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Photovoltaic-green roof energy communities can uphold the European Green Deal: Probabilistic cost-benefit analyses help discern economically convenient scenarios

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ABSTRACT

The new roadmap of the European Union (EU), the European Green Deal, aims at tackling climate adaptation, energy, biodiversity, and pollution challenges. To contribute to such aim, the latest EU Renewable Energy Directive defines for the first time renewable energy communities. Among them, Photovoltaic-Green roof Energy Communities (PGECs) emerge as a potential option in urban areas. This paper investigates whether and under which conditions PGECs are capable to meet the objectives of the European Green Deal in an economically convenient manner. Since some conditions are context-specific, this research is showcased using a case study (Luxembourg). First, European legislation was reviewed to determine the suitable legal model for PGECs. Second, a systematic literature review helped identifying lifecycle costs and benefits of photovoltaic-green roofs and their value ranges. Third, a model for probabilistic social and private cost-benefit analyses was developed and tailored to Luxembourg. Lastly, Scenario Discovery was used to identify the ranges of input values leading to desirable net present values. Results show that PGECs can contribute to achieving multiple objectives of the European Green Deal in an economically convenient manner. From the societal perspective, PGECs are found to be economically convenient for any cost, benefit, and discount rate in the case study. From the private perspective, PGECs remain convenient in 62% of the scenarios, with green roofs' installation cost and electricity generation benefit playing pivotal roles. This paper presents a rare combination of probabilistic cost-benefit analyses and scenario discovery, It supports policymakers designing incentive schemes for PGECs, and can be replicated in other countries.

1. Introduction

The world is currently facing environmental challenges of unprecedented scale and urgency (European Environment Agency, 2019). In particular, rapid rate of biodiversity loss, climate change impacts, and environmental risks to human health have been identified as persistent global challenges affecting the European Union (EU) (European Environment Agency, 2019). In the attempt to address these global challenges, the EU set in 2019 a comprehensive new growth strategy, the European Green Deal (EGD). This strategy seeks to advance energy and environmental policies, among others, towards specific objectives. The following objectives stand out: the provision of clean and affordable energy; the restoration and preservation of ecosystems and biodiversity; a zero pollution ambition; and strengthened efforts on climate change adaptation (European Commission, 2019).

Given the vast scope of the EGD objectives, all EU policies and derived actions are required to contribute in a coordinated manner to the strategy's targets, so to exploit the available synergies across policy areas (European Commission, 2019). Nevertheless, the impact assessment of the 7th Environmental Action Program only notes a "very weak link" between objectives of energy and environmental policies (European Commission, 2012). Targeted actions addressing biodiversity and

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health issues are still lacking in EU energy policies (European Commission, 2012), while the planning and implementation of climate adaptation solutions remains slow (European Commission, 2021).

To overcome current limitations of energy policies, nature-based solutions offer an attractive opportunity for mainstreaming environmental targets into sectors where they are not usually considered (Nesshöver et al., 2017). As an umbrella concept, nature-based solutions are understood by the European Commission as actions aiming to help societies address environmental, social, and economic challenges, while being inspired by and supported by nature (Bauduceau et al., 2015). Through the supply of ecosystem services, i.e., flows derived from ecosystems that can generate benefits for humans (La Notte et al., 2017), nature-based solutions can contribute to addressing challenges of global relevance (Babí Almenar et al., 2021). In fact, nature-based solutions have been regarded within the EU Biodiversity Strategy for 2030 as a measure that should be systematically integrated in urban planning and design of buildings, calling for ambitious urban greening plans in EU municipalities over 20.000 inhabitants (European Commission, 2020). Similarly, the EU Climate Adaptation Strategy asserts that nature-based solutions would contribute to multiple EGD objectives, including the strengthening of climate change adaptation efforts (European Commission, 2021).

Within nature-based solutions, green roofs are considered solutions that, in combination with energy technologies, have the potential to contribute to EGD objectives. Green roofs are rooftops specifically designed to host vegetation, of various species, on their upper surface. They can enhance biodiversity and curtail habitat fragmentation, mitigate urban heat island effect, increase stormwater storage during extreme storm events, and improve urban air quality through the provision of regulating ecosystem services (Babí Almenar et al., 2021; Berardi et al., 2014).

When combined with solar photovoltaic (PV) panels, green roofs contribute to increasing their energy production capacity (Nash et al., 2016), thus developing a PV-green roof synergy that may uphold EGD objectives. Moreover, the combination of these technologies is suitable for urban areas, where energy demand is high and space for power generation technologies is limited (Sattler et al., 2020). In this sense, urban areas offer an ideal setting to unlock the potential benefits of combining PV panels with green roofs.

Despite their synergic benefits, green roofs have not been widely deployed in combination with energy technologies to date (Sattler et al., 2020; Shafique et al., 2020). However, the EU energy directives and regulations – published within the latest *Clean Energy for All Europeans package* – provide a hitherto untapped potential to embed green roofs into new forms of shared energy generation. Various legal models were defined in the package, such as Citizen Energy Communities, Renewable Energy Communities (RECs), Renewable Self-consumers, and Jointly Acting Renewable Self-consumers. These models respond to the growing number of collective energy initiatives in Europe involving citizens and other market actors in small-scale energy generation (Lowitzsch, 2019). Importantly, some of these legal models appear particularly prone to address the wider EGD objectives, which are also addressed by PV-green roofs. For instance, the primary purpose of RECs and Citizen Energy Communities is "*to provide environmental, economic or social community benefits for its shareholders or members or for the local areas where it operates, rather than financial profits*" (Directive 2018/2001 recast, art. 2 (18)). In addition, EU Member States are explicitly required to devise support schemes for RECs considering communities' "*specificities*" (Directive 2018/2001 recast), which could be represented by the combination between PV panels and green roofs. Thus, PV-green roofs could be successfully incorporated in a suitable legal model of energy communities.

Given that several EU Member States have not yet fully transposed all the latest EU Energy Directives, the REC definition, and REC's support schemes (Hinsch et al., 2021; Lowitzsch et al., 2020), an important policy window remains open. As Member States have to further specify EU legal models and support schemes, recommendations on how to adapt them become pivotal. Scholars have also explicitly called for research clarifying how (EU and national) regulatory conditions could support the development of various forms of energy communities (Blasch et al., 2021), and clarifying how energy communities' potential benefits could support EU climate and energy goals (Caramizaru and Uihlein, 2020).

This open policy window provides the opportunity to study whether energy communities based on the combination between green roofs and PV panels, hereafter photovoltaic-green roof energy communities (PGECs), can contribute to EGD objectives. Theoretically, PGECs can fulfil the primary purpose of RECs and Citizen Energy Communities as expected by Directive (2018/2001 recast) and represent a community specificity. Nevertheless, there is still a lack of knowledge on how a PGEC, as a form of energy community, would fit within the current EU legislation, and thus would benefit from the support schemes contemplated by the EU legislator. Additionally, there are no studies identifying links between PGECs' financial, economic, and socio-environmental benefits and the EGD objectives. Nor are there studies assessing the potential economic convenience of PGECs, which if not fulfilled could jeopardize their real contribution to EGD objectives. In fact, current studies assessing PV-green roofs (Chemisana and Lamnatou, 2014; Hui and Chan, 2011; Kim et al., 2021; Lamnatou and Chemisana, 2015; Schindler et al., 2018; Shafique et al., 2020) do not focus on determining whether PGECs are economically convenient. To harness the current policy window and address this gap, this paper aims at investigating whether and under which conditions PGECs are capable to meet EGD objectives in an economically convenient manner.

2. Methods

To fulfil the aim of this paper, a combined methodological workflow was deemed necessary. Such workflow is summarized in Fig. 1 and described below. First, a systematic review of the policy literature and one of academic literature relevant to PGECs were carried out (Section 2.1). The policy review helped delineate the suitable legal model for PGECs within the EU legislation and determine the links between PGECs' benefits and EGD objectives. The review of the academic literature was used to identify and quantitatively estimate all costs and benefits associated with PV panels and green roofs, considering implementation, operational, and end-of-life costs. Next, since PGECs' costs and benefits depend on context-specific factors, a case-study in Luxembourg was identified (Section 2.2). Subsequently, two probabilistic cost-benefit analyses were performed: at the social and private levels (Section 2.3). As input data for these cost-benefit analyses, the ranges of values for costs and benefits identified in the systematic academic literature review, and relevant for Luxembourg, were used. In this way, the economic convenience of PGECs from the point of view of society and of PGEC members was determined for the Luxembourg case study. Lastly, the social cost-benefit analysis was coupled with Scenario Discovery to identify the conditions in which PGECs are economically convenient. Through this combined methodology, both the suitable legislative and the economic conditions unlocking the economic convenience of PGECs are determined. The following sections describe in detail each of these methodological steps.

2.1. Double literature review: policy documents and cost-benefit analyses

A systematic policy literature review was carried out to identify all binding legal acts concerning RECs (Section 2.1.1). In this way, the most suitable legal model for PGECs was determined. Concurrently, another systematic review of peer-reviewed cost-benefit analyses was also performed to identify all the costs and benefits associated with PV-green roofs (Section 2.1.2). In doing so, an overview of costs and benefits of PV-green roofs as well as of their monetization was elicited.

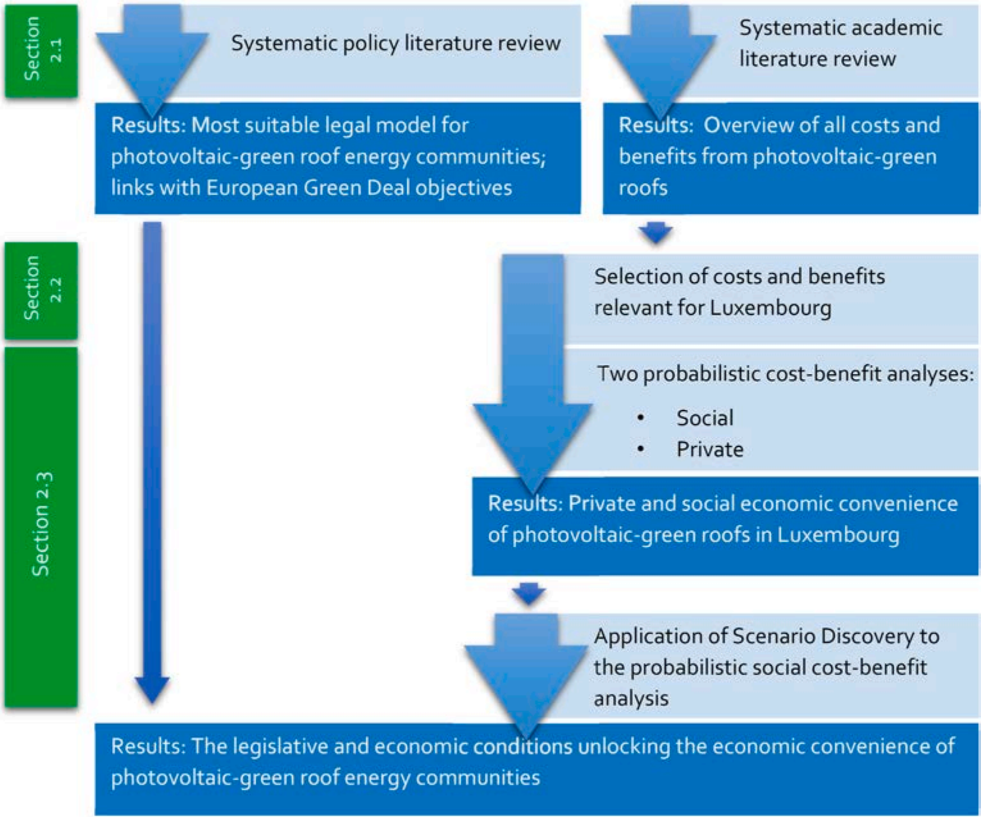

Fig. 1. Overview of methodological workflow of the paper.

