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Enhancing the environmental performance of industrial settlements: An economic evaluation of extensive green roof competitiveness

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ABSTRACT

This paper evaluates the private and social costs and benefits of adopting an extensive green roof as opposed to a cool roof in an existing industrial building in Trieste (North-Eastern Italy). The evaluations from social and private viewpoints both consider costs and benefits of refurbishments, energy consumption, and maintenance. From the social side, the externalities derived from green or cool roofing, such as aesthetic aspects, biodiversity preservation and natural habitat provision, carbon reduction, air quality improvement, and hydrological aspects, are monetized using cost-benefit transfer approaches. The first analysis result is the poor convenience of adopting a green roof compared to a cool one from the private investor's viewpoint. The second finding is the positive net present value of the social cost-benefit analysis for the green roof compared with the cool roof, due to the positive externalities of the former. Monetization of externalities allows calculating the economic incentives needed to promote the spread of green roofing in the Mediterranean area. Consequently, two different types of incentives are proposed: direct contribution for refurbishment intervention and annual reduction of local property tax. A final sensitivity analysis using the Monte Carlo method is performed on intrinsic and random variables, defined by triangular or uniform distributions. The probability evaluation of economic affordability is provided from the private investor's viewpoint, first considering private costs and benefits and, second, introducing the financial incentives for balancing the public benefits provided by an extensive green roof.

1. Introduction

Green roofs (GRs) provide several benefits through the implementation of a vegetable layer on the covering of both new and existing buildings [1]. The benefits provided, as well as the visual enhancement, reduction of stormwater runoffs, energy performance improvement, and mitigation of the heat island effect, relate to both private and public objectives [2,3]. Moreover, different performance levels are provided by intensive and extensive GRs. Intensive GRs are characterized by a thicker growing medium, which allows a greater development of plant species and provides recreational spaces, but requires frequent maintenance. On the other hand, a reduced thickness of the growing medium allows extensive GRs to be installed on existing buildings with a redevelopment purpose, which involves reduced plant height and variety.

In Italy, GR technologies are still not widespread [4], mainly due to high construction costs, in addition to a lack of information about their social and private benefits [5–7]. Therefore, the need for an increase in information quality and quantity is key to encouraging stakeholders' choices towards GRs technologies in the redevelopment of existing buildings against other traditional roofing techniques [8]. Moreover, GRs can overcome the negative impacts of industrial settlements in Italy [9]. This paper investigates refurbishment options for existing rooftops, comparing two possible alternative solutions: a cool roof (CR) with white reflective coating and an extensive GR. The economic aspects of both private and public viewpoints are investigated in Trieste Municipality, north-eastern Italy, to measure and define possible incentives for increasing the spread of GRs in Mediterranean climate urban contexts.

This study determines the maximum willingness to pay to improve environmental quality through the extensive GR installation on a reference building, compared to CR performance. For each type of environmental benefit considered, reference is primarily made to data in the literature in multiple fields, preferably related to the specificities of this study. The overall willingness to pay for the environmental improvements of GRs can determine a reasonable incentive amount necessary to ensure the economic indifference between the installation of an extensive GR rather than a CR.

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2. Literature review

CRs and GRs are suitable solutions to refurbish existing rooftops, and also capable of increasing environmental performance in urban contexts. Moreover, a remarkable improvement is provided in performance related to energy as well as operation targeted by private owners and tenants.

Porsche and Kohler [10] consider GRs a solution to contrast the negative effects of the continuous growth of cities by improving urban climate. Benefits such as extended longevity of roof waterproofing systems, reduction of stormwater runoffs, and improvement of thermal insulation can be valuated according to financial criteria. Compared with traditional roofing techniques, higher production and initial installation costs are the main barriers to implementation, which are only partly balanced by the longer lifespan of GR layers. A literature analysis highlights GR installation cost varies between 108 and 248 $/m^2$ [11]. These values are significantly higher than the installation of traditional roofs, and the GR operational cost saving hardly justifies installation cost [12].

The major finding of the life cycle cost (LCC) study conducted in Singapore by Wong et al. [13] points out the positive net savings provided by extensive GRs, considering installation, life cycle maintenance, and energy costs, as opposed to the more accessible intensive GR solution. The latter is penalized by an insignificant increase in energy performance. A significant result has been obtained by a LCC analysis (LCCA) study on the United States, focusing on installation and replacement, energy, global cooling, and stormwater-related costs. With reference to dark-coloured roofs, Sproul et al. [11] find that CRs with a white finishing layer provide a net value 25 USD/m^2 under a 50-year lifecycle, while GRs have a negative net value of 71 USD/m^2, thus not being capable to compensate their initial installation cost. Notwithstanding this immediate value loss, the annualized cost difference between CRs and GRs is evaluated at 3.20 USD/m^2.

Although local and regional policies encourage GRs technologies, the deterring effect of initial installation costs is underlined by Clark et al. in a cost-benefit analysis (CBA) conducted at building scale in the U.S [14]. Beyond upfront capital costs, private benefits provide an NPV reduction between 20.3 and 25.2% compared to a conventional roof over a 40-year lifespan. Environmental benefits drive the change in current GRs policies through an adequate valuation of cost reduction related to stormwater system management and air pollution mitigation. As such, direct incentives can reduce initial GR costs, while air pollution emissions could be considered in allowance markets. Stormwater fee reduction and health benefits were then evaluated by Niu et al. [15], confirming a net present value (NPV) about 30–40% lower than a conventional roof. Moreover, Bianchini and Hewage [16] highlight that the probability of profit with GRs is much higher than the potential investment loss.

Zhang et al. [6] focus on Hong Kong and identify extensive GRs as an important mean to mitigate air pollution and overheating in densely populated areas. In Southern European cities, architectural solutions based on GRs are not hitherto widespread despite private and external benefits [5]. In Italy, there is remarkable potential demand for rooftop greening that should be supported by governments and decision makers as to encourage GR investments. Consequently, information campaigns to increase the awareness of this technology should be considered along with monetary incentive strategies.

Therefore, this study evaluates the difficulties and possible strategies for the diffusion of extensive GRs in building refurbishments. In Italy, this target can be achieved by enlarging the shortlist of social benefits to be discussed and valuated.

3. Materials and methods

There are essentially two ways to promote investments that generate positive environmental externalities: market-based instruments (incentives) and a direct regulatory approach. Economists prefer market mechanisms over regulatory controls, since the former involves lower transaction costs [17]. Economic incentives refer to two main categories: direct or indirect intervention on prices or costs. Direct intervention includes taxes on products or processes that generate products, such as an electricity tax. On the other hand, indirect intervention includes subsidies and credit or tax incentives, such as tax deductions for major renovations or improvement of the energy performance of buildings.

