°)	Distance (m)	Hypothesis (code)	Incident solar radiation (kWh/year)	Power (kWp)	Techn.	Total estimated production (kWh/year)	Specific production (kWh/kWp year)
						74	poli_Si	91,459	1238
						40	a-Si	47,739	1193
			0,2	3.5-A_SO	730,206	101	mono_Si	118,243	1173
						90	poli_Si	107,034	1193
						48	a-Si	56,301	1169

compulsory according to ISO 14040 and ISO 14044 codes, as statedin section 3.3. This phase aims to quantify the environmental impacts according to their respective units. Each substance in the life cycle contributing to a given impact category has been multiplied in SimaPro by a characterisation factor, representing the substance's relative contribution. Then, in the normalisation phase, the results of the impact indicators were compared with the respective impact categories (Table 9).

A previous study [62] demonstrated that the normalisation phase has a greater influence on the results than the weighting phase. This is because in the normalisation phase, through outranking, the impact categories are ranked with a more balanced contribution and higher value sensitivity compared to the ponderation phase.

Table 10 reports the results of the weighting phase. This phase eases result interpretation as it aggregates the results of the characterisation phase in a single score, thus allowing for comparisons among the different scenarios. Zanghelini et al. [63] highlight the importance of this step for communicating LCA results.

7.4. Interpretation of results

The LCA constitutes a list of environmental impacts or damages that can serve as performance indicators of the analysed product system.

The last phase of LCA is result interpretation, where the results of the LCI assessment and the LCIA are synthesised and discussed.

Block B, that is, scenario 3, n. 1.1-B_E 106 kWp, with a_Si technology at 73.32 MPt yielded the most impactful solution, followed by the solution of scenario 1, n. 2-A_SE 11 kWp with a_Si technology, at 7.61 MPt.

These solutions were therefore disregarded, whereas the other possible alternatives were compared to each other through the single-score phase, as shown in the histograms related to the damage categories (Fig. 7) and the impact categories (Fig. 8).

These results allowed the determination of the optimal solutions with the lowest environmental impact corresponding to the lowest scores.

For block A with a 10° slanted roof, the most impactful solution results were yielded by single_Si 24 kWp with 2.13 kPt; multi_Si 21 kWp technology has 1.96 kPt.

The analysis of the solution of scenario 1, n. 2-A_SE 21 kWp multi_Si shows that the impact categories and substances with higher environmental damage are as follows:

- "fine particulate matter formation", with 45 % (0.882 kPt), is mainly caused (43.3 %) by the "sulphur dioxide" in "aluminium wrought alloy" by 17.7 %, and in "silicon, solar grade" by 16.6 %; is attributed to "particulates <2.5 μm" (40.8 %) accounting for 25.7 % in "silicon, solar grade" and by 12.6 % in "aluminium, wrought alloy";
- "global warming, human health", with 34,2 % (0.67 kPt), is mainly caused (86.6 %) by "carbon dioxide fossil", which accounts for 21.4 % in "silicon, solar grade", by 14.1 % in "aluminium, wrought alloy", and 10.3 % in "electricity";
- "human non-carcinogenic toxicity", with 8.8 % (0.173 kPt), is mainly caused (65.7 %) by arsenic, which accounts for 34 % in "copper, cathode", and (33 %) by "photovoltaic systems, electric installation".

The environmental impacts are mainly caused by the production processes of the photovoltaic panels, with 62 % (1.22 kPt) due to photovoltaic cells, followed by (17 %, 0.33 kPt) photovoltaic system mounting processes. "Human health" was ranked highest concerning severity of the damage (96.1 %), followed by "ecosystems" at 2.79 %, and "resources" at 1.11 %.

For block A with a flat roof, the most impactful solution results were yielded by single_Si 109 kWp with 9.45 kPt; compared to the multi_Si 95 kWp technology that yielded 8.64 kPt.

The analysis of the solution of Scenario 2, n. 1.2-A_SW 95 kWp multi_Si shows that the impact categories with the most serious environmental damage are as follows:

- "fine particulate matter formation", at 45.2 % (3,9 kPt), is mainly caused (43.4 %) by sulphur dioxide, which accounts for 16.9 % in "silicon, solar grade", and 16.1 % in "aluminium, wrought alloy"; it is also caused (40.7 %) by "particulates <2.5 μm", which accounts for 26.3 % in "silicon, solar grade" and 11.5 % in "aluminium, wrought alloy";
- "global warming, human health", at 34.5 % (2.99 kPt), is mainly caused (86.5 %) by "carbon dioxide fossil", which accounts for 21.7 % in "silicon, solar grade", 12.7 % in "aluminium, wrought alloy", and 10.4 % in "electricity";
- "human non-carcinogenic toxicity", at 8.94 % (0.773 kPt), is mainly caused (65.5 %) by arsenic, which accounts for 34.4 % in "copper, cathode" and 33.4 % in "photovoltaic plant, electric installation".

The environmental impacts are mainly attributed to the construction processes of the photovoltaic panels (63.6 %, 5.5 kPt), particularly photovoltaic cells, followed by photovoltaic system mounting processes (14.8 %, 1.28 kPt). "Human health" results were ranked highest concerning damage (96 %), followed by "ecosystems" at 2.82 %, and "resources" at 1.19 %.

Finally, for block B with a 34° slanted roof, the most impactful solution results were yielded by multi_Si 213 kWp, with 19.9 kPt, compared to the single_Si 216 kWp technology with 19.2 kPt.

The analysis of the solution of scenario 3, n. 1.1-B_E 216 kWp single_Si, shows that the impact categories and the substances with the most severe environmental damage are as follows:

- "fine particulate matter formation", at 45 % (8.64 kPt), is mainly caused (43.4 %) by sulphur dioxide, which accounts for 17.5 % in "aluminium, wrought alloy", and 16.4 % in "silicon, solar grade"; and by "particulates <2,5 μm" (40.8 %), which accounts for 25.3 % in "silicon, solar grade", and 12.4 % in "aluminium, wrought alloy";
- "global warming, human health", at 34 % (6.53 kPt), mainly caused (86.6 %) by "carbon dioxide fossil", which accounts for 21.2 % in "silicon, solar grade", 14 % in "aluminium, wrought alloy", and 10.2 % in "electricity";
- "human non-carcinogenic toxicity", at 8.99 % (1.73 kPt), is mainly caused (66.2 %) by arsenic, which accounts for 34.3 % in "copper, cathode", and by "photovoltaic plant, electric installation" (33.6 %);
- "human carcinogenic toxicity", at 6.24 % (1.2 kPt), was mainly caused (90.7 %) by "chromium", which accounts for 51.2 % in "steel, low-alloyed", and 13.9 % in "aluminium, wrought alloy".

Table 4
Synthetic table – B block.