2.1.1. *Systematic literature review of policy documents*

The policy literature review consists of two phases, which are summarized in Fig. 2. In the first phase, EU-level legislation concerned with RECs was reviewed using the EUR-Lex official gateway of EU law. Such portal provides access to all EU documents and it is updated daily (Publications Office of the European Union, 2021). In the second phase, two exemplary national legislations (Italy and Luxembourg) defining RECs were reviewed. The Italian case was reviewed since Italy provided one of the earliest national transpositions of EU laws related to RECs. Recent analyses showed that such legislation has possibly made the greatest progress in the transposition of these EU laws (Hinsch et al., 2021). The Luxembourgish case was reviewed for two reasons. First, to inform the case study of this research. Second, Luxembourg is currently defining its decarbonization strategy, and it carried out an international consultation to inform its spatial vision (further details at www.luxembourgintransition.lu). Thus, policy implications stemming from the study of PGECs can be particularly valuable to national policymakers.

The first phase of the review identified four binding legal acts relevant to RECs and currently in force:

- The Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources (recast) (RED II).
- The Regulation 2018/1999 on the Governance of the Energy Union and Climate Action.
- The Directive (EU) 2019/944 on common rules for the internal market for electricity and amending Directive 2012/27/EU.
- The Regulation (EU) 2019/942 establishing a European Union Agency for the Cooperation of Energy Regulators.

The documents were analyzed to (1) identify the legal models currently defined by the EU legislation for decentralized electricity generation, and (2) characterize each of these models, based on seven dimensions (i.e., eligibility, conditions on members, purpose, governance, activities, conditions on activities, and benefits) specified by the laws. This analysis helped determine which legal model best suits PGECs.

The second phase of the review surveyed the official databases of both Italian and Luxembourgish laws: the *Normattiva* Database and the *Journal officiel du Grand-Duché de Luxembourg* (The Official Gazette of the Grand Duchy of Luxembourg). Three Italian legal acts and one Luxembourgish law currently in force were identified:

- Legge 22 Aprile 2021, n. 162. Delega al Governo per il recepimento delle direttive europee e l'attuazione di altri atti dell'Unione europea - Legge di delegazione europea 2019–2020[1].
- Legge 17 Luglio 2020, n. 77 recante misure urgenti in materia di salute, sostegno al lavoro e all'economia, nonché di politiche sociali connesse all'emergenza epidemiologica da COVID-19[2].
- Legge 28 Febbraio 2020, n.8 recante disposizioni urgenti in materia di proroga di termini legislativi, di organizzazione delle pubbliche amministrazioni, nonché di innovazione tecnologica[3].
- Loi du 3 février 2021 modifiant la loi modifiée du 1er août 2007 relative à l'organisation du marché de l'électricité[4].

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[1] Unofficial English translation: Delegation to the Government for the transposition of European directives and implementation of other acts of the European Union - European Delegation Act 2019–2020.

[2] Unofficial English translation: Law 17 July 2020, n. 77 containing urgent measures in the field of health, support for work and the economy, as well as social policies related to the epidemiological emergency from COVID-19.

[3] Unofficial English translation: Law 28 February 2020, n.8 containing urgent provisions concerning the extension of legislative terms, the organization of public administrations, as well as technological innovation.

[4] Unofficial English translation: Law of February 3, 2021 amending the law of August 1, 2007 on the organization of the electricity market.

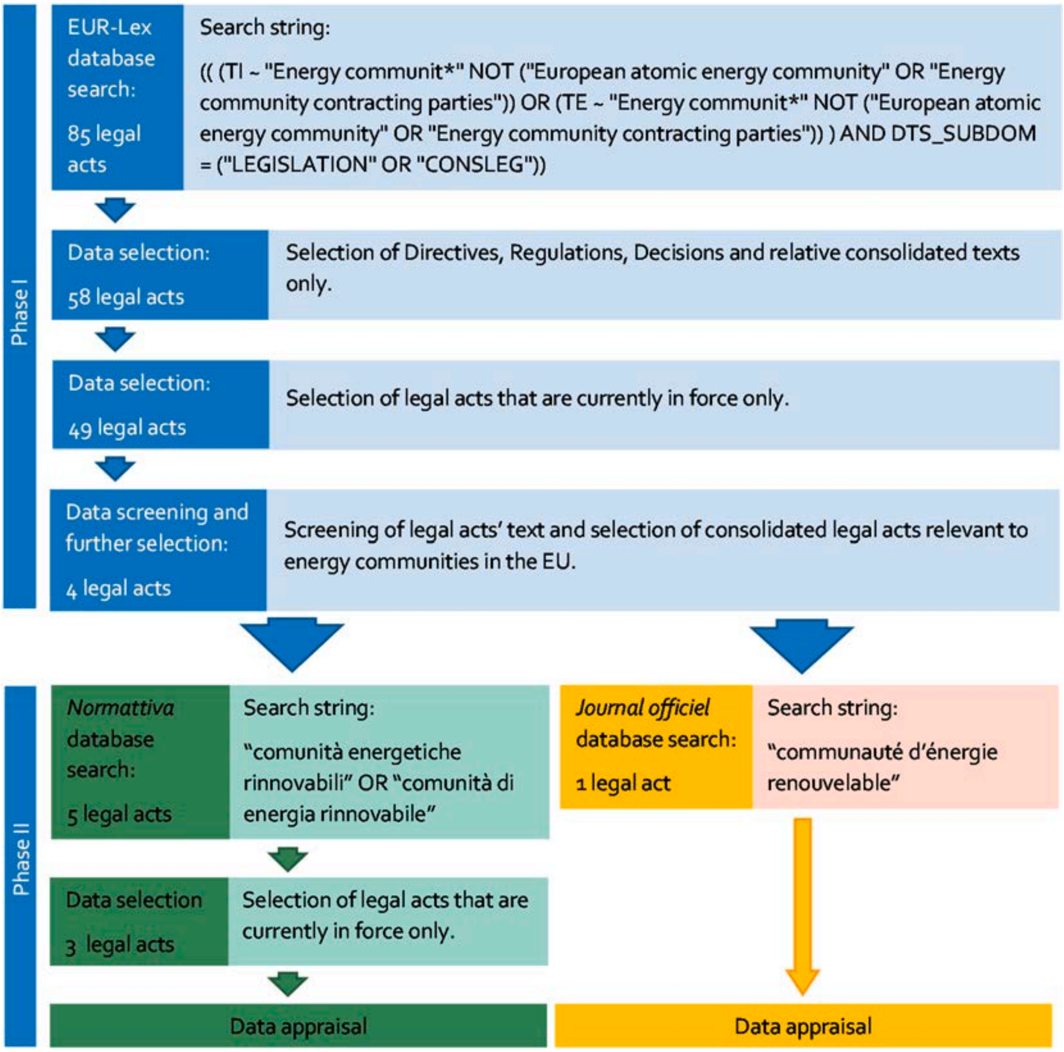

Fig. 2. Structure of the two-phase systematic literature review of legal acts concerning renewable energy communities. The first phase concerns EU-level legislation and is represented in blue, while the second phase concerns the Italian and Luxembourgish legislations. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

To gain further insight into the national transpositions of EU law, interviews with Luxembourgish government officials and an Italian industry expert on the implementation of RECs were carried out. Such interviews complemented the interpretation of the Italian and Luxembourgish laws. They also provided insights on potential contrasts with EU laws and elicited the opinion of policy and industry experts regarding potential barriers to be faced by PGECs.

2.1.2. Systematic literature review of cost-benefit analyses

The review of CBAs from peer-reviewed papers is composed of three phases, which are summarized in Fig. 3. First, CBAs conducted on green roofs were searched using the Scopus database. Second, additional articles quantifying the increase of PV panels' performance due to synergies with green roofs, PV installation and maintenance costs, as well as PV electricity generation benefits were also included to overcome the low number of CBAs quantifying these items. In this second phase, two recent reviews (Lugo-Laguna et al., 2021; Manso et al., 2021), as well as international reports were used. A complete list of the sources used is provided in Supplementary Material 1.

At the data appraisal stage, the physical features of the new and baseline roofs were recorded as presented in Table 1. These include the new technology and green roof type, the plant species used, the building type in which the technology was installed, its roof slope, and the baseline roof type, including its insulation properties. The new roof was associated with a series of costs and benefits which were also recorded with respect to a baseline. Lastly, the geographical, time, and climate features of each case study were recorded as well.