This study uses cash flow analysis (CFA) for the private evaluation and CBA for the public evaluation, and investigates the use of incentives for the rehabilitation of private properties generating positive environmental externalities. An economic model makes it possible to estimate the amount of incentives that can generate private convenience in choosing a GR solution for rooftop refurbishment compared to a white CR. As per Section 2, studies have shown that GRs have a low probability to be chosen due to their high initial costs compared to traditional roofs. On the other hand, GRs generate external benefits, raising the interest in promoting incentive tools capable of providing a higher dissemination.

The evaluation model presented below has been built on the following assumptions. The assessment refers to the installation of an extensive GR, as alternative to a CR solution, on an industrial building located in the industrial settlement of Trieste as described in subsection 4.1. GR's lifespan is set at 40 years [1,10,18]; during this period, appropriate maintenance operations are considered, especially the CR solution requiring substituting the waterproofing layer after 20 years [19–21]. The remaining lifespan of the existing rooftop is considered close to 0, hence the implementation of the refurbishing solution is set at 0 time. The proposed model valuates the present value of private cash flows, and social benefits and costs.

We assume that:

- $C_{GP\ gr}$ is the present private cost of GR;
- $C_{GP\ cr}$ is the present private cost of CR;
- $B_{P\ gr}$ is the present private benefit of GR;
- $B_{P\ cr}$ is the present private benefit of CR;
- ΔC_{GP} is the difference between the present private cost of GR, $C_{GP\ gr}$, and the present private cost of the CR, $C_{GP\ cr}$;
- ΔB_P is the difference between the present private benefit of the GR, $B_{P\ gr}$, and the present private benefit of the CR, $B_{P\ cr}$;
- ΔB_{PN} is the net present private benefit, given by the difference between ΔB_P and ΔC_{GP};
- $B_{E\ gr}$ is the present social benefit of GR;
- $B_{E\ cr}$ is the present social benefit of CR;
- ΔB_E is the difference between the present social benefit of GR, $B_{E\ gr}$, and the present social benefit of CR, $B_{E\ cr}$.

The present private cost of the GR $C_{GP\ gr}$ (s_i) is expressed as follows:

$$C_{GPgr}(s_i) = \sum_{t=0}^{40} C_{Pgr}(s_i)_t \cdot e^{-\delta \cdot t} \tag{1}$$

where δ is the instantaneous market discount rate, t represents time in years, and s_i is the GR surface.

The present private cost of CR, $C_{GP\ cr}(s_i)$, is:

$$C_{GPgr}(s_i) = \sum_{t=0}^{40} C_{Pgr}(s_i)_t \cdot e^{-\delta \cdot t} \tag{2}$$

The present private benefit of GR, $B_{P\ gr}(s_i)$, is:

$$B_{Pgr}(s_i) = \sum_{t=0}^{40} B_{Pgr}(s_i)_t \cdot e^{-\delta \cdot t} \tag{3}$$

The present private benefit of a CR, $B_{P\ cr}(s_i)$, is:

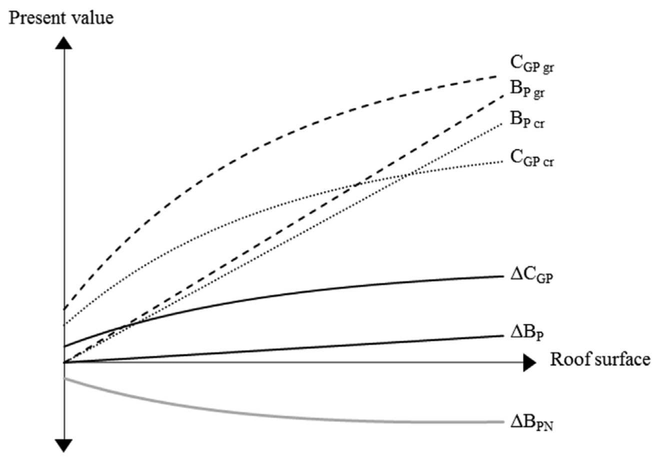

Fig. 1. Private benefits and costs of GR and CR.

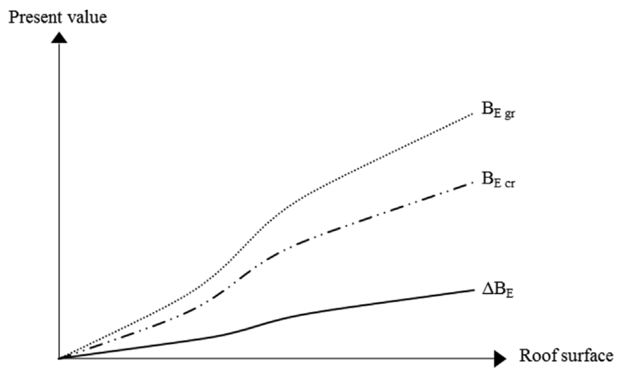

Fig. 2. Social benefits of GR and CR.

$$B_{Pcr}(s_i) = \sum_{t=0}^{40} B_{Pcr}(s_i)_t \cdot e^{-\delta \cdot t} \tag{4}$$

Fig. 1 shows the trends of present private costs and benefits according to the surface of the refurbished roof. $C_{GP\ gr}$ and $C_{GP\ cr}$ have upward and marginally decreasing trends. This is justified considering that the unit costs of GRs and CRs are lower for large surfaces and higher for smaller ones, with nonlinear variation. The present private benefit $B_{P\ gr}$ is assumed to be a straight line. In fact, it is mainly related to the reduction of energy consumption for heating and cooling, which is proportional to the intervention surface size, s_i.

For a CR solution, the trend of the private benefit function, expressing the present private benefit $B_{P\ cr}$ related to surface s_i, is linear but with a slope less than the present private benefit provided by GR. This means that present GR private benefit, $B_{P\ gr}$, with the increase of the covering surface, grows more than corresponding present private benefit $B_{P\ cr}$ of CR.

Assuming the present global private cost difference ΔC_{GP} between the cost of a GR, $C_{GP\ gr}$, and a CR, $C_{GP\ cr}$, is greater than the present private benefit difference ΔB_P between the private benefit provided by a GR, $B_{P\ gr}$, and by a CR, $B_{P\ cr}$, for each value of surface intervention s_i [8]:

$$\Delta C_{GP} = C_{GP\ gr} - C_{GP\ cr} > \Delta B_P = B_{P\ gr} - B_{P\ cr} \tag{5}$$

As such, there is no private convenience in refurbishment by an extensive GR compared to CR, since the net private benefit ΔB_{PN}, given by the difference between ΔB_P and ΔC_{GP}, is below 0 for each intervention surface s_i:

$$\Delta B_P - \Delta C_{GP} = \Delta B_{PN} < 0 \ \ \forall \ \ s \tag{6}$$

The present external benefits of a GR, $B_{E\ gr}\ (s_i)$, and a CR, $B_{E\ cr}\ (s_i)$, related to surface area s_i are:

$$B_{E\ gr}(s_i) = \sum_{t=0}^{40} B_{Egr}(s_i)_t \cdot e^{-\gamma \cdot t} \tag{7}$$

$$B_{E\ cr}(s_i) = \sum_{t=0}^{40} B_{Ecr}(s_i)_t \cdot e^{-\gamma \cdot t} \tag{8}$$

where γ is the instantaneous social discount rate.