Orientation	Block	Tilt (°)	Distance (m)	Hypothesis (code)	Incident solar radiation (kWh/year)	Power (kWp)	Technology	Total estimated production (kWh/year)	Specific production (kWh/kWp year)
East	B	10°	0,1	1.1-B_E	1,379,138	129	mono_Si	156,009	1205
						13	poli_Si	15,916	1203
						79	a-Si	91,183	1150
			0,2	1.2-B_E	1,343,551	125	mono_Si	151,976	1213
						127	poli_Si	152,944	1204
						73	a-Si	83,926	1154
			0,3	1.3-B_E	1,223,044	141	mono_Si	171,072	1217
						126	poli_Si	152,604	1207
						69	a-Si	80,287	1159
			0,5	1.4-B_E	1,168,044	133	mono_Si	162,157	1217
						121	poli_Si	146,621	1207
						67	a-Si	77,971	1156
			0,6	1.5-B_E	1,082,213	133	mono_Si	162,157	1216
						70	poli_Si	84,380	1199
						62	a-Si	71,174	1155
		34°	**0,1**	**1.1-B_E**	**1,517,598**	**216**	**mono_Si**	**263,445**	**1222**
						213	**poli_Si**	**258,620**	**1217**
						106	**a-Si**	**123,520**	**1166**
			0,2	1.2-B_E	1,521,869	212	mono_Si	260,820	1229
						215	poli_Si	261,786	1217
						106	a-Si	123,648	1167
			0,3	1.3-B_E	1,552,649	205	mono_Si	251,940	1230
						213	poli_Si	259,692	1217
						115	a-Si	133,722	1165
			0,5	1.4-B_E	1,512,402	213	mono_Si	262,870	1233
						189	poli_Si	230,860	1224
						138	a-Si	161,990	1172
			0,6	1.5-B_E	1,108,759	141	mono_Si	173,451	1233
						132	poli_Si	161,823	1222
						71	a-Si	83,431	1171
South	B	0°	0,5	1.1-B_S	989,789	122	mono_Si	145,632	1190
						106	poli_Si	125,419	1180
						58	a-Si	67,896	1175
			0,1	1.2-B_S	1,258,561	157	mono_Si	186,271	1188
						137	poli_Si	160,490	1175
						74	a-Si	86,897	1179
			0,3	1.3-B_S	1,196,502	148	mono_Si	171,632	1158
						129	poli_Si	152,267	1178
						69	a-Si	82,936	1200
			0,6	1.4-B_S	993,537	122	mono_Si	145,534	1189
						132	poli_Si	175,250	1331
						58	a-Si	68,526	1177
			0,2	1.5-B_S	1,207,041	148	mono_Si	176,038	1188
						132	poli_Si	155,275	1180
						71	a-Si	83,591	1178
		10°	0,5	2.1-B_S	1,224,159	140	mono_Si	172,398	1228
						121	poli_Si	151,165	1245
						66	a-Si	79,751	1202
			0,1	2.2-B_S	1,390,491	152	mono_Si	188,859	1243
						143	poli_Si	176,928	1241
						77	a-Si	96,011	1246
			0,3	2.3-B_S	1,263,435	144	mono_Si	175,932	1222
						127	poli_Si	157,464	1243
						67	a-Si	83,825	1249
			0,6	2.4-B_S	1,072,794	122	mono_Si	154,013	1258
						106	poli_Si	132,638	1248
						58	a-Si	72,322	1251
			0,2	2.5-B_S	1,301,520	148	mono_Si	181,270	1223
						127	poli_Si	157,626	1245
						70	a-Si	88,543	1261
		34°	0,5	3.1-B_S	1,311,598	152	mono_Si	192,603	1267
						132	poli_Si	165,633	1259
						72	a-Si	91,056	1267
			0,1	3.2-B_S	1,413,904	198	mono_Si	238,316	1203
						172	poli_Si	205,771	1196
						92	a-Si	111,308	1204
			0,3	3.3-B_S	1,385,341	175	mono_Si	217,512	1244
						153	poli_Si	189,422	1237
						82	a-Si	103,421	1259
			0,6	3.4-B_S	1,269,897	150	mono_Si	192,700	1281
						132	poli_Si	167,414	1272
						71	a-Si	91,011	1279
			0,2	3.5-B_S	1,407,608	184	mono_Si	219,202	1193
						162	poli_Si	197,201	1218
						87	a-Si	108,299	1239

Table 5
NPV, DPB, and LCOE in block A.