Studies were carried out in different years and locations, and therefore monetary values were adjusted to be comparable. According to unit value transfer methodology for nature-based solutions proposed by Petucco et al. (2018), the following steps were applied (equations presented in Table 2):

1. Correction for inflation from the year of the case study to 2020 values, using the Gross Domestic Product (GDP) deflator indexes provided by the World Bank (2021);
2. Conversion from the currency of the case study's country to European Union (EU27) euros, using the purchasing power parity exchange rates of the year 2020 (OECD, 2021a);
3. Correction for the difference in income between the original location and the European Union (EU27) when monetary values represented a willingness to pay. The income elasticity of willingness to pay was considered to be unitary (Tyllianakis and Skuras, 2016; Petucco et al., 2018). Two main types of baseline situations were considered by the literature reviewed: (1) the implementation of a bare roof (i.e., either a conventional black, gravel, or white roof), or (2) a situation

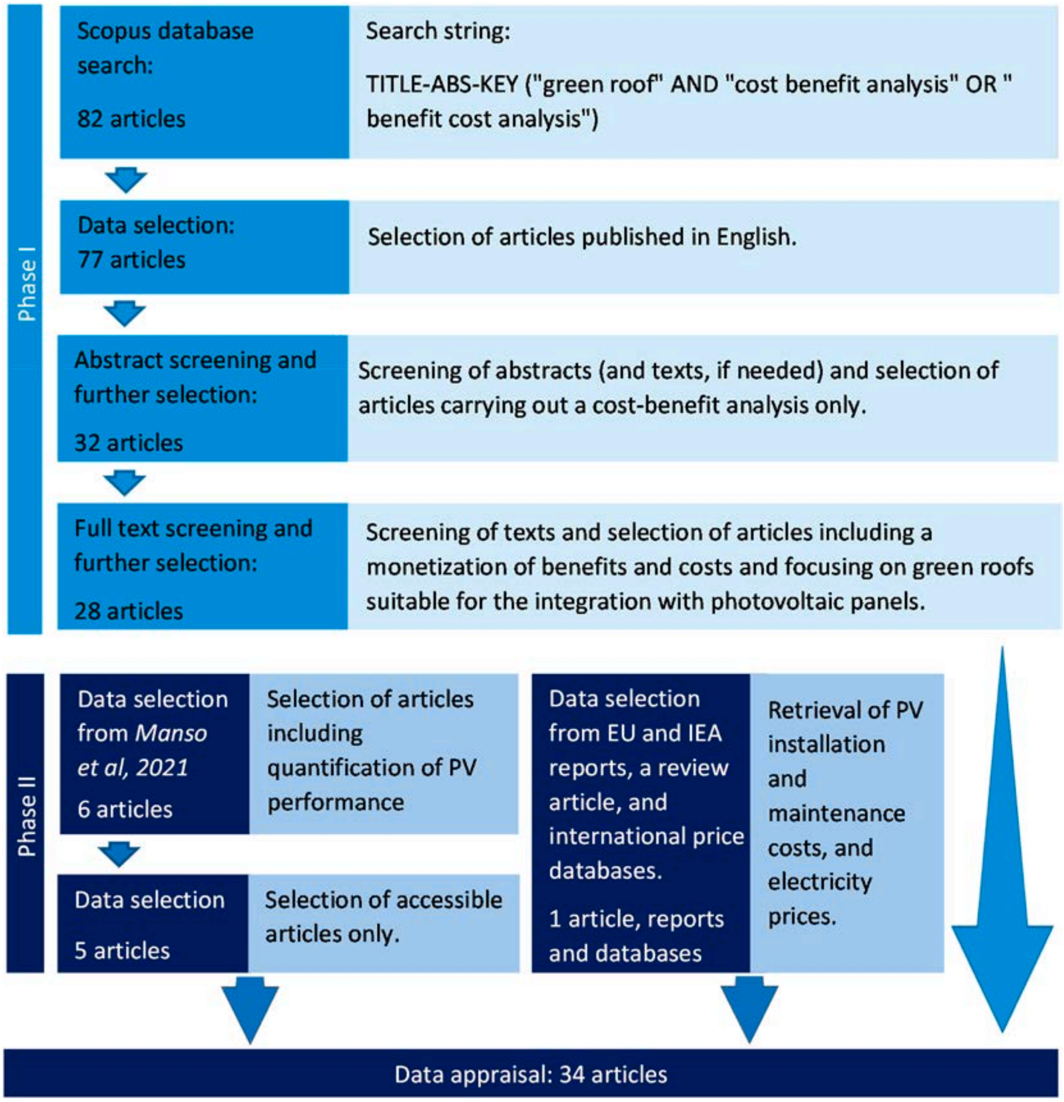

Fig. 3. Structure of the two-phase systematic literature review of academic articles concerning green roofs and PV green roofs. The first phase focuses on cost-benefit analyses, while the second one integrates studies focused on photovoltaic panels' costs and power output increase benefits, due to green roofs underneath. IEA: International Energy Agency. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

in which the roof is already installed, thus no bare roof is implemented.

The literature review results were clustered in two groups:

a) a global analysis of results, utilizing all reviewed studies, whereby all baseline roofs (i.e., black, gravel, and white roofs) were considered.
b) a local analysis of results, only considering data from studies in equivalent conditions to this paper's case study (Luxembourg). For this purpose, only the black roof was used as the baseline roof and only studies carried out in EU context and temperate oceanic climate were considered.

As for the PV costs and electricity generation benefit, these were recorded for a PGEC equivalent in size and total installed power to the Luxembourgish case study.

In the following section the details of this paper's case study are provided.

2.2. *Case study: PGEC in Quartier Alzette, Esch-sur Alzette (Luxembourg)*

Quartier Alzette of Esch-sur-Alzette (Luxembourg) is used as the specific case study for this research. Luxembourg was selected as it is one of the EU countries with tangible advances on the transposition of Directive (EU) 2018/2001 into national law (Loi du 3 février 2021). Additionally, its urban areas, ideal settings for PGECs, are expected to continue increasing, making the outputs relevant also to current Luxembourgish urban development policies in relation to the RED II and EGD.

Specifically, the Alzette neighborhood is an ex-industrial area of steelworks located in the municipalities of Esch-sur-Alzette and Schifflange (Fig. 4a). Recently, it became the subject of an urban redevelopment project (Fig. 4b), which won a conceptual urban design competition promoted by the Government of the Grand-Duchy of Luxembourg (AGORA, 2019). Although being location-specific, Quartier Alzette represents a good example of the typical urban regeneration that could occur in many of the industrial brownfields of the south of the country, as well as in many other places worldwide. In fact, several decarbonization spatial visions proposed in the international

Table 1
Overview of features recorded during the literature review.

	Recorded Feature	Feature values
New technology features	New roof	Green roof, PV-Green roof
	New roof's lifetime	Numerical value (whole number)
	If roof is green roof or PV-green roof:	
	Green roof type	Extensive, semi-intensive
	Plant species	Sedum, Dianthus, Gazania, Xeric, Koelieria Macarantha, Moss, Grass lawn, or Gramineous.
	Consideration of plants' irrigation	Yes, No, or Not mentioned
	If roof is PV-green roof:	
	PV panel type	Monocristalline, Polycristalline, Monocristalline silicon, Polycristalline silicon, or not specified.
	Location of PV panels on green roof	Same location, or Different locations
	Distance PV panels - green roof	Numerical value (whole number)
	Distance PV panels – baseline roof	Numerical value (whole number)
Cost/Benefit features	Item	Various
	Effect	Cost, or Benefit
	Spatial scale[a]	Building, Community-wide, Urban societal
	Type[a]	Economic, Financial, Socio-environmental
	Monetary value (with time and currency)	Numerical value (whole number)
	Year at which item is accounted	Year, or year range
	Method for monetary valuation	Avoided cost, Contingent valuation, Hedonic pricing, Market value, or Replacement cost
Baseline features	Baseline roof	Black roof, Gravel roof, White roof, PV-Black roof, PV-Gravel roof, or PV-White roof
	Building type	Commercial, Residential, Office, Industrial, School, Transport, or Mixed
	Presence of insulation layer	Insulated, or Non-insulated
	Roof slope	Flat, or Slanted
Case study features	Continent	Europe, Asia, North America, or South America
	Country	Names
	City	Names
	Climate	One of the Koppen-Geiger climate classes.
	Season	Summer, or Annual average
Article features	Authors	Names
	Article year	Publication year
	Title	Various
	Study type	Cost-Benefit Analysis, or Photovoltaic performance analysis

[a] Details on the classifications used in the spatial scale and type can be found in Supplementary Material 2.

consultation of Luxembourg in Transition prioritize this kind of urban regeneration to absorb future population growth. Based on the award-winning masterplan, all buildings were classified according to the national Land Use Land Cover Classification (Fig. 4c), and only those buildings and rooftop areas that are suitable for a PGEC were selected (Fig. 4d).

Buildings shaded by others and roof edges were considered unsuitable. The necessary space between PV panels to avoid mutual shading at this latitude was also considered. As a result, the eligible rooftop area for PV-green roofs was estimated to be ca. 160,000 m^2.

In the next section, two probabilistic CBAs are described. As inputs, only costs and benefits from the literature review that were previously used in socio-economic and climatic contexts equivalent to the Luxembourg case study were used.

Table 2
Equations used for unit value transfer.

Variable adjusted	Equation	Equation's variables
Price level	$v' = v \bullet \left(\frac{D'}{D}\right)$	v': Monetary value adjusted to the policy site. v: Monetary value of the original case study's site. D': GDP deflator index for the year of the policy site assessment. D: GDP deflator index for the year of the original case study's assessment.
Purchasing power and currency	$v' = E \bullet v$	v': Monetary value adjusted to the policy site. v: Monetary value of the original case study's site. E: Purchasing power parity-adjusted exchange rate between policy and original case study's site currencies.
Income	$WTP' = WTP \bullet \left(\frac{Y'}{Y}\right)^{\varepsilon}$	WTP': Willingness to pay adjusted to the policy site. WTP: Willingness to pay of the original case study's site. Y': Per capita income of the policy site. Y: Per capita income of the original case study's site. ε: Income elasticity of the willingness to pay.

2.3. *Social and private economic convenience of PGECs*

From the literature review of section 2.1, only costs and benefits elicited from papers focusing on socio-economic and climatic conditions equivalent to Luxembourg were selected. Such values are used as inputs to a social and private cost-benefit analyses of PV-green roofs. In this section, the way in which the cost-benefit analyses were performed is described in detail. First the social cost-benefit analysis is illustrated (Section 2.3.1), followed by an explanation of its coupling with the Scenario Discovery technique (Section 2.3.2). Next, the private cost-benefit analysis is explained (Section 2.3.3).

2.3.1. *Probabilistic social cost-benefit analysis*

The economic convenience of PV-green roofs was studied from a societal perspective by means of a probabilistic social cost-benefit analysis. The *social* attribute means that both private benefits and costs (i.e., direct tangible money flows to/from PGEC members) and non-private ones were considered. The CBA was tailored to the Luxembourgish case study and thus focused on costs and benefits of roofs installed in socio-economic and environmental conditions equivalent to Luxembourgish ones, i.e., EU context in a temperate oceanic climate class (Cfb). As a result, only costs and benefits retrieved from the *local analysis of results* described in Section 2.1.2 are used.

The analysis was performed in a *probabilistic* fashion to embrace the variety of cost and benefit values that were elicited from the academic literature reviewed. In fact, scientific knowledge represented by the published CBA results has become subject to debate (Vijayaraghavan, 2016), whereby studies can be found contradicting one another (see for instance, Jim and Tsang, 2011; Santamouris et al., 2007; Zhao and Srebric, 2012). Such a context of uncertainty and disagreement over cost and benefit values in CBAs has traditionally been dealt with probabilistic CBAs (Nassar and Al-Mohaisen, 2006). According to such method, input variables can take a range of values instead of corresponding to a single value. As a result, multiple net present values are obtained from the probabilistic CBA, each of which with a different probability.