The following function represents the difference of external benefit ΔB_E between the external benefit function for GR, $B_{E\ gr}$, and for CR, $B_{E\ cr}$:

$$\Delta B_E = B_{E\ gr} - B_{E\ cr} \tag{9}$$

We assume that functions $B_{E\ gr}$ and $B_{E\ cr}$ have a growing trend with the increase of roof surface (see Fig. 2). Initially growth is almost exponential, then decreases, assuming a nearly linear trend. This fact is well described by the heat island effect, for both GRs and CRs. In fact, for small surfaces of GR and CR, the positive effects associated with surface temperature reduction are very low. As this surface grows, the effects become increasingly important and increase almost exponentially until, for each additional surface, the marginal benefit increase tends to be constant, as much of the possible benefits have already been obtained. This trend can also be validated for other external benefits, such as air quality and, in the case of GRs, the increase in biodiversity level through new wildlife ecological corridors.

Using the two functions ΔB_E and ΔB_{PN}, we can define the minimum surface $s_{\min}$ for which ΔB_E is above ΔB_{PN} (Fig. 3). For green covered areas greater than $s_{\min}$, the value of positive environmental externalities is above private costs and GR is convenient from the social viewpoint. The model also allows estimating the economic incentives required to ensuring private convenience in choosing GR over CR, that is, at the maximum equal to ΔB_E value and at minimum to ΔB_{PN}. For a surface area below $s_{\min}$, the positive externalities derived by GR, and therefore the maximum value of any incentive, are not sufficient to guarantee private convenience for the intervention.

4. Calculation

4.1. Case study

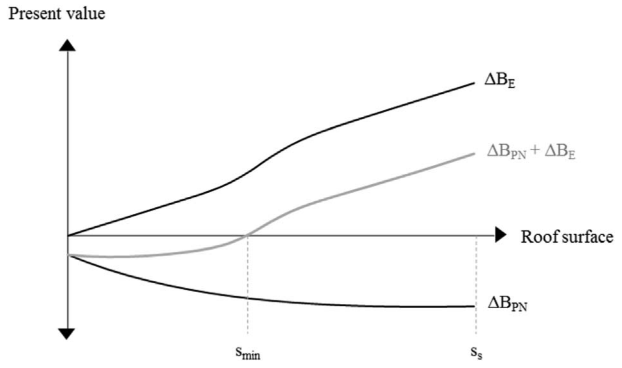

Fig. 3. Private and social benefits functions.

The building assumed in the valuation is a three-story industrial building, located in the productive settlement in Trieste, Italy. The analysis focuses on the upper floor as an independent thermal zone. The gross area of the third upper floor is 780.33 m^2, corresponding to the building footprint. The net air-conditioned volume is 2479 m^3 and occupant intensity is 8 m^2/person. The building is supported by a linear reinforced concrete structure. Facades consist of 25 cm thick hollow block bricks, with an 8 cm thick internal brick wall and double insulation layer in extruded polystyrene foam (XPS) as external coating and in the air gap, for an overall 6 cm thickness, and of aluminium-framed, double-glazed windows. The building is capped by flat roof in

Table 1
Climatic data inputs for sensitivity analysis.

Climatic data	Values			Distribution
	MIN	ML	MAX	
Average temperature in winter [°C]	8.2	10.8	13.6	Triangular
Average temperature in summer [°C]	25.2	22.5	20.0	Triangular
Solar radiation on the horizontal, winter [MJ/m^2]	5.5	8.1	10.7	Triangular
Solar radiation on the horizontal, summer [MJ/m^2]	22.9	20.0	17.0	Triangular
Annual precipitation height [mm]	534	855	1334	Triangular
Length of drought periods [days]	116	182	258	Triangular

reinforced concrete 28 cm thick, and hollow tiles mixed floor, covered by a bituminous waterproofing membrane and squares of gravel 4 cm thick (status quo solution, SQ). The total surface of the thermal zone envelope is 1299.38 m^2, distributed as follows: windows 10%, external walls 30%, and roof 60%. Natural gas is the primary heating fuel, with electricity being used for indoor space cooling and as auxiliary energy carrier for the thermal plant. The building, whose construction dates to 1988, is representative of the construction techniques for industrial buildings in Trieste during that period.

The building's energy performance for heating and cooling services has been studied for the climate of Trieste, N 45° 38′, E 13° 48′, with an elevation of 2 m above the sea level. The climate data have been provided by the regional meteorological observatory of Friuli-Venezia Giulia OSMER FVG [22]. The annual number of heating degree days in Trieste is 2102. The average summer and winter temperatures are 21.0 and 10.3 °C, respectively. The annual average precipitation is 855 mm and relative humidity is 50%. The following climate data for 1996–2015 were used: dry bulb temperature, direct and diffuse solar radiation, annual precipitation and consecutive drought periods, as per Table 1. A triangular distribution has been associated to each dataset to generate minimum (MIN), most likely (ML), and maximum (MAX) values for energy consumption and stormwater management cost variations.

Note: For each dataset, minimum (MIN), most likely (ML), and maximum (MAX) values are considered.

The building envelope and the profile of operative use are uniquely defined throughout the analysis, except the flat roof. Therefore, two refurbishing alternatives to the SQ technological solution are considered: CR and extensive GR. The existing flat roof, widespread in buildings from the 1970s and 1980s, is made of a supporting layer 25 cm thick, waterproofing membrane adherent to a slope layer, and a finishing layer in discontinuous squares of washed gravel, 4 cm thick; the solution is devoid of any insulation layer. Both refurbishment solutions have the same supporting and slope layers. CR considers a new waterproofing membrane, 0,4 cm thick; a thermal insulation layer in expanded polystyrene (EPS), 14 cm thick; and a finishing waterproofing layer with a reflective paint coating on the external surface, with a solar absorptance of 0.3. The extensive GR consists of a double waterproofing membrane layer, with the insertion of an EPS insulation layer 10 cm thick, a water storage element, a geotextile fibre layer above which is 10 cm of soil substrate and a vegetation layer, a combination of sedum and aromatic plants with minimal maintenance needs.