Tech	Hypothesis	Power [kWp]	EstimProd (kWh/y)	% of self-cons.	NPV [€]	DPBT [year]	LCOE [€/kWh]	Hypothesis	Power [kWp]	EstimProd (kWh/y)	% of self-cons.	NPV [€]	DPBT [year]	LCOE [€/kWh]
mono_Si	**1.1-A_SE**	65	77,887	35 %	70,734	8	0.0786	**1.4-A_SO**	85	96,700	35 %	81,974	9	0.0828
				45 %	87,198	7					45 %	102,481	8	
poli_Si		60	71,896	35 %	67,443	8	0.0766		74	85,618	35 %	76,929	8	0.0793
				45 %	82,915	7					45 %	95,354	7	
a-Si		39	44,222	35 %	28,915	12	0.0967		40	46,435	35 %	31,840	11	0.0944
				45 %	38,134	9					45 %	41,530	9	
mono_Si	**1.2-A_SE**	60	72,899	35 %	67,331	8	0.0776	**1.5-A_SO**	102	118,896	35 %	87,621	9	0.0809
				45 %	78,061	7					45 %	115,389	8	
poli_Si		69	83,107	35 %	78,361	8	0.0762		84	98,257	35 %	89,508	8	0.0784
				45 %	96,246	7					45 %	110,652	7	
a-Si		37	42,565	35 %	28,667	12	0.0953		48	53,062	35 %	32,817	12	0.0992
				45 %	37,547	9					45 %	43,875	11	
mono_Si	**1.3-A_SE**	72	88,115	35 %	82,025	8	0.0770	**2.1-A_SO**	72	88,229	35 %	82,246	8	0.0769
				45 %	100,712	7					45 %	100,968	7	
poli_Si		66	79,736	35 %	75,452	8	0.0759		63	77,274	35 %	74,380	8	0.0748
				45 %	92,611	7					45 %	91,009	7	
a-Si		37	42,565	35 %	28,662	12	0.0953		35	41,208	35 %	29,029	11	0.0931
				45 %	37,547	9					45 %	37,633	9	
mono_Si	**1.4-A_SE**	61	73,417	35 %	67,000	8	0.0783	**2.2-A_SO**	91	111,299	35 %	103,509	8	0.0770
				45 %	82,555	7					45 %	127,136	7	
poli_Si		48	57,631	35 %	54,192	8	0.0764		79	96,083	35 %	91,610	8	0.0754
				45 %	66,594	7					45 %	112,286	7	
a-Si		33	37,374	35 %	24,369	12	0.0968		43	51,506	35 %	37,445	11	0.0915
				45 %	32,167	9					45 %	48,205	9	
mono_Si	**1.5-A_SE**	65	77,572	35 %	70,040	8	0.0789	**2.3-A_SO**	80	97,423	35 %	90,139	8	0.0774
				45 %	81,514	8					45 %	110,821	7	
poli_Si		42	50,327	35 %	47,243	8	0.0765		69	83,383	35 %	78,923	8	0.0759
				45 %	58,073	7					45 %	96,867	7	
a-Si		31	34,907	35 %	22,495	12	0.0974		37	44,367	35 %	32,321	11	0.0914
				45 %	29,765	11					45 %	41,586	9	
mono_Si	**2.1-A_SE**	86	85,344	35 %	57,681	12	0.0949	**2.4-A_SO**	76	93,091	35 %	86,726	8	0.0769
				45 %	75,686	9					45 %	106,488	7	
poli_Si		69	68,123	35 %	48,085	11	0.0929		66	80,112	35 %	76,210	8	0.0756
				45 %	62,745	9					45 %	93,450	7	
a-Si		37	34,900	35 %	13,219	15	0.1162		36	43,488	35 %	32,092	11	0.0907
				45 %	20,368	13					45 %	41,179	9	
mono_Si	**2.2-A_SE**	61	64,964	35 %	49,948	11	0.0885	**2.5-A_SO**	91	111,183	35 %	103,274	8	0.0771
				45 %	63,611	8					45 %	126,876	7	
poli_Si		66	69,155	35 %	54,058	9	0.0876		79	95,982	35 %	91,405	8	0.0755
				45 %	68,940	8					45 %	112,060	7	
a-Si		38	37,882	35 %	17,653	14	0.0915		43	51,050	35 %	36,521	11	0.0923
				45 %	25,488	12					45 %	47,183	9	
mono_Si	**2.3-A_SE**	72	78,845	35 %	63,282	9	0.0860	**2-A_SE**	24	30,440	35 %	29,415	8	0.0743
				45 %	79,937	8					45 %	35,965	7	
poli_Si		66	72,149	35 %	60,090	9	0.0839		21	26,380	35 %	25,965	7	0.0730
				45 %	75,615	8					45 %	31,642	7	
a-Si		34	35,907	35 %	19,871	13	0.1038		11	14,090	35 %	11,348	9	0.0855
				45 %	27,316	11					45 %	14,380	8	
mono_Si	**2.4-A_SE**	71	81,332	35 %	69,647	9	0.0822	**3.1-A_SO**	86	106,900	35 %	101,299	8	0.0758
				45 %	86,854	8					45 %	123,997	7	
poli_Si		71	80,203	35 %	69,876	8	0.0812		74	90,777	35 %	87,385	8	0.0748
				45 %	87,135	8					45 %	106,920	7	
a-Si		36	39,147	35 %	23,320	12	0.1008		41	49,937	35 %	37,376	11	0.0900
				45 %	31,450	11					45 %	47,815	8	
mono_Si	**2.5-A_SE**	68	78,567	35 %	68,074	8	0.0816	**3.2-A_SO**	112	129,059	35 %	93,393	11	0.0818
				45 %	84,689	8					45 %	123,530	8	
poli_Si		69	77,957	35 %	67,939	8	0.0812		97	110,698	35 %	97,738	8	0.0804
				45 %	84,715	8					45 %	121,559	7	
a-Si		35	37,932	35 %	22,419	13	0.1011		53	61,975	35 %	43,093	11	0.0937
				45 %	30,291	11					45 %	56,033	9	
mono_Si	**1.1-A_SO**	86	100,962	35 %	89,271	8	0.0803	**3.3-A_SO**	93	112,791	35 %	103,850	8	0.0777
				45 %	110,689	7					45 %	127,791	7	
poli_Si		76	87,962	35 %	79,067	8	0.0793		81	97,844	35 %	92,566	8	0.0760
				45 %	97,996	7					45 %	113,622	7	
a-Si		41	46,735	35 %	30,891	12	0.0962		44	52,590	35 %	38,084	11	0.0917
				45 %	40,639	9					45 %	49,071	9	
mono_Si	**1.2-A_SO**	109	124,129	35 %	88,112	11	0.0828	**3.4-A_SO**	85	105,825	35 %	100,459	8	0.0757
				45 %	117,093	8					45 %	122,932	7	
poli_Si		95	108,044	35 %	94,967	8	0.0807		74	91,459	35 %	88,761	8	0.0742
				45 %	111,284	8					45 %	108,442	7	
a-Si		51	59,477	35 %	41,149	11	0.0940		40	47,739	35 %	34,480	11	0.0919
				45 %	53,561	9					45 %	44,453	9	

(*continued on next page*)

Table 5 (*continued*)

Tech	Hypothesis	Power [kWp]	EstimProd (kWh/y)	% of self-cons.	NPV [€]	DPBT [year]	LCOE [€/kWh]	Hypothesis	Power [kWp]	EstimProd (kWh/y)	% of self-cons.	NPV [€]	DPBT [year]	LCOE [€/kWh]
mono_Si	**1.3-A_SO**	100	115,892	35 %	100,741	8	0.0813	**3.5-A_SO**	101	118,243	35 %	87,738	9	0.0805
				45 %	125,333	8					45 %	115,346	8	
poli_Si		85	98,609	35 %	88,899	8	0.0791		90	107,034	35 %	99,444	8	0.0772
				45 %	110,119	7					45 %	122,478	7	
a-Si		46	51,609	35 %	32,987	12	0.0977		48	56,301	35 %	39,385	11	0.0935
				45 %	43,745	11					45 %	51,134	9	

The environmental impacts are mainly caused by the construction processes of the photovoltaic panels (61.2 %, 11.8 kPt), particularly that of the photovoltaic cells, followed by the PV system mounting processes (16.8 % and 3.23 kPt). “Human health” results were ranked highest concerning damage, 96.1 %, followed by “ecosystems” (2.78 %), and “resources” (1.11 %).

8. Discussion

The results obtained from studies on solar systems serve only to determine the optimal intervention scenario according to photovoltaic producibility and do not consider economic aspects that may lead to a different choice based on cost-benefit analysis. For block A, the solution with the optimal annual production is n. 1.2-A_SW, characterised by a system power of approximately 110 kWp, a horizontal position of photovoltaic modules (0° tilt), and a distance of 10 cm. The resulting production is 124,129 kWh/year, with monocrystalline silicon technology, and the photovoltaic output of the 10° slanted roof covering the southeast orientation; n. 2-A_SE, is approximately 30,440 kWh, with a power of approximately 24 kWp. For block B, the maximum producibility for hypothesis n. 1.1-B_E is approximately 263,445 kWh/year for a 216 kWp system composed of modules with east orientation and optimal tilt (34°), and a distance of 10 cm. However, this result is similar to that obtained with the south orientation (optimal tilt and 10 cm distance). Notably, the shading effect between panel rows leads to considerable reductions in incident solar radiation and productivity.