2.3.2. *Scenario discovery*

In this paper, in addition to running a conventional probabilistic

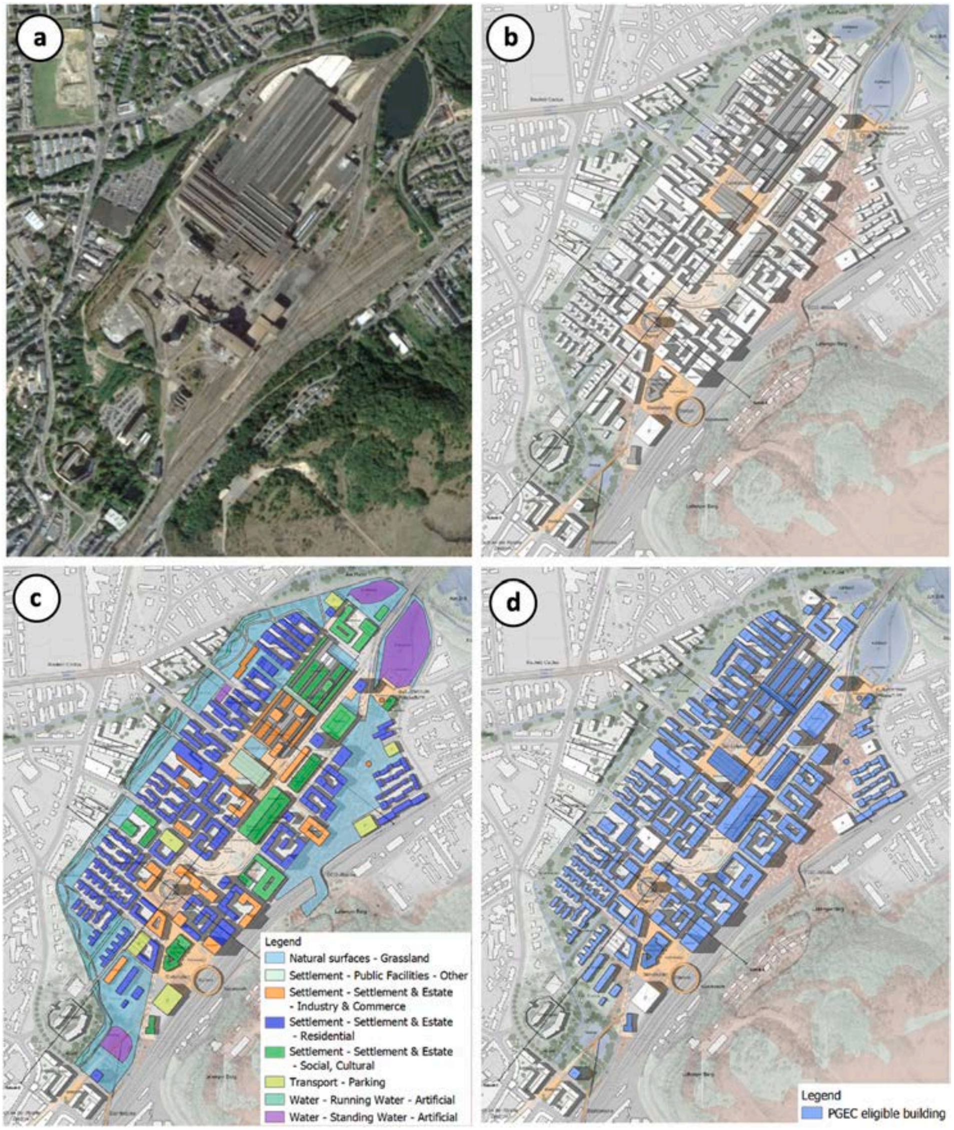

Fig. 4. Aerial view of Quartier Alzette: (a) Current state of the district, (b) winning project for the urban district renovation, (c) classification of buildings according to the national Land Use Land Cover Classification, (d) suitable rooftops for PGECs.

social CBA, the CBA was also coupled with the Scenario Discovery technique (Kwakkel, 2017). Such coupling of methods allowed to identify the conditions for which PV-green roofs are economically convenient for society. Namely, it allowed to determine the ranges of input cost and benefit values which result in a positive net present value.

To couple the two methods, the probabilistic social CBA was structured using the XLRM framework by Lempert (2003). According to this framework, the variables describing the relevant characteristics of the system at hand can be classified either as *uncertainties* (X) or *levers* (L). While the former cannot be directly controlled by the problem owner, direct control can be exerted on the latter. The *relations* (R) between uncertainties, and, if present, levers are represented by a function f that associates uncertainties and levers with a set of *performance metrics* (M). These metrics quantitatively denote the system's outcomes of interest.

In this work, cost, benefit, and discount rate variables represented uncertainties. The values of these variables varied within the ranges defined in the literature found in the CBA review described in Section 2.1.2. The relation R between the cost, benefit, and discount rate variables is expressed by Eqn 1. Such equation also defined the model's performance metric M as the net present value (NPV) of PV-green roofs.

Eqn 1. Analytical formulation of the social CBA model. Several cost variables $(\boldsymbol{c_1},\ldots,\boldsymbol{c_m})$ and benefit variables $(\boldsymbol{b_1},\ldots,\boldsymbol{b_n})$ exist, and they are accounted for each year $\boldsymbol{t}$ within the project's lifetime $\boldsymbol{T}$. Each benefit $\boldsymbol{b_i}$ and cost $\boldsymbol{c_j}$ is a variable, which can take several values within those identified in the reviewed literature. The algebraic sum of cost and benefit variables is discounted by means of the social discount rate variable $\boldsymbol{r}$.

$$NPV = f(b_1,\ldots,b_n,c_1,\ldots,c_m,r,t) =$$

$$= \sum_{t=0}^{T} \frac{b_{1,t}+\ldots+b_{n,t}-(c_{1,t}+\ldots+c_{m,t})}{(1+r)^t}$$

The time variable t represented the various accounting years between 0 and the social CBA's time horizon. For simplicity, only one CBA time horizon of 40 years was considered, which equals the average service life of green roofs (Sproul et al., 2014).

As it can be noticed in Eqn. 1, the social CBA is a vectorial function f that maps multiple uncertainties $x_1,\ldots,x_n$ (namely cost variables such as the green roofs' installation cost, benefit variables such as energy consumption reduction, and the discount rate variable) to a specific performance metric m (i.e., the NPV).

The range of possible values for each uncertainty x_i was defined by looking at the distribution observed in the literature for that cost, or that benefit, or of the social discount rate. In particular, boxplots for each distribution were obtained and the relative upper and lower whiskers defined the range of possible values for each uncertainty x_i. This means that outliers recorded through the literature review were excluded, considering the central parts of distributions instead. When considered together, the ranges of possible values defined for each uncertainty composed the *uncertainty space X*.

The probabilistic social CBA can be intended as a model of the system of interest and not only as a vectorial function. To run the social CBA model, the function f was implemented in Python (the complete code is available in Supplementary Material 4). To obtain multiple NPVs, the social CBA model had to be computed multiple times. Each of the NPVs was derived from a specific set of values sampled from the uncertainty space X. The set of all uncertainty values sampled together for one model run generating one NPV is called a *scenario*.

Sampling was performed using the Latin Hypercube method, which assumes a uniform distribution for each of the uncertainties' range and divides such range into bins. The bins were widened in such a way to have the same probability to be drawn from. Next, for each bin, the algorithm sampled an uncertainty value. It is worth noting that by using this method low computational power was used compared to other sampling methods, such as full factorial sampling, while attempting to cover all the range at hand.

The social CBA model was simulated 100.000 times using the Exploratory Modelling and Analysis Workbench by Kwakkel (2017) producing one NPV value for each simulation. This means that 100.000 scenarios were identified, and the same number of NPV values were obtained. Each simulation run used a different set of values as inputs to the social CBA, generating one NPV that corresponded to a different valuation of costs, benefits and/or choice of discount rate. A schematic representation of the social CBA model simulation is provided in Fig. 5.

Once the 100.000 NPVs $(m_1, \ldots, m_{100.000})$ were obtained from repeated simulations, Scenario Discovery (Kwakkel, 2017) was performed. This is a method aimed at finding the subspace of the whole uncertainty space X that maps each scenario to a range of NPVs of interest. In the case of this research, NPVs of interest were defined as all the positive NPVs. These are the *desired* NPVs and together they define the desired area of the codomain of f. Finding the subspace of the uncertainty space X leading to desired outcomes means finding the conditions for which the PV-green roofs studied bring higher benefits than costs over their whole life-cycle.

The Patient Rule Induction Method, as defined by Friedman & Fisher (Friedman and Fisher, 1999) was used to perform Scenario Discovery. It iteratively calculates at each step a subspace of the initial uncertainty space, trying to maximize the *coverage* (the fraction of scenarios of interest falling within the new selected subspace, out of all sampled scenarios of interest available) and the *density* (the fraction of scenarios of interest out of all scenarios in the selected subspace). The objective of peeling the original uncertainty space into smaller subspaces is to find a subspace with enough scenarios leading to a desired outcome (a positive NPV), but still covering a significant number of scenarios of interest out of all the sampled ones.

2.3.3. Probabilistic private cost-benefit analysis

A positive social CBA indicates that society obtains positive net benefits from the installation of PV-green roofs. Yet, potential PGEC members would not purchase PV-green roofs and would not create an energy community if PV-green roofs were not economically convenient from their point of view. In such case, an incentive would become necessary to make PV-green roofs economically attractive and let society reap the associated net positive social benefits. To this end, a probabilistic private CBA was performed to determine whether potential PGEC members would purchase PV-green roofs and form a PGEC in the case incentives were not made available.

In the case PV-green roofs were not economically convenient, the private CBA would help estimate the amount of the necessary incentive. The minimum incentive would be the amount returning a non-negative private NPV, i.e., private benefits at least as high as private costs (Eqn. 2 and 3).

