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Solar Photovoltaic Optimal Tilt Angles in Public Building

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***Abstract* – The reduction of the consumption of fossil fuels that cause climate change and the encouragement of the use of cleaner renewable sources, appears to be a fundamental objective for achieving the climate aims agreed in Paris. Moreover, the sustainability of the implementation of solutions for energy efficiency in public administration buildings has played a fundamental role in recent years, strengthened also by the regulatory context of energy and environmental policies of European countries. The research fits into this context and it intends to promote a methodology that is able to evaluate the economic and environmental performance of a photovoltaic system applied in a school located in Italy when only the roof inclination angle changes. The economic and environmental performances are evaluated respectively through Life Cycle Cost Analysis and the avoided CO_2 emissions. The results show that although the case study does not present the optimal roof inclination angle, there are economic and environmental advantages. Furthermore, the research notes that, considering the characteristics of the photovoltaic system concerned, the optimal roof inclination angle is equal to 40 degrees from an economic and environmental point of view. This methodology could easily support the decision-making process of designers and administrators to make the energy upgrading choices for the promotion of renewable sources. It was applied to a case study, that is a school located in Italy, in the Abruzzo region, in the province of L'Aquila, but it could be easily replicated in other existing public buildings in different locations.**

***Keywords* – Environmental analysis; optimal tilt; public school; solar photovoltaic; LCCA**

1. INTRODUCTION

The sustainability of the implementation of solutions for energy efficiency in public administration buildings has played a fundamental role in recent years, strengthened also by the regulatory context of energy and environmental policies of European countries [1]. In this context, Public administrations can act as drivers for the development of this sector, due to the considerable number of real estate units on which to operate and the opportunity to access multiple financing instruments that are able to counterbalance the spending review policies. And in fact, many authors are looking for decision support tools [2] and models [3]; they try to identify the key actors to facilitate the process [4].

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A particular category of public buildings is certainly the one aimed at carrying out school activities. In Italy, according to the fourth "Economic and forecast report on the market for the installation of systems 2018–2021" processed by Cresme, 51 904 buildings are for exclusive or prevalent educational use, of which 48 275 are owned by the public sector. In agreement with MIUR data [5], most of these schools are housed in buildings built before 1976 that is the year of entry into force of the first national law [6] concerning the energy consumption of buildings. From the constructive point of view there is a prevalence of mixed structures in reinforced concrete and masonry which represent 67 % of the total, followed by the load-bearing stone and brick masonry and the load-bearing brick masonry. These are mostly schools located within a single building. Between them, 97 % are equipped with a traditional heating system. Therefore, it seems clear that in the school area it is necessary to invest in terms of improving energy efficiency, plant implementation and, particularly, in the use of energy production from renewable sources [7]. And this is not only to achieve environmental and economic objectives, but also for social purposes [8]. School buildings represent one of the strategic places for the formation of a modern society, because in them the educational process thanks to which future citizens are trained, takes place. Consequently, it is important that the learning process develops in a functional way and there is a strong need for comfortable, bright and efficient buildings to reach this result. As was pointed out previously, the situation on the national territory still remains far from these standards. For this reason, it is necessary to promote methodologies and case studies aimed at promoting energy efficiency and the diffusion of renewable sources in existing school buildings. Currently, the climate change, the depletion of natural resources and the ecosystems deterioration represent the main environmental problems [9].

In fact, the reduction of the consumption of fossil fuels that cause climate change and the encouragement of the use of cleaner renewable sources, appears to be a fundamental objective for achieving the climate aims agreed in Paris [10] and the SDG 7 [11].

Therefore, it becomes necessary to use clean energy sources. Photovoltaic systems are viable alternatives to conventional electricity generation plants [12]. Solar energy has always been used by human beings but, only in the last century, the opportunity to transform solar energy into electricity using photovoltaic cells was discovered [13]. Solar energy technologies have undergone a further development and price reduction in recent years [14]. Due to the continuous increase of such technologies, several researchers have analysed the optimal conditions of a photovoltaic system. Factors like the shape of the roof, the roof pitch, the surrounding obstacles and the structural integrity may influence the design of photovoltaic systems in terms of optimal implementations, output efficiency of the photovoltaic system and aesthetic characteristics [15]. For [16], the main factors that may influence the solar energy stored by a photovoltaic panel are the geographic location, the environmental temperature, the transparency index, inclination and orientation of the panel. On the other hand, according to [12], since the energy production of photovoltaic systems strongly depends on external factors such as variable solar radiation, the risk that the photovoltaic system does not meet production expectations is very high. Only with the diffusion of accurate models that may accurately predict the future performance of a photovoltaic system the investor confidence in photovoltaic systems could be increased. [17] compared 10 different simulation software that are able to simulate and optimize the photovoltaic system and among these Homer, SAM and PVsyst are the most effective tools for their ability to perform multiple analysis in an easy and fast way to evaluate different system configurations.