Further considerations must be made regarding aesthetic-configurational aspects to identify the most suitable solution for the case study. For example, despite no landscape constraints in the intervention area, the ideal solution to minimise the visual impact of the new technological additions could be represented by the 10° tilt modules. In fact, in this case, the height of the modules is below that of the building; hence, the intervention will not be visible from the surrounding open spaces. Moreover, future research will focus more on the technological aspects; detailed elements on the roofs, such as the Faraday cage, could require different positions of the photovoltaic modules, in addition to causing further shading.

In economic terms, the most profitable solution differs from that with optimal total annual production. In fact, for block A, solution 1.2-A_SW leads to a maximum economic revenue of 117,093€, with a minimum and maximum payback period of 8 and 11 years, respectively. The same applies to block B; solution 1.1-B_E has a maximum NPV of 115,138€ and a DPB ranging from eight to 12 years. This proves that technical evaluations must always be combined with economic assessments as they can often contrast with one another.

The system yielded profitability in all hypotheses. However, considering any factors affecting the system’s profitability would improve it further. According to Khatri [64], the system’s service life, discount rate, inflation rate, and recovery value influence the financial feasibility of the system. In addition to considering these aspects in this study, the research focus on related factors that could affect the system’s profitability. These include the material employed, orientation, tilt, spacing distance between modules, and finally, percentage of energy self-consumption. Combining the first three variables led to 26 hypotheses for block A and 25 for block B. Then, three different typologies of panels (mono_Si, poli_Si, and a_Si) and two values of energy self-consumption (45 % and 35%) were considered for each block. Therefore, this study analysed 156 cases for Block A and 150 for Block B. Notably, two different values of energy self-consumption share were considered based on the FER1 Decree, which grants an additional premium of 10 €/MWh if $Q_{selfcons}$ exceeds 40 %. In fact, the share of self-consumption was 35 % under normal conditions, without specific action.

The FER1 Decree plays a vital role in the profitability of PV systems [65]. The analysis was performed with $Q_{selfcons}$ at 35 % and 45 % and showed that when $Q_{selfcons}$ is 45 %, there is a non-negligible increase in profitability under similar conditions.

For block A, the 3.3-A_SW hypothesis had the highest profitability in terms of NPV, with a 45 % share of energy self-consumption and Mono_Si. In this case, NPV equals 127,791€, DPB is seven years, and LCOE is 0.0777 €/kWh. For block B, the hypothesis with the highest NPV was 2.2-B-E, with a 45 % share of energy self-consumption and poli_Si as the employed material. In this case, NPV is 258,873€, DPB is eight years, and LCOE corresponds to 0.754 €/kWh.

The value of DPB also confirms the system’s profitability: the time needed for positive cash flows to balance expenses is always lower than the service life of the PV system. The lowest value of DPB is seven years, which means that at least seven years are required to balance the expenses with the positive cash flow of the investment. The highest value is 15 years, which is still less than 20 years, which is the system’s service life.

In this study, the value of LCOE was calculated for each hypothesis. LCOE helps assess the economic convenience of PV systems. It represents the recommended sale price of the energy generated during the system’s service life to balance all the costs it produces during its life cycle. Since 2010, the LCOE associated with large-scale PV systems has decreased by 73 %, owing to a continuous decrease in the cost of this technology [66]. In the case study, the maximum value of LCOE for block B was 0.0955 €/kWh and 0.1011€/kWh for block A.

Various photovoltaic technologies have been subjected to a comparative LCIA, considering the optimal solution of solar studies in terms of photovoltaic production. The photovoltaic systems and their related processes were modelled in the inventory phase according to photovoltaic technology, tilt, and kWp. LCA studies are limited to the construction phase and do not consider the operation, maintenance, and disposal phases. The LCA results allowed us to identify the optimal solutions for lower environmental impacts.

For scenario 1 (2-A_SE) of block A with a slanted roof of 10°, the optimal choice uses the multi_Si 21 kWp technology with 1.96 kPt rather than single_Si 24 kWp, with 2.13 kPt, which had been identified as the optimal solution in the solar study, and a_Si 11 kWp, with 7610 kPt. Regarding environmental impact, concerning the Ecoinvent 3.8 dataset [67], multi_Si 21 kWp and single_Si 24 kWp technologies differ substantially in terms of tCO2-eq. The multi_Si 21 kWp slanted-roof technology has an impact of approximately 45.78 tCO2-eq, compared to a single_Si 24 kWp slanted-roof, which is approximately 60.48 tCO2-eq, with a difference of approximately 24 %.

Concerning scenario 2 (1.2-A_SW) of block A with a flat roof, the multi_Si 95 kWp technology with 8.64 kPt is optimal, rather than single_Si 109 kWp technology with 9,45 kPt, which had been identified as

Table 6
NPV, DPB, and LCOE in block B.