4.2. Private costs and benefits

Private costs and benefits related to both refurbishment intervention scenarios are described. Initial installation costs are provided for substituting the existing roof in washed gravel tiles with CR or extensive GR. Maintenance costs of a new roof are evaluated in both intervention scenarios, proportionally increasing annually to maintain constant private and environmental performance. Costs related to yearly energy consumption are defined by the difference with the existing roof; energy consumption has effects on carbon dioxide emissions and is evaluated as a public benefit. Initial substitution cost is set at the end of intervention year, while costs associated to maintenance and energy consumption have been quantified within an annual time frame, beginning the year following refurbishment and lasting over the 40-year lifespan of the new roof.

4.2.1. Initial refurbishment costs

The cost of initial installation is determined according to price lists for civil engineering products [23]. Refurbishment costs consider, in both scenarios, the removal and disposal of existing washed gravel tiles and underlying waterproof membrane, which is 32.92 EUR/m^2. The cost for CR installation is 81.39 EUR/m^2, accounting for a new waterproof membrane, EPS insulation, and a second self-adhesive membrane with a reflective paint coating. Extensive GR installation cost is evaluated at 140.88 EUR/m^2, including new waterproof membrane, drainage system and vertical waterproofing layer at perimeter, hollow profiles, control sump costs.

4.2.2. Energy costs

Both refurbishment solutions provide a primary energy reduction in cooling and heating services provision [24]. Particularly, a higher energy performance of extensive GR is achieved over summer, while an additional insulation layer provides adequate performance in winter [25,26]. A semi-stationary calculation of the primary energy consumption for heating and cooling in the thermal zone underneath the rooftop allows an estimation of annual costs. The evaluation considers a triangular distribution for outdoor climatic conditions (Table 1) and for the energy prices of natural gas and electricity carriers (Table 2).

The existing roof shows an annual heating and cooling cost between 5.97 and 13.60 EUR/m^2; the most probable value is 9.98 EUR/m^2, obtained with the most likely climate conditions and energy prices. The annual cost for energy consumption is estimated between 1.30 and 7.40 EUR/m^2 for CR, and between 1.31 and 7.03 EUR/m^2 for extensive GR, with the most likely values being 3.96 EUR/m^2 and 3.72 EUR/m^2, respectively. Therefore, for lower values of energy price and consumption, CR expresses a 4.73E-3 EUR/m^2 benefit compared with GR. For the most severe price and climate conditions, extensive GR has a private benefit of 0.373 EUR/m^2. In the most likely conditions, the extensive GR benefit is 0.240 EUR/m^2, when compared to the energy performance of CR. Air-conditioning plant adaptation costs are considered an invariance in the economic valuation, due to the energy performance improvement of both solutions. Regarding the mitigation of the urban heat island effect, both solutions provide valuable performance in decreasing surface temperature, due to CR's high albedo and the energy absorption to activate photosynthesis process in GR [27]. The positive effect on urban heat island mitigation of both refurbishment solutions is considered invariant and has not been evaluated [28,29].

4.2.3. Maintenance costs

The valuation of maintenance costs considers planned maintenance operations on each technological roof solution. The maintenance annual cost has been derived by specific operations at different time frames. To consider the partial non-effectiveness of performance restoration, a multiplicative coefficient increases equivalent costs

Table 2
Energy price data inputs for sensitivity analysis.

Energy carrier price	Values			Distribution
	MIN	ML	MAX	
Natural gas [EUR/m^3]	0.292	0.375	0.437	Triangular
Electricity [€ = EUR/kWh]	0.115	0.184	0.237	Triangular

Table 3
Private costs of GR and CR for sensitivity analysis [EUR/(m^2 yr)].

Private costs	CR			Extensive GR			Time frame	Distribution
	MIN	ML	MAX	MIN	ML	MAX		
Initial refurbishment		81.39			140.88		40 years	One-time
Energy consumption	1.30	3.96	7.40	1.31	3.72	7.03	Annual	Triangular
Maintenance	2.86			2.00			Annual	Constant

annually during the lifespan. The annual performance loss is set at 2.50% for SQ roof and 0.75% for CR and GR.

For the existing roof, the cleaning of tiles, eaves and drainpipes occurs every six months and the substitution of deteriorated tiles every five years, with an equivalent annual maintenance cost of 11.72 EUR/m^2. The expected lifespan of GR is 40 years, while CR's is about 20 years. Therefore, the GR has a longer lifespan for the waterproofing membrane being protected against UV light and temperature fluctuations [10,20]. To ensure adequate water tightness and reflection performance for CR, a re-roofing intervention has been considered after 20 years in addition to the half-yearly cleaning of covering and drainpipes; its equivalent annual cost is 2.86 EUR/m^2. In extensive GR, the control of vegetation health and cleaning are yearly. Moreover, every 20 years, the restoration of vegetation and soil substrate is provided. The equivalent maintenance annual cost is 2.00 EUR/m^2. Therefore, GR has a lower maintenance annual cost by 0.86 EUR/m^2 compared to CR.

Table 3 summarizes the private costs and benefits used in the economic valuation.

4.3. Public benefits

Extensive GRs contribute to reducing several costs related to environmental protection and management. In the following analysis, public benefits have been valued, such as landscape aesthetic improvement, biodiversity preservation, reduction of carbon dioxide emissions, air quality, and reduction of costs related to stormwater treatment. Positive performance is provided in some of these aspects by CRs as well. Furthermore, the positive effect on urban heat island mitigation given by both refurbishment solutions is considered invariant, therefore this externality has not been valuated [28,29]. The vegetation canopy considered for extensive GR solution, consists in a mixture of sedum and herbaceous aromatic plants. The use of a vegetation cover based on Sedum spp. and Salvia spp., or other shrubs and herbaceous plants, has several functional advantages. In fact, shrubs and herbs have been shown to maximize the cooling capacity and rainfall interception by green roofs [30,31]. On the other hand, succulent plants are better adapted to survive severe dry conditions [32], thus assuring maintenance of vegetative cover and aesthetic value of green roofs even in case of very harsh summer conditions. Hence, a mixture of different plant functional types is expected to keep almost constant technical performances and related externalities during the year, under fluctuating environmental conditions [33] and to offer a more valuable habitat.

Except for the aesthetic benefit, whose value is set two years after the refurbishment intervention, each social benefit has been quantified within an annual time frame, starting two years after refurbishment and lasting for the 40-year lifespan of the new roof.