This paper is part of solar energy research field and it appears in line with ambitious international projects [18]. In particular, it intends to promote a methodology that is able to demonstrate the convenience of the investment in renewable technologies [19]–[21] even in the presence of not optimal existing conditions. Subsequently, the methodology was applied to a case study which is a school located in Italy, in the Abruzzo region, in the province of L'Aquila. The first part of the article defines all the quantities and parameters that are necessary for the implementation of the photovoltaic system located in the school. Once all the system parameters defined in the case study have been set, the research continues with the aim of evaluating how the economic and environmental performance of the system changes when the only roof inclination angle changes. The goal is to determine the optimal roof inclination angle that guarantees the best economic and environmental performance, because this parameter is one of the elements that most influence the system productivity [22], [23].

Economic performance is assessed by Life Cycle Cost Analysis (LCCA), a tool widely used by governments, companies and scientists that allows to compare alternative scenarios through cost optimization in a specific period of time [24]. Instead, the environmental performance is evaluated through the saved CO_2 emissions as the roof inclination angle varies.

2. METHODOLOGY

The redevelopment of an existing building may take place through the introduction of several technologies for the improvement of the energy efficiency of the envelope and the systems but, as already explained, in this paper the attention focused on the use of renewable energies, in particular the solar photovoltaics. The study of this technology has an abiding interest, because, on a global level, installations on roofs or in power plants will continue to grow quickly [25], [26]. These systems may integrate the electricity supply, starting from the following methodological approach:

- analysis of ante-operam consumption;
- elaboration of different intervention scenarios;
- definition of priorities;
- analysis of the different cost-benefit profiles according to the scenarios identified;
- choice of the intervention to be performed.

Within this methodology, the research focused on the roof inclination angle, as it is one of the elements that most influence the productivity of the plant [22], [23]. As this parameter changes, the annual energy production was calculated using the *Pv Sys*t software [17]. This application provides access to different meteorological data sources available from the Web and includes a tool that is useful to import them into the software. Then, according to the so-called "Conto Energia" [27], the incentive, savings on consumption and the consequent revenue for all the different configurations were calculated. These values were used in the LCCA for all the different configurations obtained by varying the roof inclination angle.

LCCA is an economic tool that allows you to evaluate all the project costs, from the 'cradle' to the 'grave' [28], [29]. LCCA is useful to support the decision maker in the choice of several alternatives that are equivalent to each other in terms of performance but which have different costs during the life cycle. In fact, the decisions regarding a certain investment should be made considering both initial costs (investment, installation) and future costs / revenues (maintenance, replacement, energy costs). In the LCCA analysis, the cash flows (difference between revenues and costs) that occur in time horizons that are different from the current time have to be discounted for the base year (the year in which the investment occurs). Therefore, the comparison between different projects is made on the net present value (NPV):

$$\text{NPV} = \text{Initial Cost} + \sum_{t=1}^{N} \text{Cash Flow}_t \left[\frac{1}{(1+i)^t} \right], \tag{1}$$

where

N life time of the investment, year;

t time interval, year;

i discount rate in percent, %.

Moreover, in the economic evaluation of an investment it should be appropriate to calculate the Pay Back Period (PBP) that allows to determine the time required for the cash flows to repay, or at least equalize, the initial outlay:

$$\sum_{t=1}^{PBP} \text{Cash Flow}_t \left[\frac{1}{(1+i)^t} \right] - \text{Initial Cost} = 0 \tag{2}$$

Furthermore, an environmental analysis was developed, which allows to estimate the saved CO_2 emissions when the roof inclination angle changes.