Tech	Hypothesis	Power [kWp]	EstimProd (kWh/y)	% of self-cons.	NPV [€]	DPBT [year]	LCOE [€/kWh]	Hypothesis	Power [kWp]	EstimProd (kWh/y)	% of self-cons.	NPV [€]	DPBT [year]	LCOE [€/kWh]
mono_Si	**1.1-B_E**	130	156,009	35 %	121,607	9	0.0779	**1.4-B_S**	122	145,534	35 %	111,082	9	0.0790
				45 %	147,899	8					45 %	135,736	8	
poli_Si		132	158,916	35 %	127,738	8	0.0762		132	175,250	35 %	158,393	8	0.0691
				45 %	155,138	8					45 %	188,608	7	
a-Si		79	91,183	35 %	61,826	12	0.0949		58	68,526	35 %	48,589	11	0.0928
				45 %	80,843	9					45 %	62,897	9	
mono_Si	**1.2- B_E**	125	151,976	35 %	119,352	9	0.0775	**1.5-B_S**	148	176,038	35 %	133,791	9	0.0792
				45 %	144,969	8					45 %	163,610	8	
poli_Si		127	152,944	35 %	122,992	8	0.0762		132	155,275	35 %	120,795	9	0.0780
				45 %	149,361	8					45 %	157,531	8	
a-Si		73	83,926	35 %	56,484	12	0.0954		71	83,591	35 %	58,880	11	0.0931
				45 %	73,959	9					45 %	76,336	9	
mono_Si	**1.3- B_E**	140	171,072	35 %	133,825	9	0.0776	**2.1-B_S**	140	172,398	35 %	137,644	9	0.0765
				45 %	162,791	8					45 %	166,866	8	
poli_Si		127	152,604	35 %	123,603	8	0.0757		121	151,165	35 %	127,403	8	0.0734
				45 %	149,913	8					45 %	153,466	7	
a-Si		69	80,287	35 %	55,309	11	0.0942		66	79,751	35 %	58,886	11	0.0907
				45 %	72,057	9					45 %	70,429	9	
mono_Si	**1.4- B_E**	133	162,157	35 %	127,735	9	0.0773	**2.2-B_S**	152	188,859	35 %	152,653	8	0.0759
				45 %	155,184	8					45 %	184,636	8	
poli_Si		121	146,621	35 %	118,836	8	0.0757		143	176,928	35 %	147,304	8	0.0742
				45 %	144,115	8					45 %	177,809	7	
a-Si		67	77,971	35 %	53,724	11	0.0942		77	96,011	35 %	74,708	9	0.0879
				45 %	69,994	9					45 %	88,629	9	
mono_Si	**1.5- B_E**	133	162,157	35 %	127,697	9	0.0772	**2.3-B_S**	144	175,932	35 %	138,950	9	0.0771
				45 %	155,183	8					45 %	168,767	8	
poli_Si		70	84,380	35 %	79,823	8	0.0761		127	157,464	35 %	131,451	8	0.0740
				45 %	92,567	7					45 %	158,600	7	
a-Si		62	71,174	35 %	47,733	12	0.0955		67	83,825	35 %	53,935	11	0.0876
				45 %	62,578	9					45 %	67,872	9	
mono_Si	**2.1-B_E**	216	263,445	35 %	207,981	9	0.0773	**2.4-B_S**	122	154,013	35 %	127,077	8	0.0747
				45 %	252,218	8					45 %	153,197	8	
poli_Si		213	258,620	35 %	210,458	8	0.0756		106	132,638	35 %	112,005	8	0.0733
				45 %	255,047	8					45 %	134,874	7	
a-Si		106	123,520	35 %	68,530	13	0.0941		58	72,322	35 %	56,276	9	0.0879
				45 %	96,569	11					45 %	66,764	9	
mono_Si	**2.2-B_E**	212	260,820	35 %	208,327	9	0.0766	**2.5-B_S**	148	181,270	35 %	143,660	9	0.0769
				45 %	252,188	8					45 %	174,384	8	
poli_Si		216	261,786	35 %	213,738	8	0.0754		127	157,626	35 %	131,770	8	0.0739
				45 %	258,873	8					45 %	158,947	7	
a-Si		106	123,648	35 %	68,695	13	0.0939		70	88,543	35 %	70,472	9	0.0867
				45 %	96,841	11					45 %	88,998	8	
mono_Si	**2.3-B_E**	205	251,940	35 %	201,006	9	0.0766	**3.1-B_S**	152	192,603	35 %	159,679	8	0.0744
				45 %	243,309	8					45 %	192,347	8	
poli_Si		213	259,692	35 %	212,431	8	0.0753		132	165,633	35 %	140,347	8	0.0731
				45 %	257,205	8					45 %	168,904	7	
a-Si		115	133,722	35 %	73,660	13	0.0943		72	91,056	35 %	72,448	9	0.0867
				45 %	104,162	11					45 %	91,203	8	
mono_Si	**2.4-B_E**	213	262,870	35 %	210,782	9	0.0764	**3.2-B_S**	198	238,316	35 %	184,274	9	0.0783
				45 %	255,066	8					45 %	224,660	8	
poli_Si		189	230,860	35 %	189,336	8	0.0751		172	205,771	35 %	163,904	9	0.0767
				45 %	229,139	8					45 %	199,382	8	
a-Si		138	161,990	35 %	90,944	12	0.0934		92	111,308	35 %	82,370	11	0.0906
				45 %	128,230	11					45 %	105,621	9	
mono_Si	**2.5-B_E**	140	173,451	35 %	138,321	9	0.0766	**3.3-B_S**	175	217,512	35 %	175,849	8	0.0758
				45 %	167,690	8					45 %	212,730	8	
poli_Si		132	161,823	35 %	133,154	8	0.0748		153	189,422	35 %	157,836	8	0.0741
				45 %	161,054	8					45 %	190,494	7	
a-Si		71	83,431	35 %	58,559	11	0.0933		82	103,421	35 %	81,945	9	0.0869
				45 %	75,977	9					45 %	103,580	8	
mono_Si	**1.1-B_S**	122	145,632	35 %	111,265	9	0.0790	**3.4-B_S**	150	192,700	35 %	162,544	8	0.0734
				45 %	135,937	8					45 %	195,234	7	
poli_Si		106	125,419	35 %	98,385	9	0.0775		132	167,414	35 %	143,701	8	0.0723
				45 %	120,008	8					45 %	172,565	7	
a-Si		58	67,896	35 %	47,311	11	0.0937		72	91,011	35 %	73,914	9	0.0855
				45 %	61,486	9					45 %	92,965	8	
mono_Si	**1.2-B_S**	157	186,271	35 %	141,027	9	0.0794	**3.5-B_S**	184	219,202	35 %	166,978	9	0.0791
				45 %	172,587	8					45 %	204,115	8	
poli_Si		137	160,490	35 %	124,115	9	0.0783		162	197,201	35 %	160,772	8	0.0754
				45 %	151,786	8					45 %	194,772	8	
a-Si		74	86,897	35 %	60,910	11	0.0934		87	108,299	35 %	84,046	11	0.0880
				45 %	79,055	9					45 %	106,695	8	

(*continued on next page*)

Table 6 (*continued*)

Tech	Hypothesis	Power [kWp]	EstimProd (kWh/y)	% of self-cons.	NPV [€]	DPBT [year]	LCOE [€/kWh]	Hypothesis	Power [kWp]	EstimProd (kWh/y)	% of self-cons.	NPV [€]	DPBT [year]	LCOE [€/kWh]
mono_Si	**1.3-B_S**	148	171,632	35 %	125,472	9	0.0813							
				45 %	154,536	8								
poli_Si		129	152,267	35 %	119,039	9	0.0777							
				45 %	145,292	8								
a-Si		69	82,936	35 %	60,674	11	0.0912							
				45 %	77,995	9								

Table 7
Input data.

Products	unit	SCENARIO 1			SCENARIO 2		SCENARIO 3		
		2-A_SE slanted-roof 10°			1.2-A_SO flat-roof 0°		1.1-B_E slanted-roof 34°		
		a-Si 11 kWp	multi-Si 21 kWp	single-Si 24 kWp	multi-Si 95 kWp	single-Si 109 kWp	a-Si 106 kWp	multi-Si 213 kWp	single-Si 216 kWp
Electricity	kWh	0,15	1,61	8,16	32,30	37,06	1,41	16,33	16,56
Inverter	kW	22,00	42,00	48,00	190,00	218,00	212,00	426,00	432,00
Photovoltaic mounting system	m^2	170,54	159,53	171,43	721,68	778,59	1643,42	1618,09	1542,89
Photovoltaic panel	m^2	175,66	164,32	176,57	743,34	801,91	1692,71	1666,65	1589,11
Electric installation	kg	184,40	352,04	402,34	1592,58	1827,28	1776,98	3570,73	3621,02

Table 8
Characterisation phase: output data. In red bolt the results with the highest environmental impact.