4.3.1. Landscaping aesthetic benefit

One of the most important benefits of roof greening concerns the aesthetic improvement of urban areas, in which GRs can reduce the perceived monotony of anthropic surfaces. An analysis based on the stated preference method valued the aesthetic features of GRs, thus overtaking the difficulties of an objective valuation of the economic impact [34,35]. Rosato and Rotaris [5] asked individuals to quantify their willingness to pay for a widespread diffusion of GRs in the surroundings of their house. Accepting a greening of 50% of visible roof area, the willingness to pay values fluctuates between EUR 82 and 205 per property area unit. The industrial settlement of Trieste is located at the bottom of a hill, in which multi-story residential buildings form a densely populated urban area directly facing to industrial area. Therefore, it is possible to relate the willingness to pay to GR surface unit. The overall property area unit facing entity for the industrial zone of Trieste (EZIT) area is about 62.950 m^2, so the property value increase varies between EUR 5.16 and 12.90 million. The roof surface visible from these dwellings is about 366.200 m^2, of which half is supposed to be refurbished as extensive GR. Thus, aesthetic improvement due to partial roof greening in this area fluctuates between 28.19 and 70.47 EUR/m^2. It is considered that the CR solution does not provide any aesthetic benefits.

4.3.2. Biodiversity preservation and natural habitat provision

Green areas in urban contexts partially contribute to biodiversity protection and ecologic corridor creation for the settlement and movement of wildlife species [19]. The replacement of impervious surfaces with extensive GRs attracts small animals, providing new spaces for wildlife directly on buildings [36]. Therefore, GRs avoid restoration costs in providing natural areas, a public benefit [37]. The Friuli – Venezia Giulia Region invests EUR 40.19 million to protect, restore, and enhance lands as natural habitat [38]; the overall protected area is 1786 km^2 [39]. Extensive GRs do not provide the same benefit level of natural habitats; thus, only 20% of this value has been considered appropriate for roof greening in urban contexts. The calculated benefit is considered constant and equal to 4.50E-3 EUR/m^2. The CR solution does not provide any benefit in biodiversity preservation.

4.3.3. Carbon reduction benefit

Both GRs and CRs provide energy reduction in cooling and heating service provision. Thus, a reduction of carbon dioxide emissions, due to a lower consumption of natural gas and electricity, must be considered. As described in subsection 4.2.2 and according to different climate conditions, GR expresses a reduction of electricity consumption that varies from 0.34 to 1.48 kWh/m^2, with a most likely value of 0.54 kWh/m^2, compared to CR. Regarding natural gas consumption, CR has a better performance, varying from 0.15 to 0.25 m^3/m^2, but the most likely value rewards GR with a 0.54 m^3/m^2 reduction. Carbon dioxide emission factor is 1.98 kg/m^3 for natural gas and 0.46 kg/kWh for electricity [40]. The carbon reduction tax is estimated as 18.00 EUR/t according to the Kyoto Protocol, though recognizing that carbon prices span from 2.00 to 131.00 USD/tCO$_2$e in European countries [41]. Therefore, the carbon reduction performance of GR varies from $-$2.56E-3 to 3.19E-3 EUR/m^2, with a triangular distribution and a most likely value of 2.69E-2 EUR/m^2.

4.3.4. Air quality improvement

Urban vegetation improvement with GRs is a strategy to reduce air pollutant concentration, allowing a dry deposition process and control of microclimate effects. Moreover, GRs can overtake the implementation of tree planting strategies in densely populated cities, exploiting rooftop surfaces, typically up to 50% of the impervious area in urban contexts [42]. Yang et al. [43] monitored the dry deposition processes on 19.8 ha of GRs in Chicago. This study has shown uptake effects on

Table 4
GR and CR social benefits for sensitivity analysis [EUR/(m^2/yr)].

Social benefits	CR			Extensive GR			Time frame	Distribution
	MIN	ML	MAX	MIN	ML	MAX		
Aesthetic		0		28.19		70.47	One-time	Uniform
Natural habitat provision		0			4.50E-3		Annual	Constant
Carbon reduction	0.121	0.261	0.365	0.123	0.234	0.361	Annual	Triangular
Air pollution uptake		0			0.066		Annual	Constant
Reduction of drained stormwater volume	6.9E-4	1.88E-3	3.30E-3	4.82E-3	1.21E-2	1.42E-2	Annual	Triangular
Reduction of infrastructural costs	5.66E-3	5.66E-3	5.66E-3	1.06E-2	1.72E-2	1.72E-2	Annual	Triangular
Flood control	3.02E-3	3.02E-3	3.02E-3	5.66E-3	9.18E-3	9.18E-3	Annual	Triangular

four pollutants, with the largest share referred to ozone (52%), followed by nitrogen oxides (27%), particulate matter PM10 (14%), and sulphur dioxide (7%). Uptake potential of GRs depends on air pollutant concentration, plant types and growth, and weather conditions. Concentrations criteria assumed in this study are similar to concentration data series available for the EZIT industrial area in Trieste for monthly mean values and yearly trends [44]. Available studies on specific pollutants uptake in controlled laboratory conditions have not been considered. For a short grass canopy, peculiar of an extensive GR, annual removal rates are determined at 0.65 g/m^2 for SO_2, 2.33 g/m^2 for NO_x, 1.12 g/m^2 for PM10, and 4.49 g/m^2 for O_3, for an overall uptake of 8.59 g/m^2. The total amount of air pollutant removal is comparable to those observed in field studies [45,46].

Barker and Rosendahl project damage costs due to SO_2, NO_x, and PM10 emissions according to the Energy-Environment-Economy Model for Europe (E3ME), using annual time-series data for 1970–1995 [47]. In Italy, avoided damage costs are estimated as 8.22E-3 EUR/m^2, 3.37E-2 EUR/m^2, and 1.69E-2 EUR/m^2 for SO_2, NO_x, and PM10 respectively. An estimation of O_3 damage was given by Rabl [48], considering the concentration-response function and economic valuation recommended by the European Commission's ExternE Project. Only the volatile organic compounds (VOC)-derived O_3 contribution is considered, to avoid double counting NO_x-derived ozone. In 1997, damage costs for O_3 emissions were estimated at 1212.5 USD/t, and at 1644.67 EUR/t now, thus recognizing uncertainty in VOC estimations. Therefore, avoided damage cost due to GR O_3 annual removal is equal to 7.38E-3 EUR/m^2; the overall air pollutant uptake is equal to 6.62E-2 EUR/m^2. As such, the CR solution does not provide any benefit in air pollutant uptake.

4.3.5. Reduction of drained stormwater volume

GRs perform a reduction of the stormwater volume drained by the public sewage system due to retention effect and evapotranspiration phenomena by vegetation and growth medium [49,50]. These effects are considered a public benefit, as they reduce the cost of drained stormwater, public sewage infrastructure management, and flood control planning.