The methodology was applied to a case study that is a school located in Italy, in the Abruzzo region, in the province of L'Aquila. In the following chapter, the case study is presented and the productivity of the plant is assessed in the existing conditions, with the roof inclination angle of 15°. In the next chapter, the LCCA and environmental analysis is performed for all the different configurations obtained by varying the roof inclination angle.

3. CASE STUDY

The "San Demetrio ne' Vestini Comprehensive Institute" is located in the municipality of San Demetrio ne' Vestini, in the province of L'Aquila and includes kindergarten, primary and secondary school. The latter is housed in an isolated building, organized according to an "L" shaped floor plan. It is spread over three floors which are completely above ground thanks to the presence of the steep terrain in the south elevation and partially underground in the north elevation (Fig. 1 and Fig. 2).

A preliminary analysis of the building and the viewing of the documentation related to electricity consumption have shown that it is a highly energy-intensive construction. For this reason, the Municipal Administration, in the capacity of building owner, has decided to take steps to mitigate this issue with the use of technologies suitable for solar energy exploitation. Below is a detailed description of the intervention.

3.1. Project Aims

The definition of the project was guided by the designation of ambitious energy – environmental and socio-economic objectives. They are summarized below:

- Environmental improvement of the entire area subject of the intervention;
- Containment of energy expenditure and, therefore, of the structure operating costs for at least 25/30 years from the completion of the work;
- Development of the sector of local installers and maintainers;

- Use for educational and demonstration purposes of the project and its advantages in order to repeat the initiative in other similar realities;
- Reduction of air pollution.

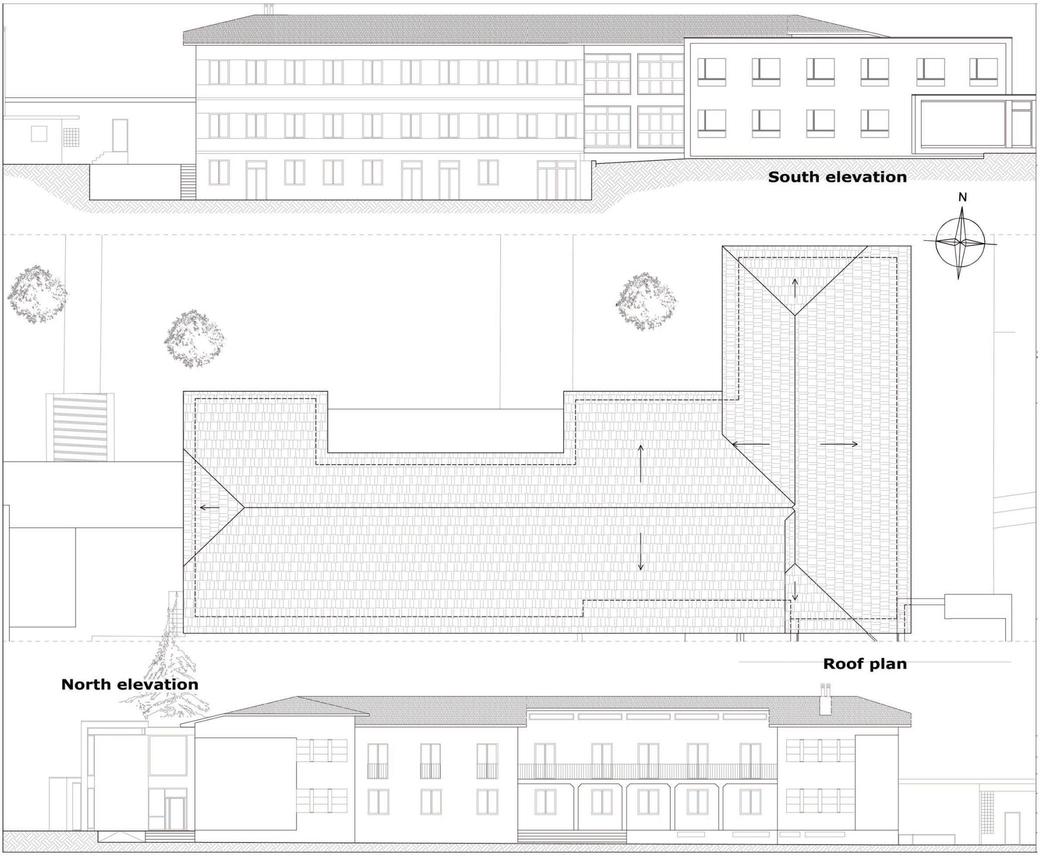

Fig. 1. The relief of the building's roof plan and the main elevations useful to provide a general overview of the object of study.