Eqn. 2 and 3. Estimate of the incentive that makes PV-green roofs economically convenient from the perspective of PGEC members. b^p denotes private benefits, c^p private costs, and r^p the private discount rate, t each year of project's lifetime, and T the entire project's lifetime.

$$\sum_{t=0}^{T}\frac{b^p_{1,t}+\ldots+b^p_{n,t}-\left(c^p_{1,t}+\ldots+c^p_{m,t}\right)}{\left(1+r^p\right)^t}+Incentive=0$$

Such that:

$$Incentive=-\sum_{t=0}^{T}\frac{b^p_{1,t}+\ldots+b^p_{n,t}-\left(c^p_{1,t}+\ldots+c^p_{m,t}\right)}{\left(1+r^p\right)^t}$$

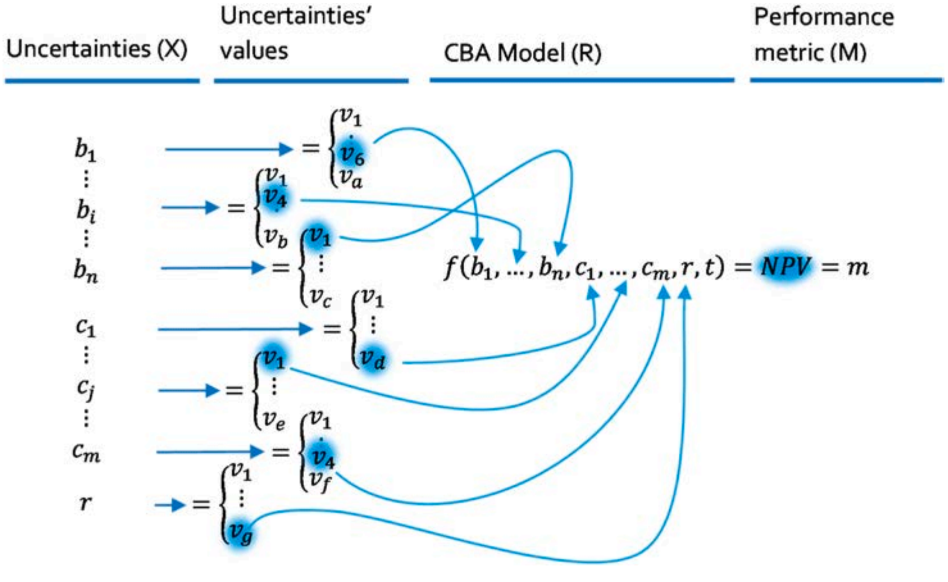

Fig. 5. Simulation run of the social CBA model. Each simulation of the model produced a single NPV value, generated by a specific set of uncertainty values. Graphically, the uncertainties' values and the performance metric's value belonging to the same simulation run are highlighted in blue. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3. Results

3.1. Review of policy documents: the suitable legal model for PGECs

The review of EU legal acts shows the existence of four different decentralized energy generation legal models: RECs, Renewable self-consumers, Joint Renewable self-consumers, and Citizen Energy Communities. They are summarized in Table 3 according to the seven dimensions anticipated in Section 2.1.1.

RECs seem to be the most suitable model for PGECs because of: (i) the primary purpose of RECs, and (ii) the benefits entailed by the legal model of RECs.

First, the RED II establishes a primary purpose for RECs that captures the potential community benefits provided by PV-green roofs. Indeed, green roofs provide a variety of socio-environmental benefits, such as lower energy bills due to an improved performance of PV modules, brought only to the community's members in the proximity of the roofs. Additionally, a considerable array of other socio-environmental benefits, such as improved management of stormwater runoff, concerns a wider group of citizens not limited to the community members. More details on community-specific and socio-environmental benefits are provided in Section 3.2.

Second, PGECs suit the REC's legal model because of the benefits that RECs are legally entitled to in Member States, which could make PGECs more economically convenient for individuals. For example, Member States are required to facilitate RECs' access to finance, information, and relevant training, which is often needed by energy community members in energy matters (Hannoset et al., 2019). As another example, regulatory and capacity-building support has also to be granted to public authorities participating and setting up RECs. This can be particularly beneficial for PGECs, since local authorities have already demonstrated to address various difficulties of energy communities (Meister et al., 2020). Finally, the RED II also establishes that support schemes for the promotion of RECs shall consider their specificities. In the case of PGECs, the combination of photovoltaic panels with green roofs may well represent such a specificity.

Regarding Italian and Luxembourgish transpositions of RECs, key commonalities and differences arise. Both countries adopt the same primary purpose for RECs, as defined by the RED II (Loi du 3 février 2021; Legge 28 febbraio 2020). The REC activities specified by the Luxembourgish law match those of the EU law, but Italy, aside from electricity sharing, production, and consumption does not define other REC activities (RSE, 2020).

Regarding eligibility and conditions on members or shareholders, both countries reflect the RED II provisions only to some extent. Both specify the proximity condition in the same way, and eligible members or shareholders are natural persons, small and medium enterprises, or local authorities, as stated in RED II (Loi du 3 février 2021; Legge 28 febbraio 2020). However, the Italian law allows participation only if it is not a primary commercial or industrial activity for the participant. Conversely, the Luxembourgish law does not pose such constraint. As for the governance, both legislations entitle the community to own the power generating installations while allowing a third party to develop and execute the electricity sharing model within the community (Loi du 3 février 2021; Legge 28 febbraio 2020).

The major differences arise in the benefits granted to RECs. The

Table 3
Overview of energy community initiatives specified in EU policies (columns). Defining attributes are displayed in bold, non-defining but characteristic attributes in normal text.

	Renewable energy community (REC)	Citizen energy community	Renewable self-consumer	Jointly-acting renewable self-consumers
Eligibility	**Natural persons, small and medium enterprises, or local authorities**	All categories of entities	**Final customer**	**≥ 2 Renewable self-consumers**
Conditions on members/ shareholders	• Open and voluntary participation • Be located in projects' proximity • For private undertakings: participation ≠ primary commercial or professional activity	**Open and voluntary participation**	**Operate within Renewable self-consumer's own premises, for its own consumption**	**Be located in the same building/multi-apartment block**
Purpose	**To provide environmental, economic or social community benefits for its shareholders or members or for the local areas where it operates, rather than financial profits**		-	-
Governance	• **REC effectively controlled by members/shareholders in projects' proximity** • **REC is autonomous** • Projects owned and developed by REC	• **Citizen Energy Communities effectively controlled by natural persons, small enterprises, or local authorities** • Decision-making powers limited to members not in large-scale commercial energy activities	Installations may be owned/managed by third party, under Renewable self-consumer's instructions	
Activities	Generation, storage, consumption, sharing within the REC, and sale	• **Generation, distribution, supply, consumption, aggregation, energy storage, energy efficiency services, charging services for electric vehicles, or other energy services to members/shareholders** • Sharing within the Citizen Energy Communities • Ownership/establishment/purchase/lease of distribution networks	• **Generation, storage, consumption, and sale** • Sharing	Renewable self-consumer actions
Conditions on activities	-	-	**For non-household Renewable self-consumers: activities ≠ Renewable self-consumers' primary commercial or professional activity**	
Benefits	• Removal of barriers to RECs • Facilitation of access to finance, information, and training • Support schemes considering RECs' specificities	• removal of barriers to operate	• Removal of barriers to self-consumption • Facilitation of access to finance • Incentives to building-owners	

Italian legislation promotes RECs with two economic incentives: 110€/MWh for 20 years (MiSE incentive) and 8 €/MWh on the electricity shared within the community (ARERA incentive) (RSE, 2020; Legge 28 febbraio 2020). It also allows to sell electricity generated at the hourly zonal price (RSE, 2020). Aside from monetary incentives, Italy foresees an enabling framework facilitating access to all regulatory support schemes (Legge 22 Aprile 2021). Differently, Luxembourg does not provide specific incentives (economic or not) for the promotion of RECs.

3.2. *Review of the academic literature: the costs and benefits of PGECs*

33 articles were analyzed in depth: 28 CBAs and 5 analyses of PV performance, whereby the oldest one dates to 2008. The complete list of articles is provided in Supplementary Material 1.

Regarding geographical focus, most articles include one or more location-specific case-analyses, totaling to 43, spanning across four continents and 15 countries (Fig. 6a). Only one analysis (Bianchini and Hewage, 2012) does not have a specific geographical focus. Most case-analyses are based in Europe (20), while as a country, the United States features most of the case-analyses (15). The case-analyses belong to nine different climate classes (Fig. 6b). The most represented ones are two temperate climates: the humid subtropical climate (Cfa), followed by the hot-summer Mediterranean climate (Csa). Only five case-studies take place in EU context and temperate oceanic climate (Fig. 6c and d).

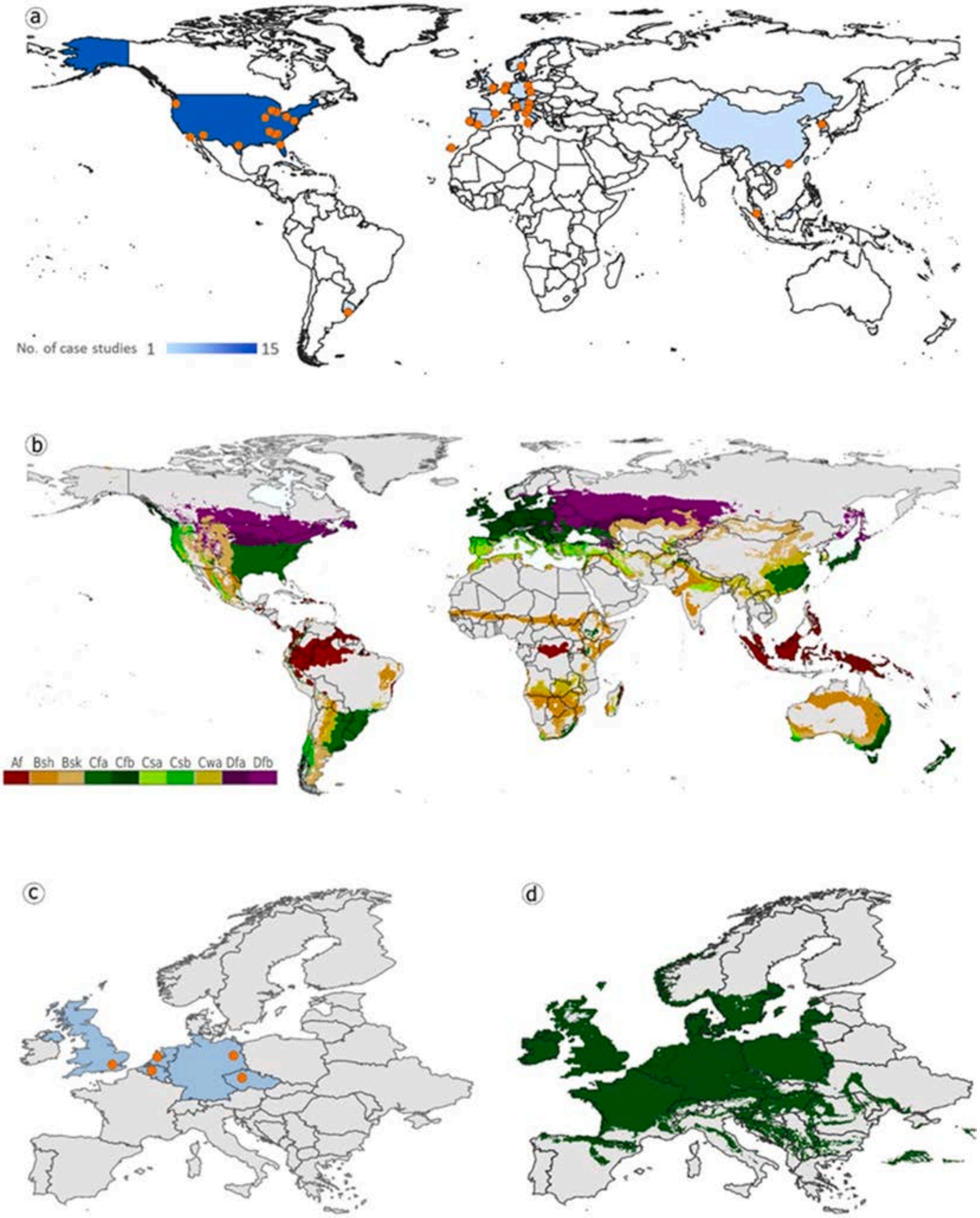

Fig. 6. Geographical distribution of case studies examined in the review and their climate classes. (a) Case studies and countries included in the global analysis; (b) geographical spread of climate classes represented by the case studies belonging to the global analysis; (c) case studies and countries included in the local analysis; (d) geographical spread of the Luxembourgish case-study's climate class (Cfb). Af: Tropical rainforest; Bsh: Hot semi-arid (steppe); BSk: Cold semi-arid (steppe); Cfa: Humid subtropical; Cfb: Temperate ocenaic; Csa: Hot-summer Mediterranean; Csb: Warm-summer Mediterranean; Cwa: Monsoon-influenced humid subtropical; Dfa: Hot-summer humid continental; Dfb: Warm-summer humid continental.