Impact categories	unit	SCENARIO 1			SCENARIO 2		SCENARIO 3		
		2-A_SE slanted-roof 10°			1.2-A_SO flat-roof 0°		1.1-B_E slanted-roof 34°		
		a-SI 11 kWp	multi-Si 21 kWp	single-Si 24 kWp	multi-Si 95 kWp	single-Si 109 kWp	a-Si 106 kWp	multi-Si 213 kWp	single-Si 216 kWp
Global warming, Human health	DALY	**153,122**	0,040	0043	0,179	0195	**1475,543**	0,407	0391
Stratospheric ozone depletion	DALY	0,027	0000	0,000	0000	0,000	0261	0,000	0000
Ionising radiation	DALY	0,006	0000	0,000	0000	0,000	0059	0,000	0000
Ozone formation, Human health	DALY	0,515	0000	0,000	0000	0,001	4960	0,001	0001
Fine particulate matter formation	DALY	**205,986**	0,053	0058	0,234	0256	**1984,952**	0,536	0518
Human carcinogenic toxicity	DALY	53,274	0,007	0008	0,028	0031	**513,364**	0,074	0072
Human non-carcinogenic toxicity	DALY	16,961	0,010	0012	0,046	0052	**163,447**	0,105	0104
Water consumption, Human health	DALY	1978	0,002	0002	0,010	0011	19,064	0,022	0021
Global warming, Terrestrial ecosystems	species.yr	0,462	0000	0,000	0001	0,001	4453	0,001	0001
Global warming, Freshwater ecosystems	species.yr	0,000	0000	0,000	0000	0,000	0000	0,000	0000
Ozone formation, Terrestrial ecosystems	species.yr	0,075	0000	0,000	0000	0,000	0726	0,000	0000
Terrestrial acidification	species.yr	0,220	0000	0,000	0000	0,000	2123	0,000	0000
Freshwater eutrophication	species.yr	0,003	0000	0,000	0000	0,000	0032	0,000	0000
Marine eutrophication	species.yr	0,000	0000	0,000	0000	0,000	0000	0,000	0000
Terrestrial ecotoxicity	species.yr	0,007	0000	0,000	0000	0,000	0068	0,000	0000
Freshwater ecotoxicity	species.yr	0,000	0000	0,000	0000	0,000	0003	0,000	0000
Marine ecotoxicity	species.yr	0,000	0000	0,000	0000	0,000	0001	0,000	0000
Land use	species.yr	0,406	0000	0,000	0000	0,000	3908	0,000	0000
Water consumption, Terrestrial ecosystem	species.yr	0,01	0,00	0,00	0,00	0,00	0,13	0,00	0,00
Water consumption, Aquatic ecosystems	species.yr	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Mineral resource scarcity	USD2013	**652623,63**	184,08	205,13	812,54	909,84	**6288918,63**	1867,06	1846,13
Fossil resource scarcit	USD2013	**11141299,13**	2864,04	3102,57	13576,59	14760,27	**107361609,79**	29048,89	27,923,10

the optimal solution in the study on solar. This is because the multi-Si 95 kWp flat-roof technology impacts approximately 205,52 tCO2-eq, while a single_Si 109 kWp flat-roof technology produces approximately 273,23 tCO2-eq: a difference of approximately 25 %.

Finally, for scenario 3 (1.1-B_E) of block B with a 34° slanted roof, single_Si 216 kWp technology with 19.2 kPt, rather than multi_Si 213 kWp technology with 19.9 kPt, and a_Si 106 kWp technology with 73,300 kPt was optimal. This solution corresponds to the optimal

Table 9
Normalisation phase: output data. In bolt red the results with the highest environmental impact.

Damage categories	Impact categories	SCENARIO 1			SCENARIO 2		SCENARIO 3		
		2-A_SE slanted-roof 10°			1.2-A_SO flat-roof 0°		1.1-B_E slanted-roof 34°		
		a-Si 11 kWp	multi-Si 21 kWp	single-Si 24 kWp	multi-Si 95 kWp	single-Si 109 kWp	a-Si 106 kWp	multi-Si 213 kWp	single-Si 216 kWp
Human health		**18008,955**	**4710**	**5130**	**20,740**	**22,684**	**173540,840**	**47,774**	**46,166**
	Global warming, Human health	6385,205	1675	1814	7463	8117	**61530,156**	16,985	16,325
	Stratospheric ozone depletion	1131	0,000	0001	0,002	0002	10,897	0,005	0005
	Ionising radiation	0,257	0000	0,000	0000	0,000	2474	0,001	0001
	Ozone formation, Human health	21,462	0,005	0005	0,020	0022	**206,813**	0,046	0045
	Fine particulate matter formation	**8589,599**	2204	2400	9757	10,669	**82772,500**	22,358	21,600
	Human carcinogenic toxicity	**2221,510**	0,305	0333	1157	1274	**21407,275**	3091	2998
	Human non-carcinogenic toxicity	707,294	0,431	0480	1932	2158	**6815,745**	4375	4317
	Water consumption, Human health	82,498	0,090	0097	0,408	0442	**794,980**	0,914	0875
Ecosystems		**802,582**	**0,136**	**0148**	**0,609**	**0664**	**7733,976**	**1387**	**1336**
	Global warming, Terrestrial ecosystems	**312,358**	0,082	0089	0,365	0397	**3009,992**	0,831	0799
	Global warming, Freshwater ecosystems	0,009	0000	0,000	0000	0,000	0082	0,000	0000
	Ozone formation, Terrestrial ecosystems	50,921	0,011	0012	0,049	0053	**490,696**	0,111	0107
	Terrestrial acidification	**148,958**	0,025	0027	0,111	0122	**1435,412**	0,254	0246
	Freshwater eutrophication	2278	0,001	0001	0,006	0007	21,956	0,014	0013
	Marine eutrophication	0,002	0000	0,000	0000	0,000	0023	0,000	0000
	Terrestrial ecotoxicity	4792	0,007	0008	0,033	0036	46,175	0,075	0072
	Freshwater ecotoxicity	0,231	0000	0,000	0000	0,000	2223	0,000	0000
	Marine ecotoxicity	0,074	0000	0,000	0000	0,000	0708	0,001	0001
	Land use	**274,125**	0,008	0009	0,036	0040	**2641,566**	0,084	0081
	Water consumption, Terrestrial ecosystem	8835	0,002	0002	0,008	0009	85,134	0,018	0018
	Water consumption, Aquatic ecosystems	0,001	0000	0,000	0000	0,000	0008	0,000	0000
Resources		**421,043**	**0,108**	**0118**	**0,513**	**0559**	**4057,323**	**1103**	**1062**
	Mineral resource scarcity	23,299	0,007	0007	0,029	0032	**224,514**	0,067	0066
	Fossil resource scarcity	**397,744**	0,102	0111	0,485	0527	**3832,809**	1037	0,997