(a) (b)

Fig. 2. The a) south elevation and b) north elevation photos.

3.2. Input Data

The design process was preceded by calculation simulations performed with the *Pv Syst* software. The project and climatic data are reported in Table 1.

TABLE 1. PROJECT AND CLIMATIC DATA

List of information	
Location	San Demetrio Ne' Vestini
Latitude, Longitude	42° 17' N, 13° 33' E
Municipal building altitude	662 m s.l.m.
Owner	San Demetrio Nè Vestini Municipal Administration
Degree-days	2437
Climatic zone	E
Land conformation	Inland mountain
Orientation	South (Azimuth 0°)
Shadows/obstructions	Missing
Surface type	Tilt = 15°
Installation type	Partial architectural integration

For the design purposes, on the basis of the value of solar radiation on the ground on the horizontal plane in the locality of L'Aquila, taken from the irradiation tables on inclined and oriented plan [30], the value of solar radiation on the modules plane, in their project inclination, was calculated with the method indicated in [31], [32].

The inclination for the installation of the modules was equal to 15° on the horizontal, due to the constraint determined by the inclination of the existing roof. Being aware of this value, from the data processing according to the aforementioned regulations, Table 2 is obtained with the monthly and annual average insolation values and the total annual insolation hours at the considered site.

TABLE 2. TOTAL MONTHLY AND ANNUAL VALUES, MJ/G

Month	**Dir.**	**Dif.**	**Alb.**	**Total**
January	4.92	2.75	0.01	7.68
February	6.21	3.74	0.02	9.97
March	8.08	5.21	0.03	13.32
April	8.63	6.78	0.04	15.44
May	11.57	7.86	0.05	19.48
June	12.71	8.26	0.05	21.01
July	16.27	7.57	0.06	23.90
August	14.28	6.88	0.05	21.21
September	12.04	5.60	0.04	17.68
October	8.70	4.13	0.03	12.85
November	5.24	2.95	0.02	8.20
December	4.25	2.46	0.01	6.71
Average	9.41	5.35	0.03	14.79

3.3. Photovoltaic Plant Description

The photovoltaic system was designed to develop a nominal power of 1.2 kWp, aimed at operating in parallel with the ENEL electricity distribution network. Its components are the photovoltaic field, the inverter, the field panel, the network interface and the support structures. The installation of the photovoltaic field is expected on the roof of the aforementioned school building with an inclination of 15° with respect to the horizontal and positioned in order to avoid mutual or due to obstacles shading. This results from the need to position the system with partial architectural integration on the existing pavilion roof with brick tile cladding. In this way, it will be possible to disturb the building architecture as little as possible, with a limitation of the visual impact of the system and the enhancement of the need to exploit the useful surface exposed to obtain the best energy performance. The photovoltaic field includes eight modules, where each has a minimum peak power rating of 150 Wp. The module consists of polycrystalline silicon photovoltaic cells connected in series, encapsulated between a high transmittance tempered glass and a set of polymeric materials (EVA) impermeable to atmospheric agents and stable to UV radiation. The structures have a rectangular plan and are all characterized by galvanized steel uprights. The single-phase 230 V/ 50 Hz outputs of the PV field will be connected to a sheet metal panel, which contains all the protections of each individual input and a busbar system that connects all the subfields in a single three-phase system with neutral.

3.4. Energy Production Level of the System

Electricity, understood as energy output from the 'generator – conversion and control group' overall system, which the plant will be able to generate on average in one year, was estimated starting from the nominal power of the photovoltaic generator and the inverter type used. From the simulation that was carried out to the various operating regimes throughout the year the average energy production level of the system (1.2 kWp) is equal to 1537 kWh/year.