Table 4

Overview of all costs and benefits recorded from the literature review, Global analysis' values are in normal text, while local analysis' values are displayed in **bold**.

Item	Effect	Spatial scale	Type	Minimum (excluding outliers)		Median		Maximum (excluding outliers)		Unit
Energy consumption reduction (heating & cooling)	Benefit	Building	Financial	−0.38*	**0.08**	0.85	**0.39**	7.31	**0.6**	€/(year • m^2)
Fire risk reduction (insurance discount)	Benefit	Building	Financial	0.00	**0.00**	0.07	**0.00**	0.11	**0.00**	€/(year • m^2)
Longevity increase	Benefit	Building	Financial	0.83	**0.83**	2.31	**2.31**	9.36	**5.73**	€/(year • m^2)
Sound insulation	Benefit	Building	Economic	0.28	**0.28**	2.02	**0.30**	36.17	**0.64**	€/(year • m^2)
Electricity generation	Benefit	Community-wide	Financial	2.46	**2.46**	11.10	**5.44**	27.78	**7.91**	€/(year • m^2)
Aesthetics increase	Benefit	Community-wide	Economic	1.97	**0.00**	75.54	**164.17**	154.8	**328.34**	€
Air quality enhancement	Benefit	Community-wide	Socio-environmental	0.01	**0.01**	0.38	**0.20**	1.48	**0.50**	€/(year • m^2)
Urban noise reduction	Benefit	Community-wide	Socio-environmental	1.70	**-**	2.00	**-**	2.30	**-**	€/(year • m^2)
Urban heat island effect mitigation	Benefit	Community-wide	Socio-environmental	0.00	**0.00**	0.38	**0.00**	7.72	**0.00**	€/(year • m^2)
Biodiversity enhancement	Benefit	Urban	Socio-environmental	0.00	**0.15**	0.01	**0.15**	0.19	**0.15**	€/(year • m^2)
Stormwater management	Benefit	Urban	Socio-environmental	0.00	**0.10**	0.08	**0.72**	1.47	**2.68**	€/(year • m^2)
Water runoff quality increase	Benefit	Urban	Socio-environmental	0.00	**0.29**	0.30	**0.31**	0.32	**0.32**	€/(year • m^2)
CO$_2$ uptake	Benefit	Societal	Socio-environmental	0.00	**0.003**	0.00	**0.003**	0.04	**0.003**	€/(year • m^2)
CO$_2$ emission reduction	Benefit	Societal	Socio-environmental	−0.03*	**0.02**	0.13	**0.03**	0.61	**0.08**	€/(year • m^2)
Installation of green roof	Cost	Community-wide	Financial	18.61	**18.61**	70.42	**87.03**	119.67	**119.67**	€
Maintenance of green roof	Cost	Community-wide	Financial	−0.89*	**0.04**	0.88	**0.47**	2.83	**1.09**	€/(year • m^2)
Replacement and disposal of green roof	Cost	Community-wide	Financial	19.77	**-**	30.14	**-**	103.86	**-**	€
Installation of PV panels (>1 MW)	Cost	Community-wide	Financial	8.97	**8.97**	60.96	**14.83**	104.7	**23.43**	€
Installation of PV panels (≤10 kW)	Cost	Community-wide	Financial	25.38	**25.38**	125.26	**30.31**	209.39	**35.25**	€
Maintenance of PV panels (>1 MW)	Cost	Community-wide	Financial	0.18	**0.18**	0.83	**0.30**	1.92	**0.47**	€/(year • m^2)
Maintenance of PV panels (≤10 kW)	Cost	Community-wide	Financial	0.51	**0.51**	2.51	**0.61**	4.19	**0.70**	€/(year • m^2)
Air pollution from green roof production	Cost	Urban**	Socio-environmental	2.12	**-**	9.34		15.69	**-**	€
CO$_2$ emission from green roof production	Cost	Societal	Socio-environmental	2.12	**-**	9.34	–	14.74	**-**	€

(*) Negative benefit values represent an economic convenience of the baseline roof compared to the green roof (among the baseline roofs considered in the global analysis, the one associated to such negative values is the white roof only); Negative cost values represent an economic convenience of the green roof compared to the baseline roof, such negative costs were recorded when the baseline roof was a white roof. (**) Air pollutant emissions due to the production of green roof affect the urban areas where the green roof is manufactured, which may not coincide with the urban area where the green roof is installed. Note: The benefit from the increase in buildings' aesthetics showcases a maximum of 328.34 € in the local analysis. Since this value is an outlier when considering all values recorded in the global analysis, the maximum in the global analysis is 164.17 €. Nevertheless, as observed in Section 4.3, this value is realistic for the local case study of this research.

The most frequent time horizon is 40 years, which is the average service life of green roofs (Sproul et al., 2014). The social discount rate used ranges from 2% to 8%, being 4.13% the average value.

Costs and benefits (items) identified (quantified or only mentioned) are provided in Table 4 differentiated by spatial scale and type. As described in Section 2.1.2, the literature review results are organized in a global and local analysis of results. The *global analysis* utilizes all reviewed articles from all regions of the world, whereby all baseline roofs (i.e., black, gravel, and white roofs) are considered. The *local analysis* only considers data from studies in equivalent conditions to the Luxembourgish case study. Namely, in the local analysis only the black roof was used as the baseline roof, since it is considered the most common type of roof, and only studies carried out in EU context and temperate oceanic climate were considered.

Detailed characterization of the different items and distinctions between interrelated ones (e.g., CO_2 uptake and CO_2 emission reduction) is provided in Supplementary Material 3.

As presented in Table 4, costs for installation of green roofs and PV panels are the highest ones globally. The former has a median value of 70 €/m^2. The latter's median equals 61 €/m^2 if the PGEC has an overall installed power capacity higher than 1 MW. This cost increases to 125 €/m^2 for communities installing only up to 10 kW. Globally, the highest yearly benefits recorded are the aesthetics increase and electricity generation, with median values of 76 €/m^2/year and 11 €/m^2/year, respectively. When considering the Luxembourg-specific local analysis, aesthetics increase and electricity generation benefits are the highest. Both in the global and, to a more limited extent, in the local analysis, cost and benefit values exhibit a variability that is generated by multiple causes which are discussed in Section 4.

3.3. Photovoltaic-green roofs contribute to meeting the European green Deal objectives

The CBAs reviewed also clarify the relationship between benefits from PV-green roofs and the EGD objectives. Such relationship is displayed by means of a causal map in Fig. 7. Following causal maps' diagrammatic conventions (Enserink et al., 2010) two *means* (i.e., actions) can be identified: the installation of PV panels, and of green roofs. Nine *ends* are depicted in dark and light green. These are the benefits of the *means*, as documented by the outputs of the CBA review. Dark green boxes refer to EGD objectives: they are not directly so but each of them represents a part of such objectives. Each of the *means* is connected to the ends via *causal factors* (if relevant), and each of the causal links is either positive or negative. A positive relationship from A to B signifies that an increase in A leads to an increase in B, while a negative relationship implies the opposite: an increase in A causes a decrease in B, holding all other factors constant.

3.4. Economic convenience of PGECs in Luxembourg: cost-benefit analyses and scenario discovery results

The probability distribution of NPV values obtained from the probabilistic social and private CBAs are visualized in Fig. 8. NPVs obtained from the probabilistic *social* CBA range from −80 €/m^2 to 636 €/m^2, with a median value of 250 €/m^2. This means that across different social valuations of PV-green roofs (i.e., including different values for social costs, benefits, and discount rates) NPVs can be valued as low as −80 €/m^2, or up to 636 €/m^2, within the cost, benefit, and discount rate value ranges found in the literature. In general, there is a probability of 99% to have a positive NPV for PV-green roofs in Luxembourg, when considering the ranges of social costs, benefits, and social discount rates found in the local analysis' literature review.

As far as the probabilistic *private* CBA results are concerned, PV-green roofs are economically convenient from the perspective of potential PGEC members in 62% of the cases. When investors only look at private costs and benefits, NPVs range from −132 to 230 €/m^2, with a median value of 16 €/m^2. Thus, incentives to make PV-green roofs economically convenient from the private perspective should range between 0 and 132 €/m^2. For instance, with the average incentive for green roofs in Benelux, i.e., 26 €/m^2 (Liberalesso et al., 2020), PV-green roofs become economically convenient in 81% of the cases from the private perspective. With a hypothetical incentive of 85 €/m^2, PV-green roofs would become a convenient investment in 99% of the cases. Namely, they would become convenient according to 99% of valuations of costs, benefits, and private discount rates within the ranges defined by the literature.