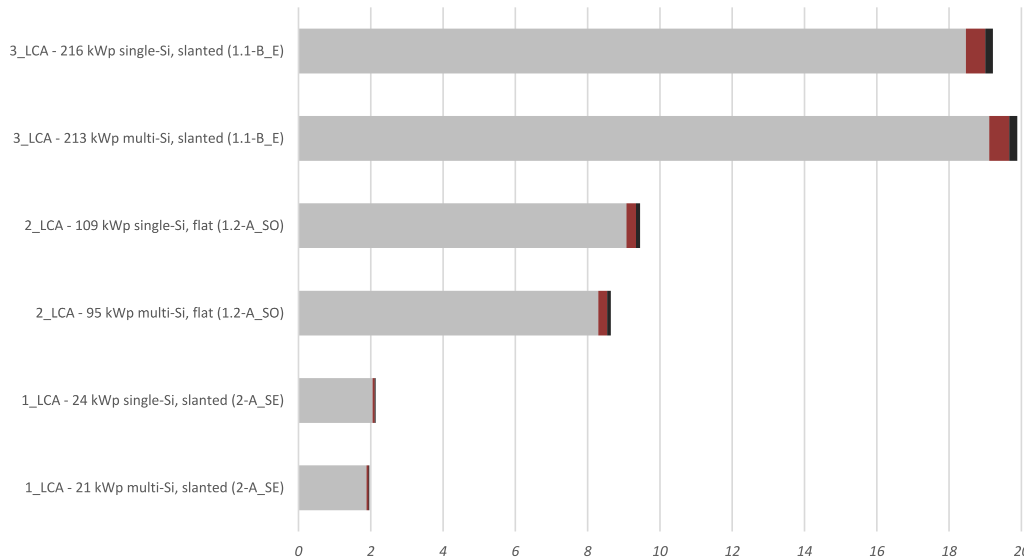
Table 10
Weighting phase: output data. The solutions with the highest environmental impact are highlighted in grey (Unit: MPt).

Impact Categories	SCENARIO 1			SCENARIO 2		SCENARIO 3		
	2-A_SE slanted-roof 10°			1.2-A_SO flat-roof 0°		1.1-B_E slanted-roof 34°		
	a-Si 11 kWp	**multi-Si 21 kWp**	**single-Si 24 kWp**	**multi-Si 95 kWp**	**single-Si 109 kWp**	**a-Si 106 kWp**	**multi-Si 213 kWp**	**single-Si 216 kWp**
Total	**7,6088236**	**0,0019606**	**0,0021348**	**0,0086424**	**0,0094511**	**73,3213915**	**0,0198855**	**0,0192134**
Global warming, Human health	2,5540820	0,0006698	0,0007256	0,0029851	0,0032467	24,6120625	0,0067939	0,0065300
Stratospheric ozone depletion	0,0004523	0,0000002	0,0000002	0,0000008	0,0000009	0,0043587	0,0000019	0,0000019
Ionising radiation	0,0001027	0,0000000	0,0000000	0,0000002	0,0000002	0,0009894	0,0000004	0,0000004
Ozone formation, Human health	0,0085847	0,0000018	0,0000020	0,0000081	0,0000088	0,0827253	0,0000184	0,0000178
Fine particulate matter formation	3,4358396	0,0008817	0,0009600	0,0039,029	0,0042676	33,1090001	0,0089430	0,0086402
Human carcinogenic toxicity	0,8886039	0,0001219	0,0001332	0,0004628	0,0005095	8,5629101	0,0012365	0,0011992
Human non-carcinogenic toxicity	0,2829177	0,0001725	0,0001919	0,0007728	0,0008631	2,7262980	0,0017500	0,0017269
Water consumption, Human health	0,0329992	0,0000360	0,0000389	0,0001631	0,0001766	0,3179921	0,0003656	0,0003499
Global warming, Terrestrial ecosystems	0,1249431	0,0000328	0,0000355	0,0001460	0,0001588	1,2039970	0,0003324	0,0003195
Global warming, Freshwater ecosystems	0,0000034	0,0000000	0,0000000	0,0000000	0,0000000	0,0000329	0,0000000	0,0000000
Ozone formation, Terrestrial ecosystems	0,0203685	0,0000044	0,0000048	0,0000195	0,0000213	0,1962783	0,0000443	0,0000428
Terrestrial acidification	0,0595831	0,0000100	0,0000109	0,0000445	0,0000486	0,5741648	0,0001017	0,0000983
Freshwater eutrophication	0,0009114	0,0000005	0,0000006	0,0000024	0,0000027	0,0087822	0,0000055	0,0000053
Marine eutrophication	0,0000010	0,0000000	0,0000000	0,0000000	0,0000000	0,0000092	0,0000000	0,0000000
Terrestrial ecotoxicity	0,0019167	0,0000029	0,0000032	0,0000133	0,0000144	0,0184699	0,0000298	0,0000287
Freshwater ecotoxicity	0,0000923	0,0000000	0,0000000	0,0000001	0,0000001	0,0008894	0,0000002	0,0000002
Marine ecotoxicity	0,0000294	0,0000000	0,0000000	0,0000001	0,0000001	0,0002834	0,0000003	0,0000003
Land use	0,1096499	0,0000033	0,0000036	0,0000146	0,0000160	1,0566266	0,0000335	0,0000325
Water consumption, Terrestrial ecosystem	0,0035339	0,0000007	0,0000008	0,0000032	0,0000036	0,0340535	0,0000073	0,0000071
Water consumption, Aquatic ecosystems	0,0000003	0,0000000	0,0000000	0,0000000	0,0000000	0,0000033	0,0000000	0,0000000
Mineral resource scarcity	0,0046597	0,0000013	0,0000015	0,0000058	0,0000065	0,0449029	0,0000133	0,0000132
Fossil resource scarcity	0,0795489	0,0000204	0,0000222	0,0000969	0,0001054	0,7665619	0,0002074	0,0001994

solution that emerged from the solar study for Block B, with an impact of approximately 544.320 tCO2-eq.

This study has limitations that must be taken into account. The analysis was carried out assuming only some standard photovoltaic technologies (monocrystalline, polycrystalline and amorphous silicon), not taking into consideration the most emerging technologies. This could certainly affect producibility values, given the higher value of peak power of new technologies. Furthermore, it does not provide indications on the life cycle of emerging technologies that could lead to the generation of lower impacts.

A further limitation concerns the hypothesized self-consumption value, which may not reflect the real values coming from the monitoring of load profiles. So, this study does not present optimization results with respect to real self-consumption and degree of self-sufficiency. Moreover, the fixed value of self-consumption assumed, could be a source of error in this analysis and may influence the cost-benefit results. The method can be improved investigating for the real optimization of this value with different strategies, mainly consisting in two types: the



	1_LCA - 21 kWp multi-Si, slanted (2-A_SE)	1_LCA - 24 kWp single-Si, slanted (2-A_SE)	2_LCA - 95 kWp multi-Si, flat (1.2-A_SO)	2_LCA - 109 kWp single-Si, flat (1.2-A_SO)	3_LCA - 213 kWp multi-Si, slanted (1.1-B_E)	3_LCA - 216 kWp single-Si, slanted (1.1-B_E)
Human health	1.884	2.0518	8.2959	9.0735	19.1098	18.4662
Ecosystems	0.0547	0.0594	0.2437	0.2657	0.555	0.5346
Resources	0.0218	0.0236	0.1027	0.1119	0.2207	0.2126

Fig. 7. Comparing product stages; Method: ReCiPe 2016 Endpoint (H) V1.05/Damage category/Single score.