A lower stormwater volume drained through the public sewage system implies a reduction of transportation and purification treatment costs, depending on the energy consumption for water treatment and electricity prices [51]. In the Trieste area, stormwater transportation and treatment require an energy consumption of 0.112 kWh/m^3. Cumulative precipitation height varies from 534 to 1334 mm/year, and the avoided cost due to the retention effect of extensive GR varies from 3.22E-3 to 1.31 E-2 EUR/m^2, with a most likely value of 1.02 E-2 EUR/m^2. Triangular distribution is asymmetric because the retention effect is influenced by precipitation profiles and drought periods [52]. Regarding CR, a constant relationship has been assumed between annual runoff and rainfall [53]: the avoided cost for non-greened roof ranges between 1.31 E-3 and 6.73 E-3 EUR/m^2, with a most likely value of 3.35 E-3 EUR/m^2.

Moreover, for extensive GRs, an additional water volume is not drained to the public system due to evapotranspiration phenomena. In summer, after a stormwater event, an extensive GR can reduce the drainage flow rate by 0.5 l/m^2 per day [21]. For evapotranspiration, the cultivation layer must match saturation conditions; thus, the minimum, average, and maximum numbers of consecutive days in which these conditions occur have been investigated during 1996–2015. For extensive GR, avoided water treatment cost due to vegetation evapotranspiration ranges between 6.9 E-4 and 3.30 E-3 EUR/m^2. The overall valuation of runoff volume reduction performed by extensive GR highlights a reduction from 2.60 E-3 to 9.67 E-3 EUR/m^2.

4.3.6. Reduction of infrastructural costs

A public benefit of GRs is stormwater retention provided, with a consequent reduction of volume drainage to the public system because of lower drainage infrastructural cost. The Trieste Municipality invests EUR 2.51 million annually to manage stormwater infrastructures over an 84.49 km^2 area [54]. Extensive GR absorbs 36–58% of rainwater and could allow savings from 4.96E-3 to 1.16E-2 EUR/m^2 yearly, compared to CR; the latter is also the most likely value, according to average precipitation intensity.

4.3.7. Sewage control benefit

GRs, as opposed to traditional roofs, decrease the volume of stormwater runoff entering the sewage system, thus contributing to reduce the risk of severe flood events by reducing rainwater amounts. The cost due to urban flooding in the water basins of the Friuli–Venezia Giulia rivers is estimated at EUR 144 million per year [55]. The total area of hydrographic basins in this region is 9073 km^2. Hence, an amount of 15,873 EUR/km^2 is expended each year for flood control. As discussed in subsections 4.3.5 and 4.3.6, extensive GR absorbs 36–58% of rainwater and could generate savings from 2.64E-3 to 6.16E-3 EUR/m^2 yearly, compared to CR. The latter is also the most likely value, according to the average precipitation intensity.

Table 4 summarizes social benefit values.

4.4. Discount rates

4.4.1. Social discount rate

The calculation of present value in CFA and CBA requires the assumption of appropriates social and market discount rates. The social discount rate is defined through the fundamental concept of social time preference rate (STPR), which represents the value society associates with current consumption with respect to future consumption [56].

STPR has two components: the rate at which individuals choose future consumption compared to current consumption, with unchanged per capita consumption (ρ) [57–59]; and an element related to the per capita consumption growth over time. Assuming future consumption is increasing over time, it will have lower marginal utility. Ramsey [60] quantifies this effect with the product of annual growth per capita consumption (g) and the elasticity of the marginal utility of consumption compared to utility (μ) [61]:

$$r = \rho + \mu g \qquad (10)$$

Table 5
Discount rate inputs for sensitivity analysis.

Discount rates [%]	Values			Distribution
	MIN	ML	MAX	
Social	3.0		3.5	Uniform
Market	3.5	4.0	6.0	Triangular

Defrancesco et al. [62] suggest different discount rates be used when considering either tangible or intangible effects, cost components, and social benefits. This approach matches the principle of time-declining discount rate. Therefore, considering the different components of costs and benefits, and time horizon, we adopt a social discount rate variable between 3.0% (referring to a period of 31–75 years) and 3.5% (referring to a period of 0–30 years) [56].

4.4.2. Market discount rate

The market discount rate was determined by assuming the investment was financed with debt capital. Considering the required amount of capital was calculated using the average interest rate applied by banks. According to statistics provided by Bank of Italy [63], it is appropriate to adopt a 4% discount rate. This parameter was considered as a random variable for sensitivity analysis and has been assigned a triangular distribution as per Table 5.

5. Results and discussion

The first analysis in this study focused on the private viewpoint using CFA, taking into account the difference in operational maintenance costs between GR and CR. Assuming the values in Sections 3 and 4, the analysis led to an NPV of EUR -29,471.06, which corresponds to -37.77 EUR/m^2 of GR. This result shows the poor convenience of adopting GR compared to CR, mainly due to the higher installation costs of GR. The sensitivity analysis based on the Monte Carlo method has been performed with @Risk 7.5 by Palisade Corporation. Conducting 10,000 simulations, it evaluated the impact of uncertainty on NPV. Fig. 4 shows the probability density function of private NPV, which is positive with a confidence value of only 0.5%.

As shown in Fig. 5, the main source of uncertainty is energy consumption, particularly electricity consumption, followed by the market discount rate.

Second, this study considered CBA from the social viewpoint. In this case, GR externalities were included and a social discount rate adopted. Based on the data reported in Sections 3 and 4, a social NPV of EUR 14,567.66 (18.67 EUR/m^2) was obtained. Again, a sensitivity analysis was performed, whose outputs are shown in Fig. 6. It should be noted that when including positive externalities, there is a 73.9% probability of a positive NPV.

The variability of social NPV is mainly due to electricity consumption and landscape aesthetic value, as shown in Fig. 7.

The present value of the externalities provided by GR compared with CR amounts to EUR 44,130.25, corresponding to 56.55 EUR/m^2 for GR. These values are comparable with the findings reported by Clark et al. [14] and Niu et al. [15]. On the basis of these results and referring to the model reported in Section 3, we can first conclude that the maximum amount una tantum contribution is up to 56.55 EUR/m^2 of GR surface, and the minimum is 37.77 EUR/m^2; second, the reduction on the annual municipality tax should amount to 55.60% at most, with a minimum of 42.54%. The sensitivity analysis, adopting the maximum amount of incentives, shows a probability of 72.2% of a positive private NPV, as reported in Fig. 8.

Regarding minimum incentive, the probability decreases to 29.9% because the triangular distribution of the market discount rate is asymmetric (see Fig. 9). This embeds the risks of an increase in the interest rate of debt capital. However, this eventuality can be neglected if the investment is financed with a fixed interest rate.

Finally, the value of $s_{\min}$, that is the threshold beyond which the economic incentive cannot generate the private affordability, is about 314 m^2. That means for GR surface extensions below $s_{\min}$ there is no private convenience to implement a GR over CR, not even with economic incentives, as calculated on the basis of the GR environmental benefits due.