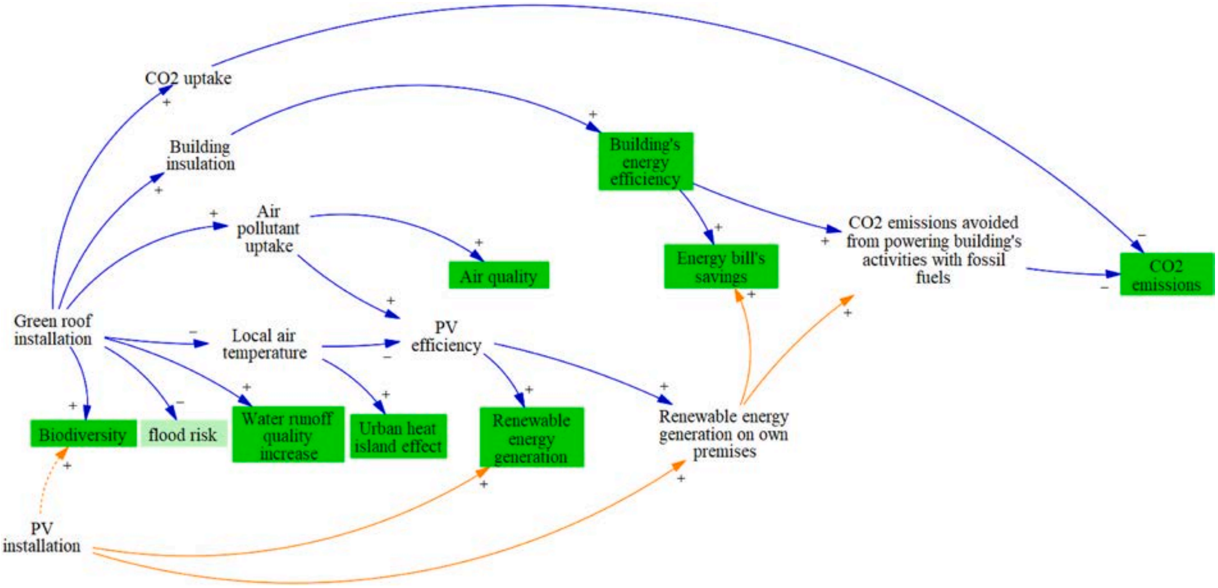

Fig. 7. Highly aggregated causal map displaying the relationship between photovoltaic-green roofs and EGD objectives. Each node represents a factor causally connected to the others, two *means* are depicted on the right, and they are connected through causal paths to the *ends* of the map. To facilitate the visual tracking of each effect to its root cause, causal links are colored according to the two existing causal roots. Positive relationships from A to B indicate that an increase in A leads to an increase in B, while a negative relationship implies that an increase in A causes a decrease in B. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

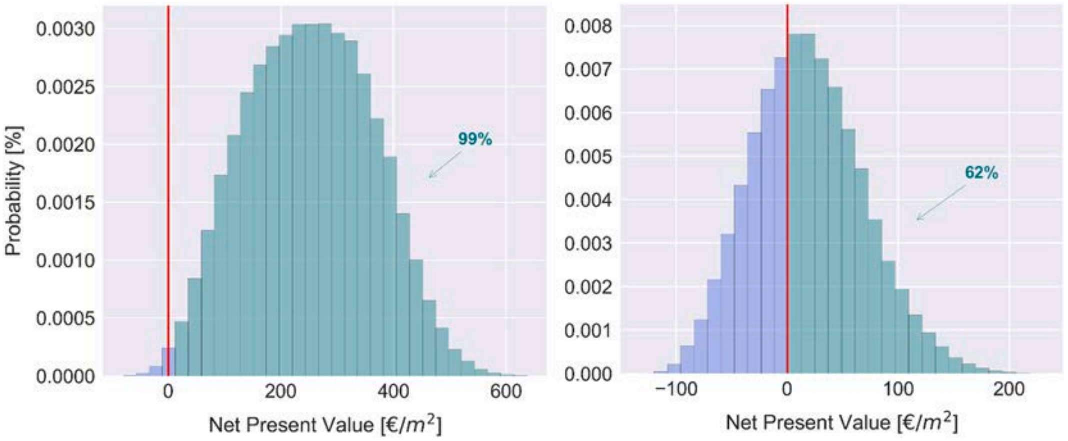

Fig. 8. Cost-benefit analysis results: social perspective (on the left) and private perspective (on the right).

Patient Rule Induction Method and Scenario Discovery results are displayed in Fig. 9. Scenario discovery, through the Patient Rule Induction Method algorithm, identifies those scenarios in which PV-green roofs exhibit a positive NPV. Specifically, a set of constraints is imposed on the uncertainties (i.e., costs, benefits and discount rate values) to identify a subregion of the uncertainty space where NPVs are positive most of the time. Various candidate subregions exist and feature different coverage and density values (Fig. 9a). Coverage represents the ratio of the number of cases of interest (positive NPVs) in the chosen subspace to the total number of cases of interest. Density is the ratio of the number of cases of interest in the subspace to the total number of cases in that space (Bryant and Lempert, 2010). In this exercise, a high density was preferred, while also keeping high coverage. Thus, density of 85% and coverage of 77% were chosen.

The resulting subregion of the uncertainty space leading to positive NPVs is constrained in two dimensions: the installation cost of green roofs, and the benefit from electricity generation (Fig. 9b). The installation cost should not exceed 82 €/m^2 while the electricity generation benefit should not be lower than 3 €/m^2/year. With such constraints, a positive NPV can be found most of the time (85%). In addition, within such constraints the scenarios leading to a positive NPV are 77% of all scenarios. An overview of the sampled scenarios leading to desired (i.e., positive) and undesired (i.e., negative or null) NPVs is provided in Fig. 10.

4. Discussion

4.1. *Definition of the conditions for implementing photovoltaic-green roof energy communities*

Following the REC's legal model, a PGEC can be defined and specified in policies and supporting schemes as:

- *open to voluntary participation of* local natural persons, local small and medium-sized enterprises, and local authorities;
- *effectively controlled by* members or shareholders in the proximity of the community's PV-green roofs, who nevertheless enable the community to remain *autonomous*; and
- with the *primary purpose* to provide environmental, economic, and/or social community benefits for its shareholders or members and/or for the local area where it operates.

With regard to incentives for PGECs, results from the private probabilistic CBA in the Luxembourg case show the need of incentives to increase the chances that PGECs become an economically convenient investment. Such incentive is reasonable on the grounds that PV-green roofs are economically convenient from a social perspective. However, no incentive was included in the Luxembourgish transposition of the RED II.

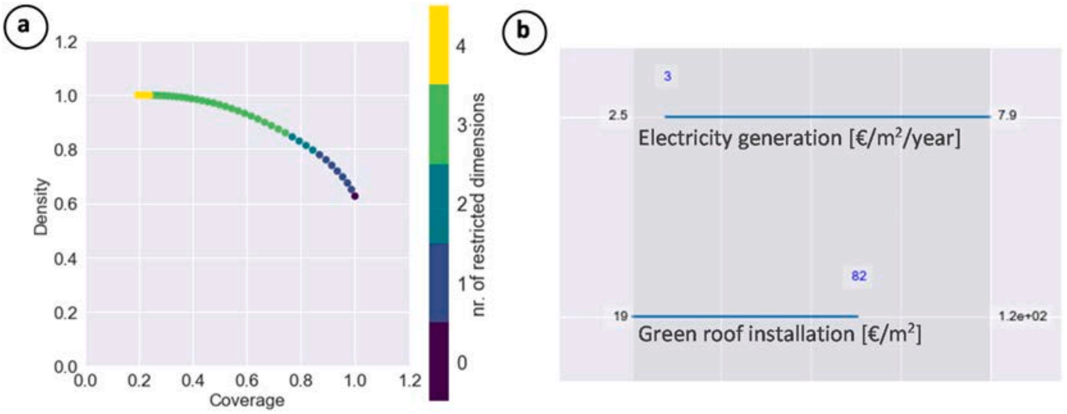

Fig. 9. (a) Patient Rule Induction Method results: possible subsets of the uncertainty space with different density-coverage values; (b) Scenario discovery results: constraints to be imposed on electricity generation and green roof installation to define the chosen uncertainty space; in such subspace a high density and coverage of scenarios with positive NPVs can be found. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

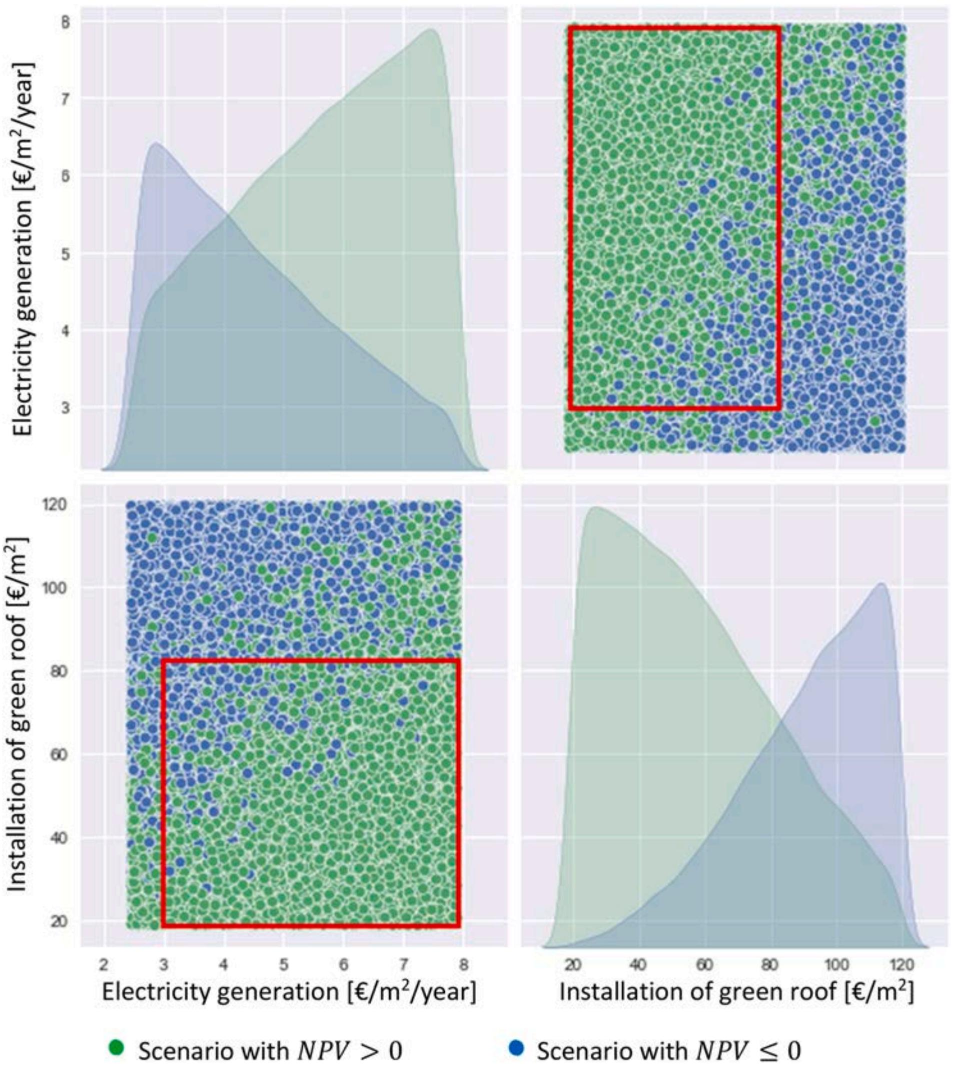

Fig. 10. Sampled scenarios. Outcomes with a positive NPV are displayed as yellow dots and outcomes with a negative or null net present value as blue dots. Constraints (displayed as red boxes) are needed on the installation cost of green roofs and electricity generation benefit to achieve positive net present values. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

According to the Luxembourg government officials interviewed, monetary incentives should not be needed for the development of RECs in Luxembourg. This is contrary to the situation of many other countries in the EU, where upfront costs call for *ad-hoc* support schemes (Verde and Rossetto, 2020). Instead, during the interview carried out with the Italian industry expert, the need for incentives was highly stressed to overcome implementation barriers. The apparent position maintained in Luxembourg may be justified by the particularly high GDP per capita of this country. Government officials also described that in the future any standing regulatory barrier will be removed and facilitation of access to information will be provided to RECs such as PGECs. As an alternative to the incentive schemes defined by RED II, the Luxembourgish law introduces a tax on electricity consumption, to be paid by end users, and a tax exemption. Such exemption is granted to installations with nominal capacity up to 100 kW or that self-consume electricity up to 1000 MWh (art. 30, Loi du 3 février 2021). Therefore, PGECs and other types of RECs within those nominal capacities might benefit from such tax exemption.