4. LCCA AND ENVIRONMENTAL ANALYSIS

All the parameters defined in the case study remained unchanged, as well as the technology used that is polycrystalline photovoltaic. The only exception is represented by the roof inclination angle. In particular, the inclination angle of the roof has been assumed to be 10°, 15°, 20°, 30°, 40°, 50°, 60°, 70°, 80° and 90°. The annual energy production varies according to the roof inclination angle and it has been calculated using the *Pv Syst* software.

Once the levels of energy production expressed in kWh/year as roof inclination angle varies are known, it is possible to determine overall incentive, energy consumption savings and overall revenues (Table 3). In particular, overall incentive and energy consumption savings expressed in €/year are calculated by multiplying the level of energy production by the coefficient 0.44 €/kWh and 0.16 €/kWh respectively. The coefficient 0.16 €/kWh represents the price of electricity in Italy [33]. Instead, the coefficient 0.44 €/kWh was obtained from Conto Energia [27]. Finally, overall revenues are derived from the sum of overall incentive and energy consumption savings for each roof inclination angle.

On the other hand, the costs involved during the life cycle are shown in Fig. 3. The costs do not depend on the roof inclination angle, so the costs are the same for each configuration.

The investment cost was equal to € 5235. Replacement costs are equal to 17 % of the initial cost of the photovoltaic system and are applied for every tenth year of functioning [34]. The annual maintenance costs of a photovoltaic system are set at 1 % of its initial cost [35].

Furthermore, in the LCCA of the different configurations obtained as the roof inclination angle changes, the analysis period is 25 years and the discount rate used to convert future cash flows to current values is set at 3 % [35]. From the environmental point of view, the saved CO_2 emissions expressed in $kgCO_2$/year are calculated by multiplying the energy production levels by the coefficient 0.4109 $kgCO_2$/kWh. The coefficient 0.4109 $kgCO_2$/kWh represents Electricity-specific factors related to Italy [36]. Table 4 reports the saved CO_2 emissions per kWh of electricity produced by the photovoltaic system using Electricity-specific factors.

TABLE 3. ENERGY PRODUCTION LEVEL, OVERALL INCENTIVE, ENERGY CONSUMPTION SAVINGS AND OVERALL REVENUES FOR ALL THE DIFFERENT CONFIGURATIONS. THE VALUES OBTAINED WHEN THE ANGLE IS EQUAL TO 15° (CASE STUDY) ARE IN EVIDENCE

Roof tilt, degree angle	**EnPrL, kWh/year**	**OvIn, €/year**	**EnCnS, €/year**	**OvRe, €/year**
10°	1493	656.92	238.88	895.80
Case study 15°	**1537**	**676.28**	**245.92**	**922.20**
20°	1574	692.56	251.84	944.40
30°	1618	711.92	258.88	970.80
40°	1623	714.12	259.68	973.80
50°	1590	699.60	254.40	954.00
60°	1519	668.36	243.04	911.40
70°	1413	621.72	226.08	847.80
80°	1275	561.00	204.00	765.00
90°	1110	488.40	177.60	666.00

EnPrL: Energy production level; OvIn: Overall incentive; EnCnS: Energy consumption savings; OvRe: Overall revenues.

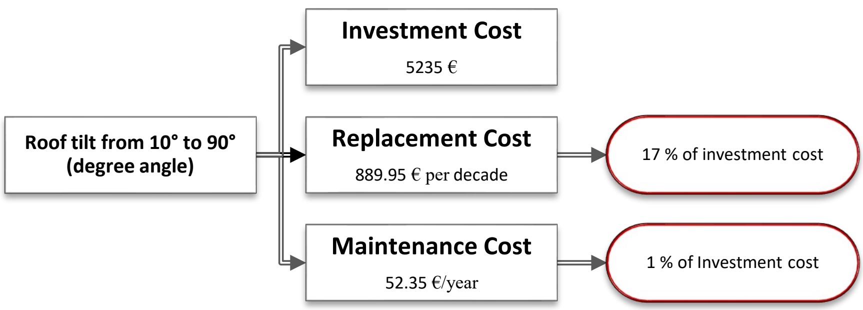

Fig. 3. Investment Cost, Replacement Cost and Maintenance Cost for all the different configurations.