6. Conclusions

CFA evaluates differences in costs and benefits from the perspective of a private investor aiming to rehabilitate a reference building's rooftop. The differences in private costs and benefits between GR and CR in terms of initial construction, maintenance, and energy management were discounted through an appropriate market discount rate, and the investment NPV determined. As expected, the result is negative and highlights the lack of affordability for the GR solution. CFA shows that the low diffusion of GRs in the Mediterranean area is due to the lack of competitiveness compared to traditional roofs (e.g. CR) due to the higher investment cost.

Subsequently, a CBA was conducted, considering private construction and maintenance costs, and energy management benefits, thus adding to the evaluation of social benefits of both CR and GR. Using an appropriate social discount rate, all values were considered and a second NPV determined. CBA highlights that GR is more convenient

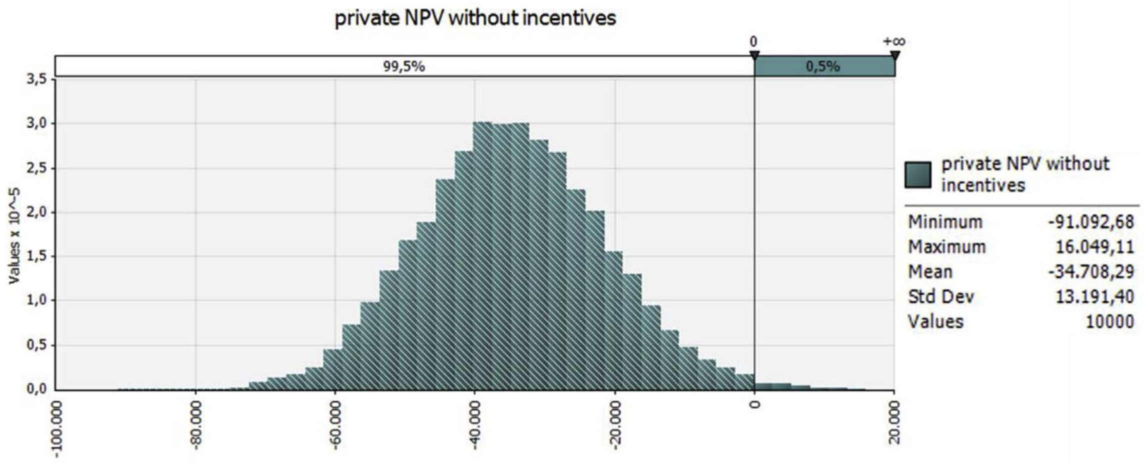

Fig. 4. Probability distribution of private NPV without incentives.

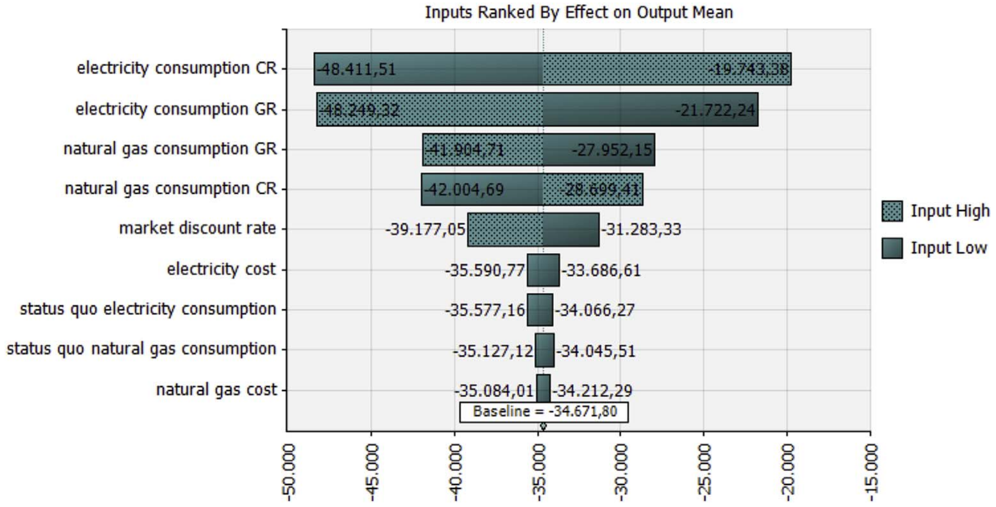

Fig. 5. The main sources of uncertainty in private NPV without incentive sensitivity analysis.

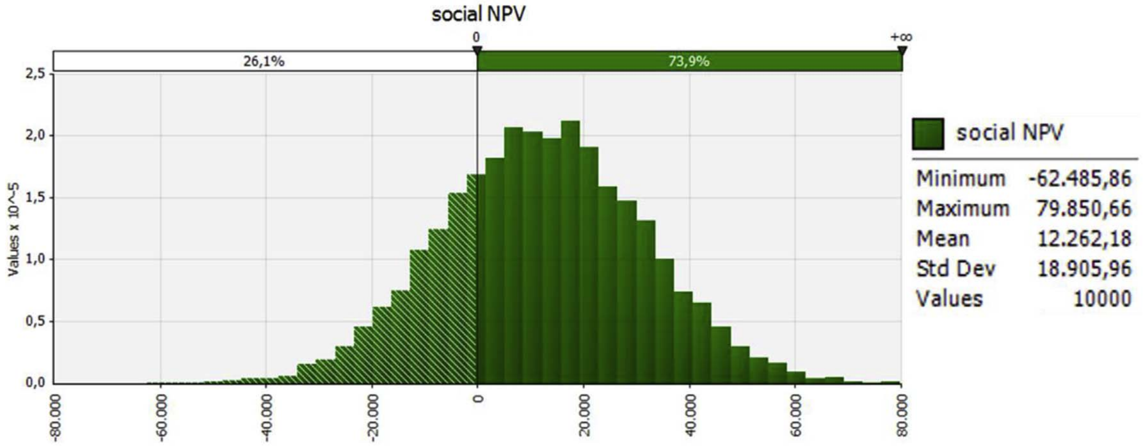

Fig. 6. Probability distribution of social NPV.