4.2. Global and local cost-benefit analyses of photovoltaic-green roofs

The reviewed literature of CBAs present limitations regarding the baseline roof and time horizon definitions. The baseline is not explicitly mentioned and was inferred in two articles, while no baseline can be identified in three other articles. Since CBA results are differentials between a baseline and an alternative situation (Harris and Roach, 2022; Romijn and Renes, 2013), the lack of this information hampers the potential use of costs and benefits from these studies as input data.

Regarding the time horizon, few studies use a shorter time (10–30 years) than average (40 years) and the residual value of the project is not considered (Shin and Kim, 2015, 2019; Gwak et al., 2017; Xing et al., 2021). According to the European Commission guidelines on CBAs (Sartori et al., 2015), the residual value of a project should be accounted for if the CBA's time horizon is shorter than the project's service life. This means that CBA results of some studies may lack a positive cash flow, which, depending on the time horizon chosen, may significantly influence the accuracy of cost and benefit values. Thus, whenever the time horizon is lower than PV-green roofs' lifetime, including a residual value in future CBAs is suggested. As for this work, only original costs and benefits were taken from the reviewed articles rather than output metrics, and a 40-year time horizon was used. Thus, such shortcomings have a very limited effect on the current analysis.

Additionally, cost and benefit values in the global and local analyses rely on a pool of valuations from different locations and years, whereby the oldest study reviewed dates to 2008. This paper corrects values considering inflation and income differences over time, as well as purchase power parity across locations. However, benefit valuations relying on methods involving tax reductions, emission permits, and fees, may significantly change as political conditions evolve over time. Thus, whenever possible, it is advisable to also consider this other factor when applying such a methodology to inform policymaking.

In the local analysis, equivalent conditions to the Luxembourgish case are considered. Practically, the geographic context (EU) as proxy for general socio-economic conditions, and the climate class (Cfb) were used. As for the CBA reference conditions against which costs and benefits are calculated, a common baseline roof (black roof) was used. Other additional characteristics could be considered to define reference conditions, and perhaps more than one reference condition may be considered in future works. For example, aspects such as the presence of a roof's insulation layer, the rooftop's slope, and the building's type (e.g., residential, commercial, school, etc.) might also influence the range of costs and benefits. However, these attributes are recorded only in some articles, and it was preferred not to further constrain the sample for the *local analysis* of this paper.

4.3. Analysis of the economic convenience of photovoltaic-green roof energy communities and their contribution to the European green Deal

This study shows that PGECs equivalent to that of the Luxembourgish case study are economically convenient from a social perspective. In addition, they are convenient from a private perspective only 62% of the times, depending on the valuation of each cost, benefit, and choice of discount rate. It is worth noting that the PGEC of this paper's case study covers a large area (section 2.2), and the overall PV installed power is greater than 1 MW, but not all PGECs can be of this size. In fact, a small-scale PGEC with a PV installed power lower than 10 kW would be economically convenient in 98% of the cases from a social perspective, but only in 45% of the cases from the private perspective. This sharp reduction in the convenience from the private perspective is due to the installation cost of PV panels, which rapidly increases as the overall installed power diminishes. In particular, costs seem to remain rather constant and low when the installed power surpasses 1 MW. Therefore, when considering incentives for PGECs, large-scale PGECs with an installed power $>$ 1 MW should be prioritized, so to unlock a significant economic convenience for these communities.

Among the value ranges for the costs and benefits reviewed, a particularly high value can be seen for aesthetics increase, displaying a maximum of 328 €/m^2. This value plays an important role in making PV-green roofs economically convenient and at first sight might seem too high. However, house prices in Luxembourg are significantly higher than those of other countries around the world (OECD, 2021b). OECD (2021b) assigns to Luxembourg the fourth highest housing price index, including the sales of newly-built and existing dwellings. Moreover, a recent review of the Luxembourgish housing market observes that housing prices in Luxembourg are around 6.000 €/m^2 (BIL, 2019). This figure would make the value of 328 €/m^2 amounting only to 5%, which is consistent with the percent values considered by other authors (Bianchini and Hewage, 2012). Thus, although this benefit's upper-limit value associated with the aesthetics increase may appear high at a first glance, it can be deemed realistic for Luxembourg.

As for the contribution of PGECs to EGD objectives, future works might attempt to quantify rebound effects that could stem from the large-scale adoption of PV-green roofs. Direct rebound effects are not expected to be particularly high. It is reasonable to believe that consumption related to heating and cooling within a building would not increase because of the energy savings unlocked by PV-green roofs. In fact, once thermal comfort is reached, the energy savings obtained should not provide an incentive to further consume energy for heating or cooling. In contrast, indirect rebound effects, which are more difficult to quantify, might be non-negligible. For example, PGEC members might use the cost savings from energy efficiency improvements to increase consumption in other products that require more energy (or entail more greenhouse gas emissions), which negatively contribute to EGD objectives. Therefore, future works estimating potential indirect rebound effects from the adoption of PV-green roofs are suggested.

4.4. Methodological advances

While the theory of exploratory modelling already exists (Bankes et al., 2013; Kwakkel, 2017), the combined methodology hereby presented has never been used before in the domain of PV-green roofs. In this paper, the combination of probabilistic cost-benefit analyses (private and social ones) with Scenario Discovery proved to be effective in enhancing CBAs of green roofs and PV-green roofs.

Despite multiple attempts to economically value costs and benefits of green roofs, scientific uncertainty revolving such economic valuation is still evident in costs and benefits' value ranges (Table 4). The combined methodology hereby presented contributes to overcoming this issue, mediating between conflicting scientific valuations. In particular, the methodology avoids the often contested "agree-on-assumptions" approach (Lempert, 2014), in which scholars and policymakers need to agree on the uncertain assumptions utilized to accept CBA results. Despite this being an often-used approach in CBAs (Kalra et al., 2014), such approach provides vulnerable results that may be disregarded or discredited based on a (possibly even strategic) disagreement on assumptions. Conversely, this paper uses an "agree-on-decisions" approach (cf. Lempert, 2014). That is, various sets of cost and benefit valuations were considered first, and their monetary consequences (i.e., the resulting NPVs) were then calculated. The corresponding "agreed" decision in this paper is the selection of positive NPVs as the desired outcomes of interest, which any party included in the modelling activity or in its discussion would desire. This approach defers any agreement on uncertain assumptions until the consequences of known, namely simulated, alternative cost and benefit valuations, and their consequences are evaluated. Then, only those monetary valuations (i.e., the electricity generation benefits and the installation cost) that were found to "make a difference" in reaching the outcome of interest are selected. Such selection provides the basis for discussion among stakeholders and policymakers just on the smaller subset of uncertainties that "make a difference". In this way, the chances to reach consensus over the economic convenience of PV-green roofs may well increase.

5. Conclusion and policy recommendations

This study investigated whether and under which conditions PGECs are capable to meet EGD objectives in an economically convenient manner. The global-scale literature review conducted clarifies that PV-green roofs, as part of PGECs, deliver a wide range of benefits that contribute to achieving both energy and environmental EGD objectives. These objectives include renewable energy generation, energy efficiency and affordability, the reduction of urban heat island effect, air quality and biodiversity enhancement. A model for probabilistic cost benefit analyses, from a social and a private perspective, was developed for PV-green roofs and tailored to a case study in Luxembourg. The model was developed to be easily replicable in other sites and countries.

From the perspective of society, PV-green roofs were found to be a convenient investment in Luxembourg, virtually for all valuations of their costs and benefits, and for any social discount rate within the ranges identified by the literature.

From the private perspective, i.e., from the perspective of PGEC members, PV-green roofs remain economically convenient in 62% of the cases, depending on cost, benefit, and discount rate valuations. An incentive of 85 €/m^2 would make them a convenient investment in 99% of the cases. Thus, it can be concluded that PV-green roofs contribute to a large selection of EGD objectives in an economically convenient manner, although not in all potential cases. The specific conditions necessary to obtain a positive NPV for PV-green roofs in Luxembourg are a green roof installation cost below 82 €/m^2 and a benefit from electricity generation not lower than 3 €/m^2/year. More stringent conditions would be necessary in the case of small-scale PGECs (with installed power $<$ 10 kW).

From a legislative standpoint, the review of legal acts carried out shows that among the various legal models available in EU policies, RECs represent the most suitable legal model for PGECs. This is mainly due to the specific purpose and support schemes envisaged by the EU legislator for such communities. Besides legal models, follow up papers should also identify suitable business models for PGECs. Such models may be identified from works investigating energy communities, PVs, urban nature-based solutions, or combined technologies' business models (Bocken et al., 2019; Egusquiza et al., 2021).

With regard to support schemes, an economic incentive for PGECs is justifiable on the grounds of the social and private CBAs conducted. Such an incentive would further increase the economic convenience of PV-green roofs.

From a policy standpoint, this paper illustrates that PGECs, defined as RECs, are capable to meet EGD objectives in an economically convenient manner although not in all potential cases. This pilot analysis shows that synergies between energy and environmental policies are possible, and actions stemming from these synergies can address EGD objectives through the deployment of PV-green roofs. For this reason, it is important that the transposition of RED II in Member States foresees the combination of "green" technologies, such as nature-based solutions, and "grey" technologies as one of the "specificities" allowed by the RED II for RECs. In this regard, it is also important that support schemes, including incentives, for RECs are designed to account for such a specificity. Since a great number of European countries have not yet fully transposed the European legislation, nor the RECs' definition and their relative support schemes, the outputs from this paper can offer valuable information to inform future analyses for policy support.

CRediT authorship contribution statement

Francesco Cruz Torres: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Javier Babí Almenar:** Conceptualization, Funding acquisition, Investigation, Methodology, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Benedetto Rugani:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing, All 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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List of abbreviations

CBA	Cost-benefit analysis
Cfa	Humid subtropical climate, according to the Koppen-Geiger climate classification
Cfb	Temperate oceanic climate class, according to the Koppen-Geiger climate classification
CO_2	Carbon dioxide
Csa	Hot-summer Mediterranean climate class, according to the Koppen-Geiger climate classification
EU	European Union
EGD	European Green Deal
GDP	Gross domestic product
kW	Kilowatts
MW	Megawatts
NPV	Net present value
PGEC	Photovoltaic-green roof energy community
PV	Photovoltaic
REC	Renewable energy community
RED II	Renewable Energy Directive recast, or Directive 2018/2001 recast
WTP	Willingness to pay

Appendix A. Supplementary data

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