TABLE 4. CO_2 EMISSIONS SAVINGS FOR ALL THE DIFFERENT CONFIGURATIONS

Roof tilt, degree angle	**EnPrL, kWh/year**	**CO_2 EmS, $kgCO_2$/year**
10°	1493	613.47
CASE STUDY 15°	**1537**	**631.55**
20°	1574	646.76
30°	1618	664.84
40°	1623	666.89
50°	1590	653.33
60°	1519	624.16
70°	1413	580.60
80°	1275	523.90
90°	1110	456.10

EnPrL: Energy production level; EmS: Emission Savings.

5. RESULTS AND DISCUSSIONS

The analysis was performed by changing only the roof inclination angle, leaving all the remaining parameters unchanged.

This choice was made because, as already argued, it is one of the elements that most influence the productivity of the PV plant. In fact, as can be seen from Fig. 4, the level of energy production varies according to the roof inclination angle. In particular, the level of energy production is equal to 1623 kWh/year with an inclination of 40° (maximum value), while it is equal to 1110 kWh/year with an inclination of 90° (minimum value).

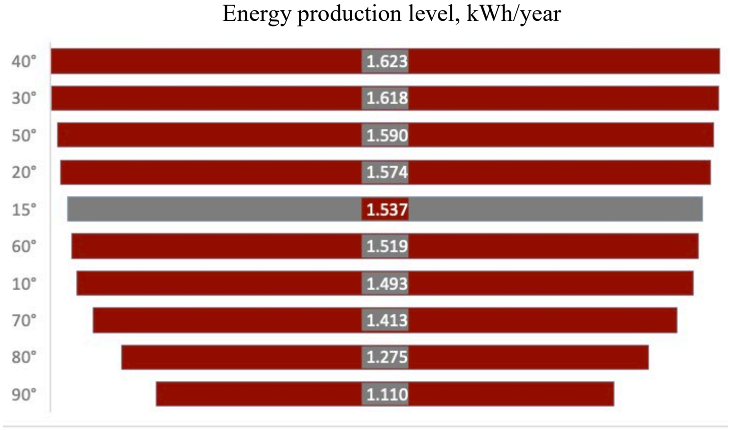

Fig. 4. Energy production level in kWh/year at different roof tilt. The value obtained when the angle is equal to 15° (case study) are pointed out in grey.

The LCCA values also vary according to the roof inclination angle (Fig. 5).

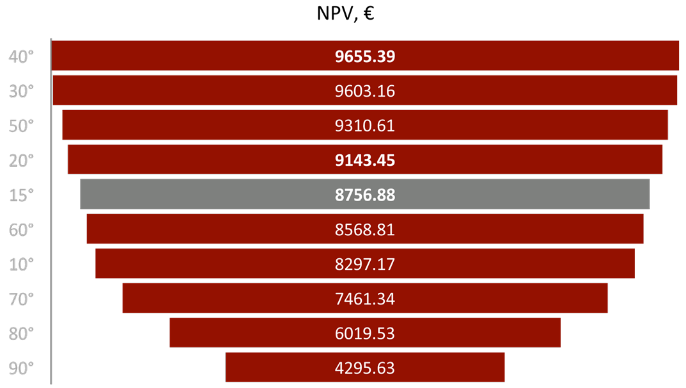

Fig. 5. NPV in € at different roof tilt. The value obtained when the angle is equal to 15° (case study) are pointed out in grey.

NPV is equal to € 9655.39 with an inclination angle of 40° (maximum value), while it becomes equal to € 4295.63 with an inclination angle of 90° (minimum value). In both cases, the value of the NPV is greater than zero; so, for any roof inclination angle the investment generates sufficient cash flows to repay the initial outflows and generate a financial benefit. Clearly, comparing the profitability of different investments, the most convenient from an economic point of view is the one with the highest NPV value, represented by the configuration with an inclination angle of 40°. On the other hand, the PBT varies between 7 years and 12 years, more precisely for inclination angles from 10° to 60° the PBT is 7 years, it is 8 years for 70°, it is 9 years for 80° and it is 12 years for 90° (Fig. 6).