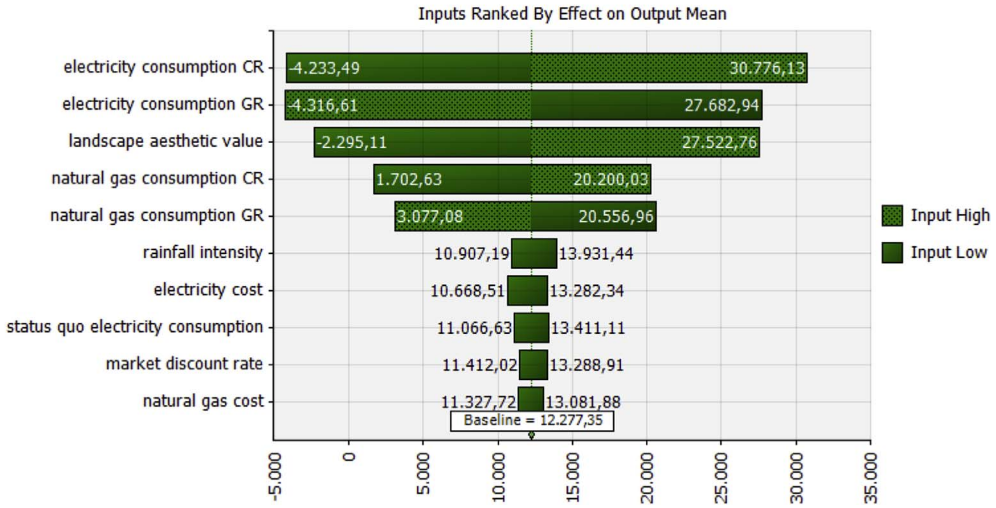

Fig. 7. The main sources of uncertainty in the social NPV sensitivity analysis.

than CR, and the comparison of the two private and social NPVs proves it is possible to overcome GR's lack of economic affordability by providing incentives proportional to the value of its social benefits.

Indeed, the evaluation made it possible to define the measure of an economic incentive that could facilitate the implementation of a GR on an industrial building located in the EZIT industrial zone of Trieste, guaranteeing the same convenience to the private investor compared to a standard CR. By setting the surface of the GR that is to be realized, it is possible to define the probability that the positive externalities resulting from its installation are sufficient to ensure at least indifference between GR and CR. CFA results show the external benefits of a GR allow to overcome the convenience difference from the private

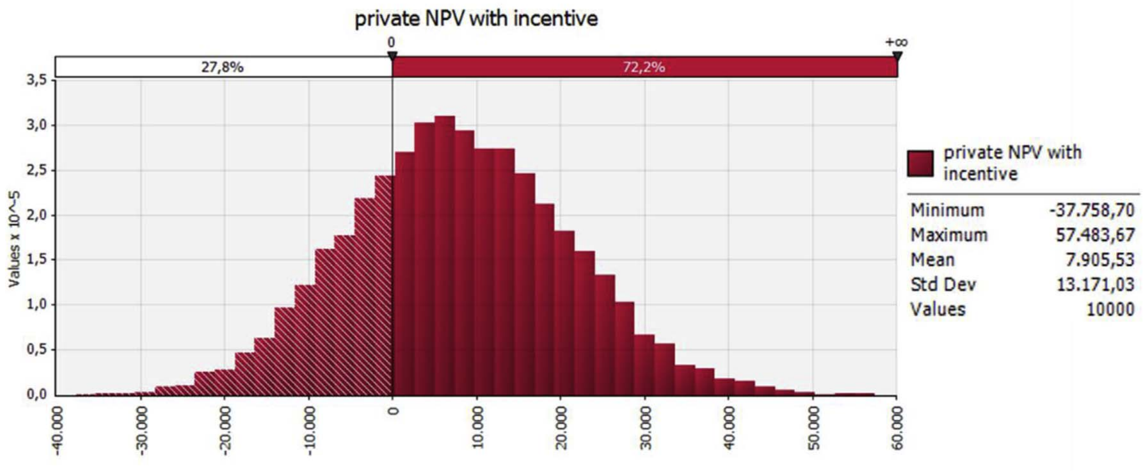

Fig. 8. Probability distribution of private NPV with incentive.

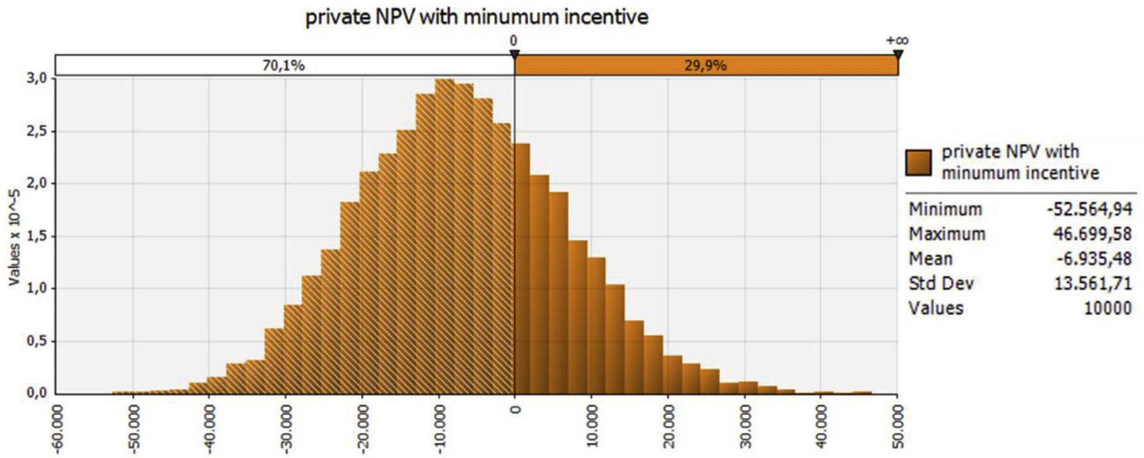

Fig. 9. Probability distribution of private NPV with minimum incentive.

viewpoint, compared to the standard CR solution, with a probability of 72.2%.

Two forms of economic incentive were also considered. Firstly, a one-time contribution, payable as a lump sum and, second, an annual reduction in the rate on local property tax on buildings for the entire useful roof lifespan (i.e. 40 years). In either case, the measure of the incentive has been calibrated to increase the convenience of GR compared to CR.

Additionally, it is important to point out that positive externalities deriving from GRs are not all easily quantifiable in monetary terms. In fact, there are aspects whose monetization is not possible due to, for example, lack of data. Among these are the reduction of the heat island effect and the creation of ecological corridors. However, even without considering the economic evaluation of these aspects, it is realistic to assume that external monetizable benefits are sufficient to justify the economic incentive for GRs.

Among all social benefits generated by GRs, the aesthetic value has the highest incidence. In an industrial context such as the case study's, this result can be easily recognized in view of the landslide degradation that these buildings can generate, highlighting how GRs should be considered as an interesting solution to reduce the negative externalities of industrial settlements.

One of the limitations of this is study is its site-specific characteristic. Indeed, all parameters considered for evaluation are related to Trieste and its territorial characteristics and are not valid for other geographic contexts. This way, further research to investigate the generalizability of the results to other geographic contexts is desirable. Moreover, a more accurate evaluation could be conducted to improve the data quality on the basis of monetizing the different considered aspects. Finally, it is important to emphasize that not all life cycle phases of GR and CR, but only the installation, use, and maintenance were considered. As such, considering all life cycle phases in terms of potential environmental impacts and monetization would be interesting.

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