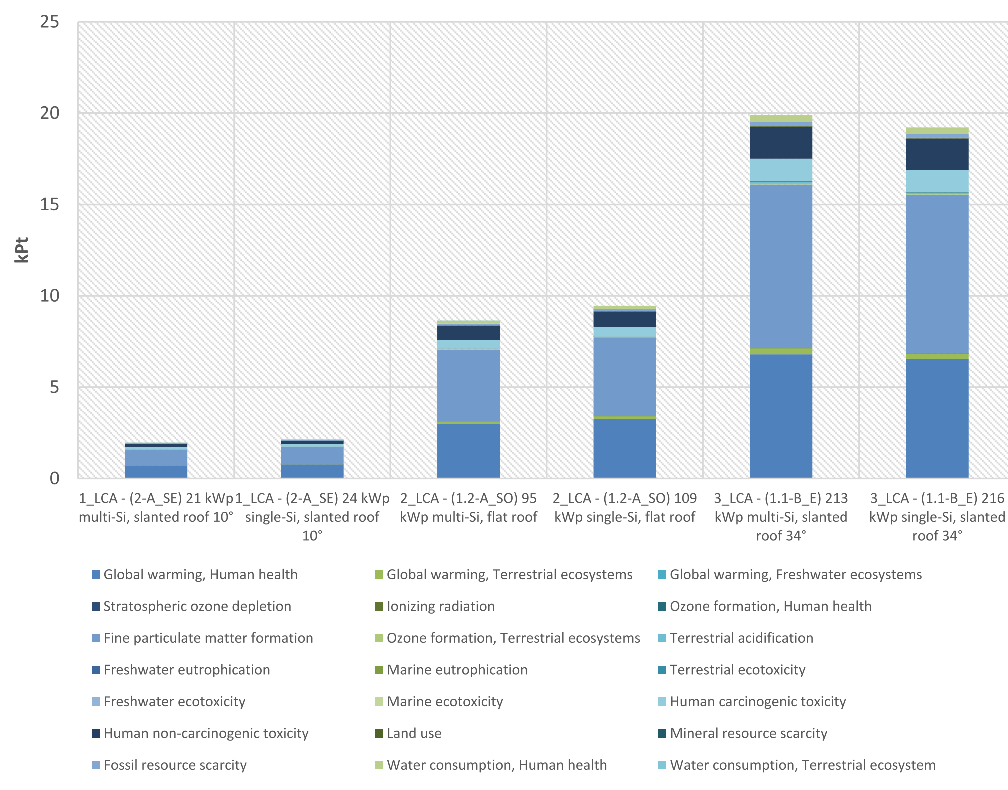


Fig. 8. Comparing product stages; Method: ReCiPe 2016 Endpoint (H) V1.05/Impact category/Single score.

use of storage systems (batteries) or the movement of active loads, defined as Demand Side Managemen, DSM [68]. This is possible only comparing the producibility hourly profile with the consumptions profile. The aim is minimizing the dependence from the grid of connected PV systems, in order to maximise the consumption of locally-produced PV energy and to reduce costs, with good impact in the life-cycle analysis, and, consequently, in the political strategies of the administration. Finally, a further potential error arises from the fact that LCA analysis was carried out for a life cycle of thirty years [38] and should take into account the different thermal degradation that the technologies undergo. For example, polycrystalline is more susceptible to this form of degradation [38], therefore in future research developments these evaluations will have to be incorporated.

9. Conclusions

The study proposes a multi-criteria and multi-disciplinary methodology for analysing different incentive scenarios in Italy according to the varying conditions of system installation and the chosen photovoltaic technology (PV). The method is based on three key factors: energy, economic, and life cycle assessment of the photovoltaic system to achieve the improvement of the energy performance of existing buildings. The approach is validated in a case study rappresented by engineering campus of the University of L'Aquila, Italy. 153 scenarios were elaborated concerning the technical evaluation of the system and 306 the economic one, plus a further 9 scenarios analysed according to the LCA approach. In particular, it was shown that:

- the solution with the highest profitability is not the same as the one that optimises total annual production. This confirms the fact that technical evaluations must always be accompanied by economic evaluations because, as in this case, the two evaluations can be discordant;
- FER1 decree plays a fundamental role in the profitability of the PV plant by allowing the profitability in each scenario, considering the most probable self-consumption values. Therefore, incentives help to implement the ongoing energy transition process;
- the environmental impacts are mainly due to the manufacturing processes of the photovoltaic panels, in particular the photovoltaic cells.

The results obtained may be useful to guide future research as well as the choices of policy makers. The adoption of multi-criteria and multi-disciplinary approaches, such as the one proposed in the work that can simultaneously analyse different investment scenarios and can be re-proposed in other case studies, is beneficial for the energy transition of public buildings. Especially because these buildings are spread throughout the European Community and differ in terms of climatic and boundary conditions, technical, architectural, landscape and historical peculiarities. This is especially true infact at the local level the engineering campus was chosen as a pilot project for the energy efficiency of the entire university building stock, with a view to achieving SDG7. The study also contributes to achieving SDG 13 in combating climate change and SDG 12 in waste reduction.

The methodological approach illustrated in this research is also valid and effective if applied in other contexts or implemented by adding other technical, economic and environmental variables. However, these results have limitations since they are based on a specific incentive regulation, for example, FER 1, which does not include differentiation in incentives between northern and southern Italy and this is a critical aspect [26]. Furthermore, the study only focuses on certain types of photovoltaic technologies and does not take into account the different thermal degradation. Nevertheless, highlighting these limitations is very important because incentives are introduced in EU countries to implement the green transition. Therefore, highlighting issues that can discourage their use can help policymakers redirect their choices.

In addition to overcoming these aspects, in future studies an optimization can be achieved using real measurement data of load profile and solar radiation as well as an analysis of the producibility according to the division of the available area using and combining different photovoltaic technologies. The multi-criteria methodology illustrated in the study can be easily implemented in others countries and regions, even with a climate variability similar to the Italian one, different or similar incentive legislation.

Author contributions

Paper conceptualisation: M.R. and F.C.; methodology: M.R and F.C.; paper management: M.R..; writing—original draft preparation, M. R. (Sections 1., 3.1, 3.3, 6.1, 7, 8., 9.), F.C. (Sections 2., 3.2, 3.3, 5.2, 6.2, 7.); L.C. (sections 3.1, 4., 5.1, 6.1); writing—revised version M. R.; supervision: M.R., F.C. and P.D.B.. All the authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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