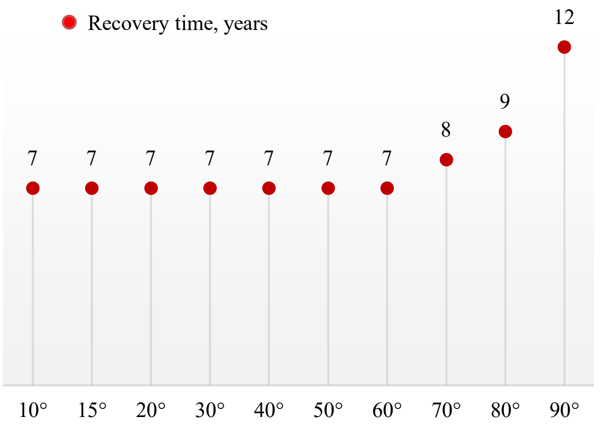

Fig. 6. PBT in year at different roof tilt.

Therefore, also from the point of view of the PBT, for any inclination the investment is profitable because the time required for the cumulative cash flows to compensate for the initial outlay is less than 25 years (investment duration). However, the best configurations are those that recover the initial investment in the shortest possible time. From an environmental point of view, if the saved CO_2 emissions increase, also the environmental benefit rises. The saved CO_2 emissions vary between 666.89 kg CO_2/year with a tilt angle of 40° to 456.10 kg CO_2/year with a tilt angle of 90° (Fig. 7).

CO_2 emissions equivalent savings, kg CO_2/year

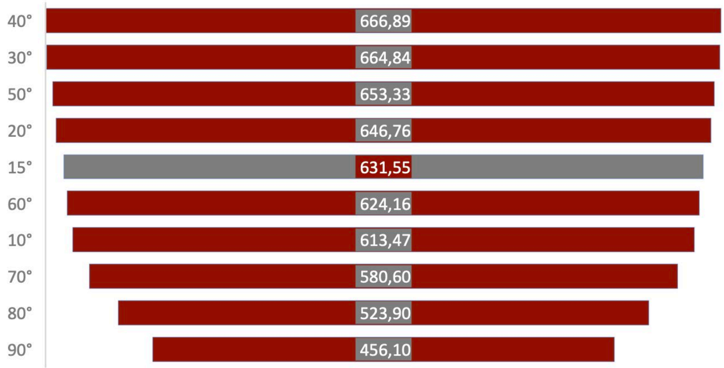

Fig. 7. CO_2 emissions equivalent savings in kg CO_2/year at different roof tilt. The value obtained when the angle is equal to 15° (case study) are pointed out in grey.

All the indicators analysed until now confirm that the optimal configuration from both an economic and environmental point of view is that which has a roof inclination angle of 40°. However, even the case study related to a school building located in Italy with an inclination equal to 15° on the horizontal for the module installation, has both economic and environmental advantages, in particular:

- NPV, equal to € 8756.88, is greater than zero;
- PBT, equal to 7 years, is inferior than the duration of the investment;
- The saved CO_2 emissions are equal to 631.55 kgCO_2/year.

6. CONCLUSIONS

This paper illustrates a research methodology aimed at the use of renewable energies in retrofitting interventions of the existing public building heritage. In particular, the study focused on the angle of inclination of a school roof located in Italy, in the province of L'Aquila. This is because, as is well known, the tilt angle of a solar energy plant is one of the most important parameters, in order to capture maximum solar radiation that falls on the solar panels. The methodology applied to the case study highlighted the convenience to invest in renewables sources, even in the presence of not optimal existing conditions.

In fact, although the case study has a roof inclination angle (15°) different from the optimal one (40°), there are significant economic and environmental advantages. In fact, in the case study the value of NPV is greater than zero and PBT is inferior to the duration of the investment. Furthermore, the saved CO_2 emissions are slightly less than the optimal case. Clearly, in the presence of optimal conditions, the benefits could be greater.

The importance of the illustrated research lies in the fact that it could be easily replicated in other existing public buildings to evaluate the optimal inclination angle in order to obtain greater economic and environmental performance and therefore support the decision-making process of designers and administrators, with the aim of making energy upgrading choices that could promote the use of renewable sources.

Authors Contribution

Marianna Rotilio wrote the paper, carried out the research and conceived the methodology with Federica Cucchiella who also supervised the research. Valeria Annibaldi did the economic analysis while Alessia Condemi worked on the literature search with Marianna Rotilio. Valeria Annibaldi and Alessia Condemi supported Marianna Rotilio and Federica Cucchiella throughout the work.

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